Reliability Analysis on Protection Devices Inclusion in LV Residential Distribution Network

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***Abstract*—The inclusion and arrangement of protection devices within the LV distribution network often neglected. By exemption of protection devices during network modelling, may result in overestimation of reliability performances. Detail network representation of UK LV residential model is used to assess network reliability performance. The analytical and improved Monte-Carlo Simulation (MCS) approaches are used to estimate system-related reliability indices.**

***Index Terms*—Analytical; Distribution Network; Monte-Carlo; Protection; Reliability.**

I. INTRODUCTION

The evolution and transformation of existing networks into future ‘smart grid’ require comprehensive/detail planning, management and operation of the distribution network. Instead, during the reliability performance analysis of HV and MV networks, LV networks are typically not presented in much detail. The most common equivalent form representation of LV network is a simple aggregate load, specifying the number of supplied customers and their peak and reactive power demands. However, the contribution of the LV networks to the overall system reliability performance in term of frequency and, particularly, duration of LIs could be significant, although permanent LV faults usually do not result in interruptions of a large number of customers.

The formulation of more detailed and accurate reliability models is accompanied by the use of the actual demand patterns and load profiles of residential customers. The time-varying demand is also correlated with daily probabilities of fault in order to specify the moment of fault occurrence for determining whether the power supply to the loads/customers will be interrupted, or not. These two additional inputs data are the improvement made for conventional MCS.

Protection system provides an important role in disconnecting healthy network from the faulted network. Neglecting any actual components will result in an underestimation of reliability performance and inaccurately calculated reliability indices. By neglecting protection system on the network, in any case of any fault power component, it will result in the power outage for all power components. Installation of DG in the network with the absence of protection system will not improve the system reliability because a faulted section of the feeder cannot be isolated.

II. TYPICAL ARRANGEMENT OF LV DISTRIBUTION NETWORK

Secondary distribution feeders can be in the type of insulated conductor (underground cable) or bare conductor (overhead lines). Underground cables are usually installed in an urban area while overhead lines are equipped in the sub-urban/rural area based on space availability. It is preferred to equip overhead lines within the sub-urban/rural area due to its lower capital cost.

Three-phase, four-wire, distribution system is used worldwide to supply LV customers, with nominal voltage in the region of 230/400 V. However, there are considerable variations in the way in which the supplies to the individual customer are connected to 3-ph systems. In the UK, it is unusual to take more than one phase of a residential customer premises. Accordingly, the typical network arrangement considered for overhead LV power distribution is illustrated in Figure 1. Based on Figure 1, one cable supplies a number of poles mounted fuse, in which several customers are protected by a single fuse.

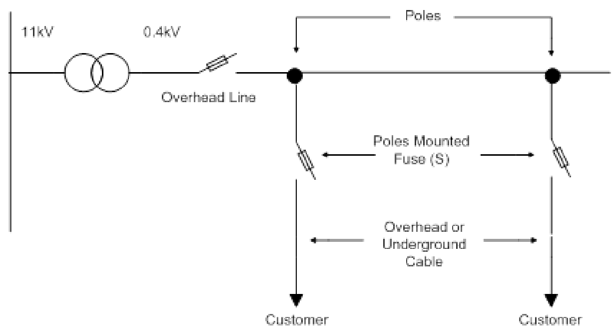

Figure 1: Typical Arrangement for LV overhead distribution systems [1]

III. GENERIC TEST NETWORK MODEL

Test network used to simulate the reliability analysis is a typical sub-urban (SU) UK LV residential distribution network configuration without and with protection device arrangements, in Figures 2 and 3, respectively. Figure 3 contains more network components (fuses and circuit breakers) within the dashed-rectangle area compare to Figure 2. The SU LV network model is defined for smaller towns and sub-urban areas around the big cities, with medium to low load demands. From MV/LV substation, the powers are transferred to customers via overhead lines, and although it is common to use bare conductors due to lower capital cost, some sub-urban areas are using aerial cables for better reliability, as bare conductors are considered vulnerable to environmental and external impact, such as lightning, snow, animal, trees and wind. The typical arrangement consists of several overhead main feeders, with about 30 m of pole-to-pole distance, in a radial configuration. Supplied load points in this network are with lower demands, and typically only the feeder head is protected by a CB, while branch/lateral feeders are protected by fuses.

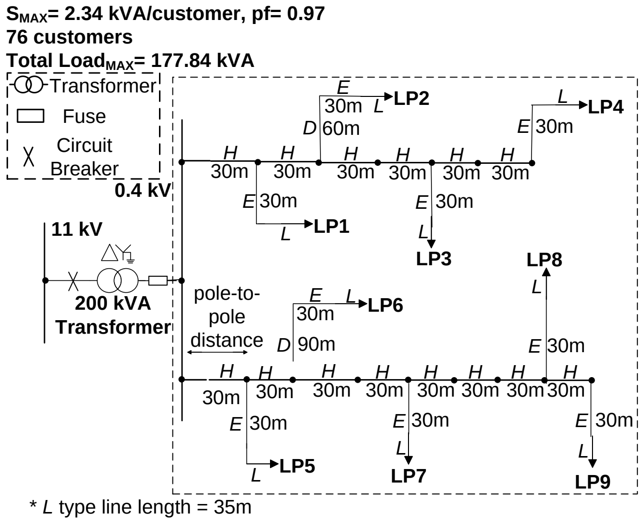

Figure 2: LV SU distribution network without fuse protection [2]–[7]

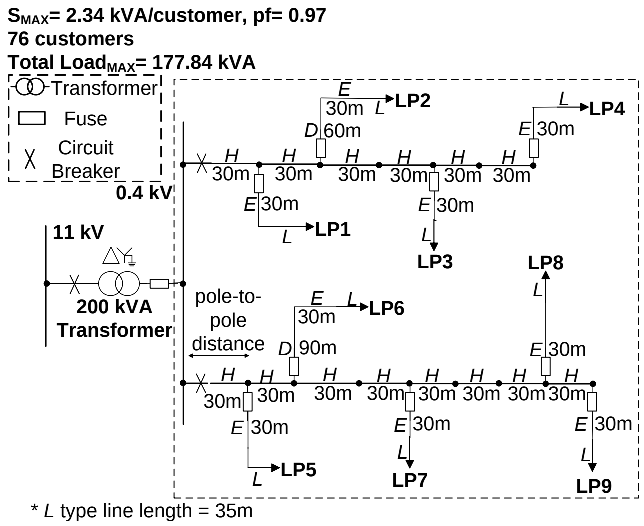

Figure 3: LV SU distribution network with fuse protection [1]–[7]

The generic SU network has no redundancy (N-1 security for distribution transformer and substation main fuse) and no alternative supply point. The substation and switchgear for this network are of the outdoor type and the maximum rating of the transformer is 200 kVA, supplying a total of 76 customers connected to nine load point (LP1 to LP9), with a maximum demand of 172.5 kW and minimum demand of 28.5 kW [8]. Due to the complexity and size, the LV networks are often represented by lumped aggregate models in order to reduce computational times in reliability analysis. However, neglecting the actual physical parts or components of a network will result in an underestimation of reliability performance and inaccurately calculated reliability indices.

A. *Reliability Simulation Method*

Two common reliability assessments of the network are applied for this analysis; analytical and probabilistic technique. Analytical approaches generally limit output results (i.e. calculated reliability indices) to only the mean values, while probabilistic approaches provide a more comprehensive information, including probability distribution functions, standard deviations and variations of the calculated reliability indices. Analytical approaches always produce one single set of output results for one single set of input parameters, while probabilistic approaches always produce results which vary in certain ranges, based on the modelling of the related random and stochastic factors (e.g. assumed probability distribution of input parameters).

Inverse Transform Method, typically known as Monte-Carlo Simulation (MCS) is one of the probabilistic techniques used to assess the impact of protection devices arrangements in LV distribution network. For MCS technique, a random generator is used to assign a random variable to an inverse distribution function in order to convert the input data of fault rates and repair times of network components in corresponding to system reliability output values. The operating and failure of every network component are determined by the corresponding network component fault rates, whereas the duration of failure states by repair times.

B. *Reliability Indices*

The performance of test network is assessed through the calculation of the standard sets of reliability indices. The System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI) and Customer Average Interruption Index (CAIDI) are indices which are generally used by most DNOs.

$$SAIFI = \frac{Total\ number\ of\ customers\ interrupted\ (LI)}{Total\ number\ of\ customers\ served} \quad (1)$$

$$SAIDI = \frac{Total\ customer\ interruption\ durations\ (by\ LI)}{Total\ number\ of\ customer\ served} \quad (2)$$

$$CAIDI = \frac{SAIDI}{SAIFI} = \frac{Total\ customer\ interruption\ durations}{Total\ number\ of\ customers\ interrupted} \quad (3)$$

$$MAIFI = \frac{Total\ number\ of\ customers\ interruptions\ (SI)}{Total\ number\ of\ customers\ served} \quad (4)$$

C. *Reliability Data*

Correct assessment of reliability performance strongly depends on the availability and accuracy of the required input data, whereof the highest importance are mean fault rates and mean repair times (or mean unavailability) of the network components in the analysed networks. Table 1 presents statistics of fault rates and means repair times values of network components [9].

Table 1
Mean Fault Rates and Mean Repair Times of Network Components [9]

Power Component	Voltage Level (kV)	Mean fault rate λ_{mean} (faults/year)		Mean repair time μ_{mean} (hours/fault)	
Overhead Lines	<11	0.168	0.21	5.7	-
	11	0.091	0.1	9.5	-
	33	0.034	0.1	20.5	55
Cables	<11	0.159	0.19	6.9	85
	11	0.051	0.05	56.2	48
	33	0.034	0.05	201.6	128
Trans-formers	11/0.4	0.002	0.014	75	120
	33/0.4	0.01	0.014	205.5	120
	33/11	0.01	0.009	205.5	125
Buses	0.4	-	0.005	-	24
	11	-	0.005	-	120
	>11	-	0.08	-	140
Circuit Breakers	0.4	-	0.005	-	36
	11	0.0033	0.005	120.9	48
	33	0.0041	-	140	52
Fuses	0.4&11	0.0004	-	35.3	-

D. Inclusion of Actual Load Profiles and Daily Probabilities Fault Rates

Traditionally, for analytical and MCS reliability assessment approaches, the supplied loads are usually represented by a bulk/lumped model, specifying rated or maximum power demands. This basically corresponds to the "worst case" scenario, as the analysis of faults will then result in the interruption of the maximum number of customers, i.e. in the maximum load/energy not supplied. However, for most of the time, the actual customer demands are lower than the maximum one, and this approach for reliability performance assessment typically (significantly) overestimates calculated reliability indices, i.e. results in lower than actual reliability performance levels [9], [10]. By incorporating actual time-variable load demands, only a part of customers, or possibly no customer will be disconnected.

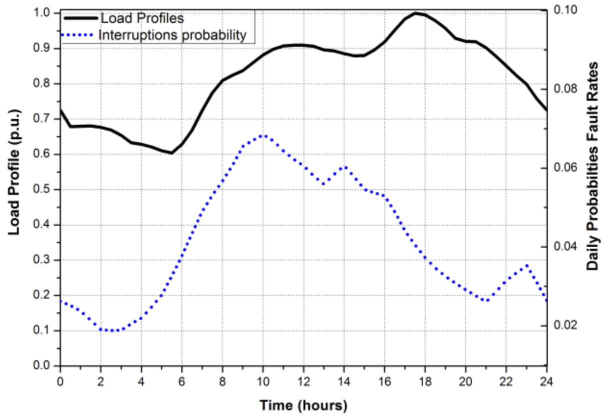

Figure 4: Correlation between daily load profile and daily probability fault rates

Moreover, a better correlation between the time at which faults occur in the network and the time-dependent changes of actual demands (represented by e.g. load profiles/curves) will significantly improve calculation of reliability indices, as the higher fault rates should be allocated to the periods of time when demand (and therefore loading conditions of network components) are higher than when the demands are lower (e.g. during the night). The daily fault probabilities used are obtained from a detailed investigation of available statistical data, i.e. two years of recordings of all SIs and LIs for one UK DNO [11], [12], while the aggregate daily load profiles are recorded from the actual annual demands of the same DNO [13].

E. Fault Types

One simple way of to differentiate SIs and LIs is by making a clear distinction between short and long supply interruption and adopted it to the reliability assessment procedure. By that purpose, past recordings collected from 14-UK DNOs between 2005 to 2009 [14] were analysed, indicate 54% of supply interruption events were temporary (SIs) and 46% were a permanent fault (LIs).

IV. RELIABILITY PERFORMANCES

Exponential and Raleigh distribution functions are used in this paper for input fault rates and repair times, respectively with a total simulation of 10,000 years. However, Gamma, Normal, Weibull and Poisson distribution could also be adopted [15].

A. Results

The reliability performance results are illustrated in Table 2 and Figures 5-10.

Table 2
Reliability Performance Results for Analytical and MCS Approaches

Reliability Indices	Analytical		MCS (Mean Values)	
	Without fuse protection	With fuse protection	Without fuse protection	With fuse protection
SAIFI	0.3167	0.0353	0.2856	0.0416
MAIFI	0.3717	0.0414	0.3385	0.0442
SAIDI	2.8760	0.4308	2.5185	0.5308
CAIDI	9.0812	12.2035	8.7999	12.7673

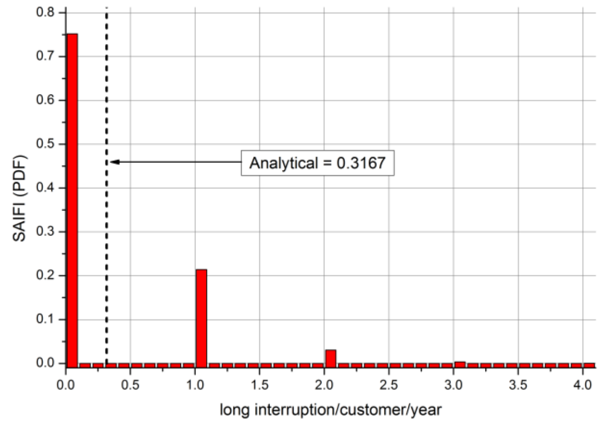

Figure 5: SAIFI (PDF) for LV Network without protection devices

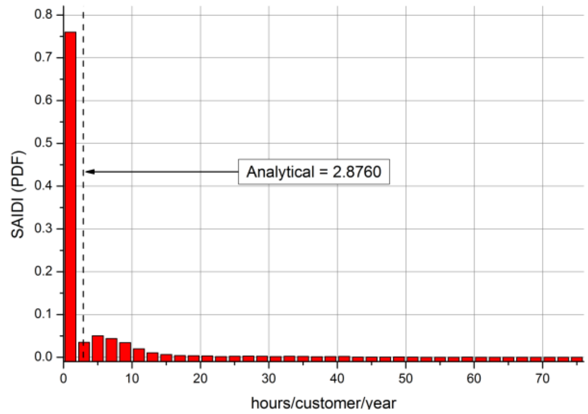

Figure 6: SAIDI (PDF) for LV Network without protection devices

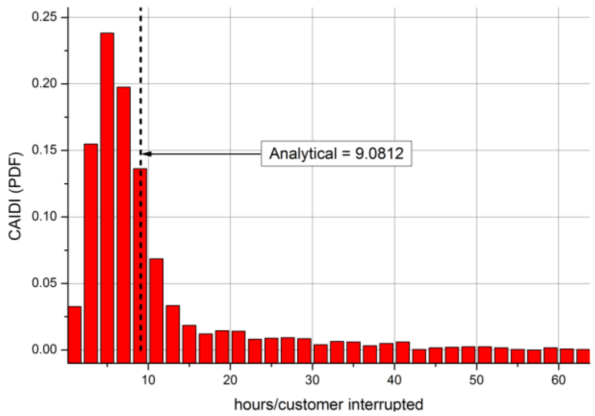

Figure 7: CAIDI (PDF) for LV Network without protection devices

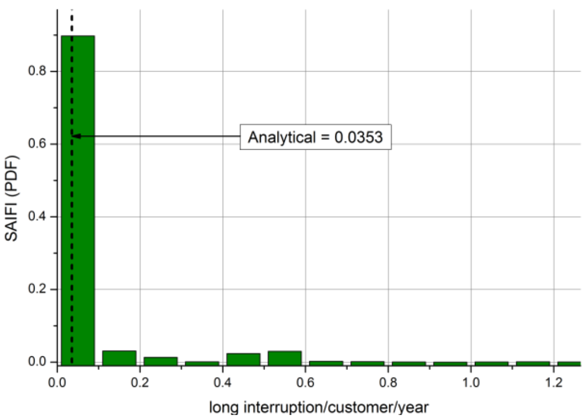

Figure 8: SAIFI (PDF) for LV Network with protection devices

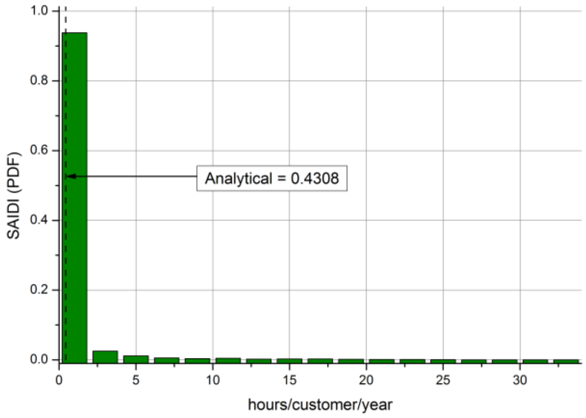

Figure 9: SAIDI (PDF) for LV Network with protection devices

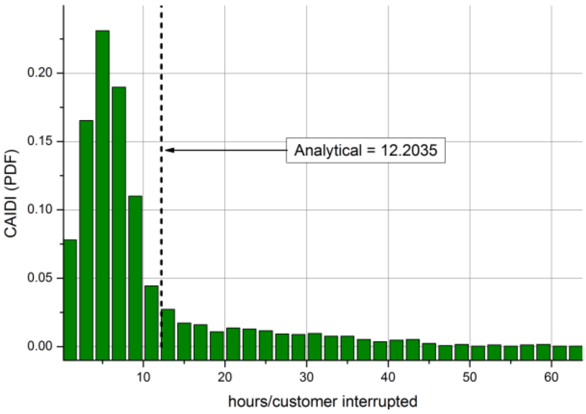

Figure 10: CAIDI (PDF) for LV Network with protection devices

B. Discussion

From a customer point of view, SAIFI and CAIDI indicate an average of total customer experienced on frequency and duration of long interruption per year, respectively. For SAIDI, it indicates the total number of duration interruption per year experienced by the average customer. In Table 2, the value of SAIFI is higher for a network without protection devices than a network with protection devices. This follows the equation of analytical approaches which describe in [16], providing the equivalent fault rate, λ_{eq}, and mean repair time, μ_{eq}, for the bus where aggregate demand is connected:

$$\lambda_{eq} = \sum_{i=1}^{N} \lambda_i \quad (5)$$

$$\mu_{eq} = \frac{1}{N} \cdot \sum_{i=1}^{N} \mu_i \quad (6)$$

where N is a total number of power components in the equivalent part of the system, each with mean fault rate, λ_i, and mean repair time, μ_i.

Based on Figure 2, there is no protection device within the dashed-rectangle area of LV network. Since there is no protection device in LV network, the equivalent fault rate and mean repair time are not divided into section, but aggregated within the network. The equation for SAIFI by including λ_{eq} as follows.

$$SAIFI = \frac{\lambda_{eq}}{TC} \quad (7)$$

where TC is the total number of served customers.

For example, any power components fail within the LV network, resulting disconnection of the main fuse (at the secondary part of 11/0.4 kV distribution transformer) causing all network component experience fault and all customers experience an interruption. Therefore, it required a number of a protection device in order to segregate the fault by section.

Proper arrangement of protection devices in LV network, will result in better reliability equivalent fault rate and mean repair times. By sectionalize the sum of fault rate and mean repair time for each power components based on the location of the fuses, the values of equivalent fault rate and mean repair time will become smaller. Below are the equations for sectionalise fault protection device:

$$\lambda_P = \sum_{iP=1}^{NP} \lambda_{iP} \quad (8)$$

where: λ_{iP} is the network component experience interruption only.

By limiting the number of network component experience interruption, through a change of λ_{eq} into λ_P in equation (7), the value of SAIFI become less. For CAIDI, the trend is otherwise. This is due to the denumerator N, wherein LV network with protection devices, the number of an affected network component is reduced, which causes an increase in CAIDI value. Although by average duration of interruption (CAIDI) in LV network with protection devices is high, in all total duration of interruption per year (SAIDI), the values less. This is due to the value of SAIFI, in which affect the performance value of SAIDI (based on equation 3).

Although the MCS is run for 10,000 years, there is still 12% mismatch of SAIFI values between analytical and MCS approaches. Based on Table 1, the mean fault rate of overhead lines for below 11kV is 0.168 faults per kilometre per year. Most of the power components in LV SU are overhead lines of type L with the length of 30 meters. By multiplying mean fault rate and length, it will result in 0.00504 failures analytically. Then by multiplying all again with 10,000 years, it shows 50.4 faults and in MCS (which is in time-series simulations), it cannot generate 50.4 faults, but it will round up the value to 51 faults. Therefore, there is about 12% mismatch between 50.4 and 51 faults, and that is the reason why there is a small mismatch between analytical and MCS approach.

The results present are to emphasize the inclusion of protection devices within the LV distribution network as its affect the reliability performance. Plus, there are no ideal, minimum or maximum values of reliability indices, as the values vary from one DNOs to another, depending on the load demand, geographical areas, location, network configuration, size of networks, network components, and etc.

V. CONCLUSION

The presented analysis demonstrates the implication of exclusion and inclusion of protection devices within the LV network. It is significant to properly model the LV network with detail as it affects the performance of the LV network itself and for whole distribution network (e.g. 11 kV and 33 kV) in general. Based on the reliability results suggest the inclusion of protection devices within LV network in order to have an accurate estimation of reliability performance. The present work also has to implement daily probability of fault rate and actual load profiles into the analysis, which resulting more accurate simulation and calculation of system-based indices for residential customers.

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