RELIABILITY ASSESSMENTS OF SINGLE AND THREE-PHASE REPRESENTATION OF LV DISTRIBUTION NETWORK

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Abstract in Bahasa Melayu

Kebanyakan kajian yang sedia ada lebih suka memodelkan rangkaian pengagihan sebagai rangkaian tiga fasa simetri, dengan menggunakan perwakilan rangkaian talian bersamaan, kerana ia memudahkan analisis. Pada amnya, ini mengandaikan bahawa komponen perlindungan (cth. Pemutus litar atau fius untuk "pemotongan bekalan", iaitu pemotongan bekalan yang rosak) beroperasi dalam mod operasi tiga tiang. Ini bermakna bahawa untuk kesalahan fasa tunggal dan fasa fasa asimetik, yang biasanya 5-6 kali lebih kerap daripada kesalahan tiga fasa, komponen perlindungan akan melepaskan ketiga-tiga fasa, bukan sekadar salah satu. Secara amnya, ini mencerminkan aplikasi dan penetapan sistem tiga kutub yang betul dalam rangkaian MV, tetapi tidak mungkin untuk rangkaian LV, di mana kebanyakan pelanggan disambungkan ke satu fasa 230 V bekalan dan di mana fius, sebagai komponen perlindungan yang paling biasa, dikendalikan dalam mod tunggal. Sebaliknya, dengan menggunakan perwakilan lini tunggal rangkaian LV bermakna tidak ada perbezaan di antara jenis kesalahan yang berlainan dan bahawa bilangan pelanggan yang terganggu akan sangat dipandang remeh. Oleh itu, jika aspek reka bentuk rangkaian LV tidak dimodelkan secara tepat, penilaian prestasi kebolehpercayaan rangkaian LV tidak betul.

Abstract in English

Most of the existing studies prefer modelling of distribution networks as symmetrical three-phase networks, using the corresponding single-line network representations, as that substantially simplifies the analysis. Generally, this assumes that the protection components (e.g. circuit breakers or fuses for "feeder cut-off", i.e. disconnection of faulted feeders) operate in a three-pole mode of operation. This means that for asymmetrical single-phase and double-phase faults, which are typically 5-6 times more frequent than the three-phase faults, the protection component will disconnect all three phases, not just the faulted one(s). Generally, this reflects the correct application and setting of the three-pole protection systems in MV networks, but it is not likely for the LV networks, where most of the customers are connected to a single-phase 230 V supply and where fuses, as the most common protection components, are operated in a single-pole mode. Conversely, using a single-line representation of LV networks means that there will be no distinction between the different fault types and that the assessed number of interrupted customers will be significantly overestimated. Accordingly, if this aspect of the LV network design is not accurately modelled, the assessment of reliability performance of LV networks will not be correct.

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Acronyms and abbreviations

HV	High voltage
MV	Medium voltage
LV	Low voltage
LIs	Long interruptions
EC	Energy Commission
DNOs	Distribution network operators
MTTR	Mean time to repair
CAIDI	Customer Average Interruption Index
SAIFI	System Average Interruption Frequency Index
SAIDI	System Average Interruption Duration Index
DG	Distributed generation
MCS	Monte-carlo simulation
R	Rural
SU	Sub-urban
PDF	Probability distribution function
TC	Total customer

Nomenclature

λ	Average failure rate
r	Average outage duration
U	Average annual outage time
Rph	Resistance per phase
Xph	Reactance per phase

Chapter 1 Introduction

During the standard reliability performance analysis of medium voltage (MV) and high voltage (HV) networks, downstream connected low voltage (LV) networks are typically not represented in much detail. The two main reasons for that are: a) a general lack of accurate information on LV network configurations (particularly service entry connections of LV customers), applied LV protection systems and actual fault rates and repair times of LV network components, and b) a significant increase in complexity of calculations, leading to excessive computational requirements and long simulation times, if LV networks with a large number of components are included in the analysis. Consequently, as the analysis proceeds from lower voltage levels to higher voltage levels (i.e. to the analysis of larger networks), more and more LV network components have to be included. Particularly important is representation of the new and emerging network components connected at LV levels, such as energy storage, microgeneration and demand-side manageable loads, as these might have strong impact on the actual reliability performance of analysed networks at all voltage levels. Nevertheless, in standard reliability analysis, LV networks are usually represented using some “equivalent form” [1]–[6], instead of a more detailed (reliability) model.

The most common equivalent form representation of LV networks is by a simple aggregate (“lumped”) load, specifying number of supplied customers and their peak active and reactive power demands (and sometimes minimum, or average demands, or daily load profiles) downstream of the MV point of aggregation, which is typically a primary or secondary distribution substation or transformer. Another common assumption is that most of the permanent faults resulting in long interruptions (LIs) of supply occur in MV networks, e.g. [7]–[9]. However, the contributions of the LV networks to the overall system reliability performance in terms of frequency and, particularly, duration of LIs could be significant, although permanent LV faults (the main cause of unplanned LIs) usually do not result in the interruptions of a large number of customers.

Chapter 2 Literature Review

Typically, the importance of reliability in distribution system has received less attention compared to generation and transmission systems. The main reason of these two systems are significant due to these two systems carries high current that affects a vast number of customer (indirectly) and considers as a backbone of electrical supply (especially transmission network). However, the importance of distribution network should not be neglected as it directly connected to the end customer.

Since distribution network supplying the most customer, it ties up by the target or minimum customer satisfaction level imposed by Energy Regular, which in Malaysia is Energy Commission (EC). These targets mostly involved the frequency and duration of interruption. To attain that target, distribution network operators (DNOs) must correctly assess their reliability performance. Therefore, it is critical to have accurate distribution network configurations and parameters. However, due to the size of distribution network, low voltage (LV) network often represented by aggregate model [10]–[15].

Typically, the aggregate model of LV network is represented by active and reactive power downstream from the point of aggregation. For certain steady-state analysis, the LV representation of active and reactive powers are enough, but in term of reliability perspective, additional information is required especially in fault rates and mean time to repair (MTTR) input. The detail reliability input from LV representation may decide the performance level of distribution network.

Furthermore, in the EC report [16], a vast number of customer interruption is originated from LV network, compared to medium voltage (MV) and high voltage (HV) networks as in Figure 1. Customer Average Interruption Duration Index (CAIDI) is defined as average interruption time per customer affected by the interruption. In the same report, CAIDI from LV network is higher than MV and HV networks as in Figure 2. From these statements, the distribution network should include reliability input of LV network for analyses of MV or HV/MV networks. Therefore, by properly illustrating the configuration of LV networks in MV or HV/MV networks, no components will be neglected in regards to the load aggregation from lower to higher voltage.

Another concern related with LV network is modelling of network diagram. Typically, most of the network is modelled as a single line diagram, where all customer of each phases (red, yellow and blue phases) are connected to single conductor. In another word, if the blue phase is faulty/interrupted, other phases (red and blue) also interrupted. The modelling of LV network in single line diagram is incorrect as the protection devices in LV network operate in individual phase. For MV and HV networks, the modelling of network as single line diagram is correct as the protection devices are operating in three phases system [1], [5], [17]–[20]. Hence, ignoring the design of LV network in three phases diagram will underestimate the reliability performance of network.

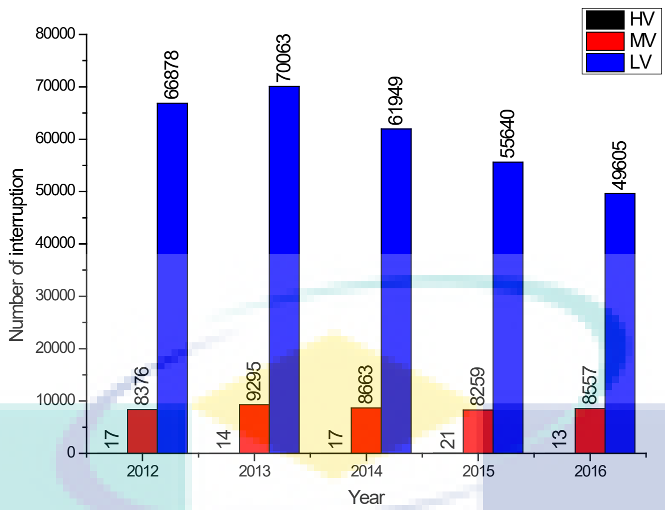

Figure 1. Number of interruption by voltage variation

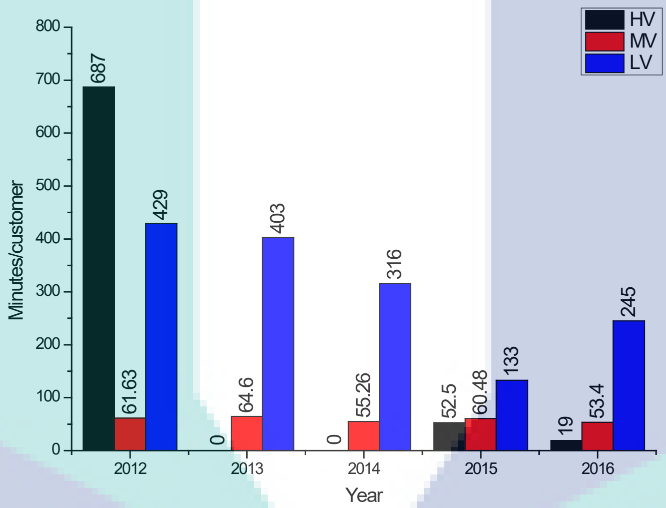

Figure 2. Duration of interruption by voltage variation

Therefore, accurate reliability performance can be obtained with detail and correct design of LV network for analyses of MV or HV/MV networks. Concerning this matter, the paper aims to present the methodology of formulating accurate LV distribution network model based on reliability inputs of network component, component parameters and network configuration.

The evolution and transformation of existing networks into future 'smart grid' required comprehensive/detail planning, management and operation of 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 a 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 importance role of disconnecting healthy network with 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.

Chapter 3 Methodology

In reliability assessment, there are two types of methods that can be used to evaluate the reliability performance of the network, which are analytical and probability assessment. The analytical method uses a mathematical based approach which evaluates the performance of reliability in power system using mathematical solution while the probability method uses random nature process. In terms of contingency, basically the analytical approach will choose the states in increasing order of which each state is evaluated in just one time. The reliability indices are then calculated using mathematic solution based on the statistical data related to each state [21]. As power system consists of a large and complex network, Monte-Carlo Simulation (MCS) will be used to equivalent and assess the performance of networks [22]–[24]. The sequential MCS technique is used which simulates the system chronological behaviour by sampling the system state sequences for several period of time. For this method, two basic inputs which are fault rate and repair time, need to be identified first before it can be randomly generated [25], [26].

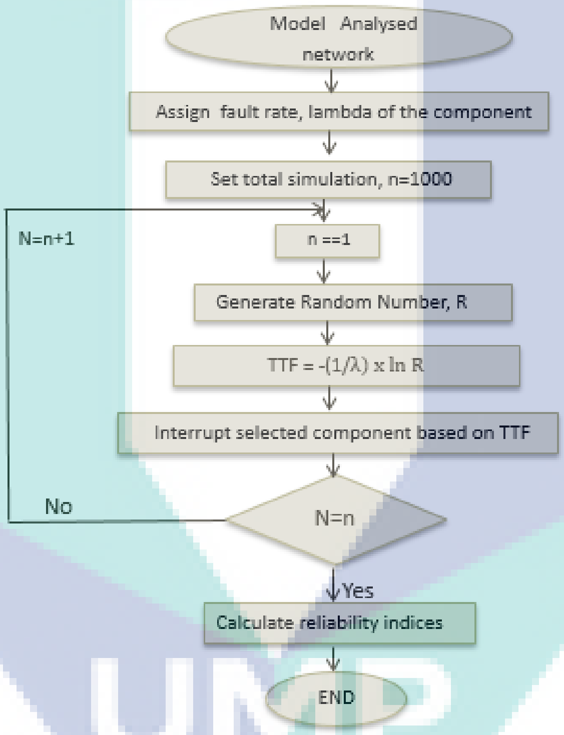

Figure 3. Flowchart of Monte-Carlo Simulation

The technique that used to determine power system reliability is a classical method which is an analytical method [22]. The reliability indices that have been evaluated using classical concept are the three primary ones of average failure rate λ_s, average outage duration r_s, and average annual unavailability or average annual outage time u_s. These indices are expected average values of total customers of the LV distribution system [22], [27]. This term of reliability indices is used to determine the number and duration of interruption.

Average failure rate; $\lambda_S = \sum_i \lambda_i$ (1)

Average outage time; $U_S = \sum_i \lambda_i r_i$ (2)

Average annual outage time; $r_S = \frac{U_S}{\lambda_S} = \frac{\sum_i \lambda_i r_i}{\sum_i \lambda_i}$ (3)

Analytical method has numerous attractive features which a precise method and computationally well-organised and possibly most important, it offers the developer with understanding of the relationship between input variables and final results. Also, analytical techniques have been necessary to provide planners and designers with the results necessary to conclude reliability performance. Analytical techniques denote the system by mathematical model and evaluation of the reliability indices from this model using direct numerical. Besides, they provided expectation indices in relatively short computing time.

LV Equivalent Scenario

Table 1. Description of cases (Network Equivalent)

Case	Description
1	LV network consists of 14 buses and 20 branches
2	MV network consists of 4 buses & 4 branches
3	Detailed (a combination of MV and LV) network consists of 56 buses & 84 branches
4	Equivalent network (a combination of MV and LV equivalent) network

Figure 3 above shows the flowchart of how the performance of reliability in the system is being assessed. In this research, two models of bus system, which are Network 14 and Network 4gs (networks from Matpower) are used to represent the distribution network. Network 14 represents LV distribution network (case 1) while Network 4gs represents MV distribution network (case 2). Both of the networks are being modified by only one generator to analyse the reliability performance of the systems. Before an equivalent network can be assessed, a few analysis needs to be done in both LV and MV networks. In distribution system, the LV network is always located to the downstream of MV network. Even though the objective of this research is to evaluate the performance of LV network, the assessment of MV network is also included to quantify and justify the importance of detailing the distribution network. Hence, there are about 4 different networks that need to be analysed.

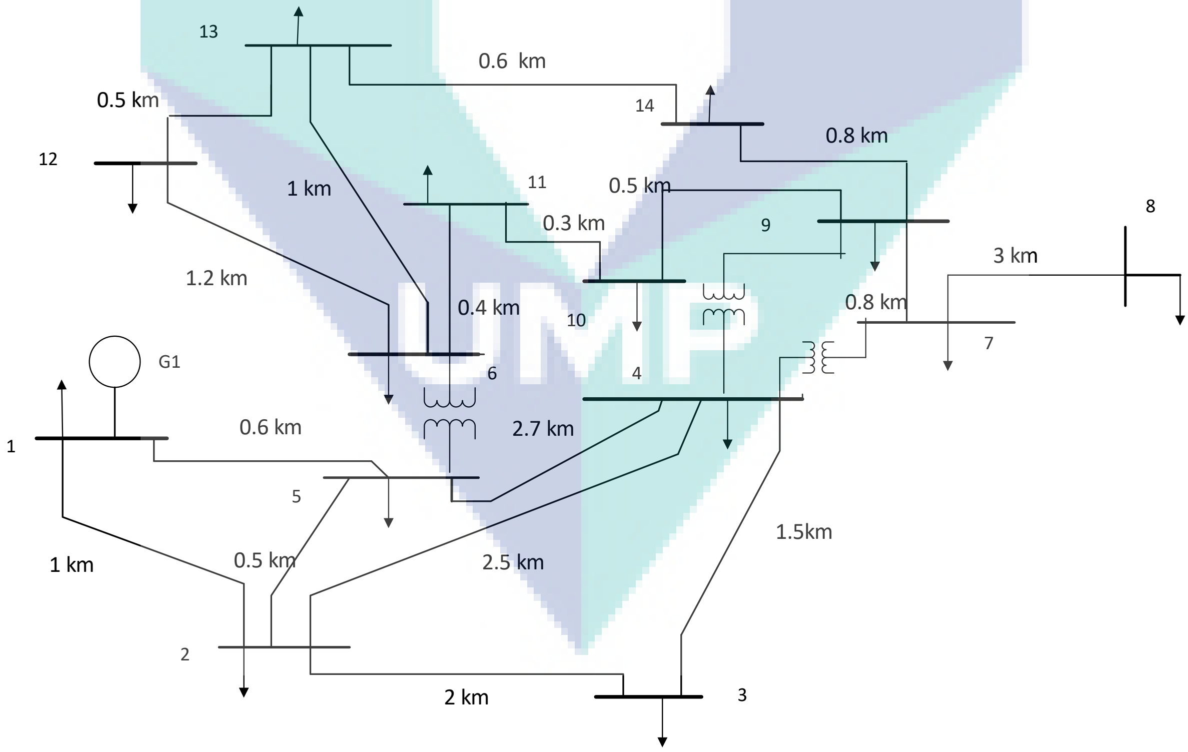

Figure 4. LV Network (case 1)

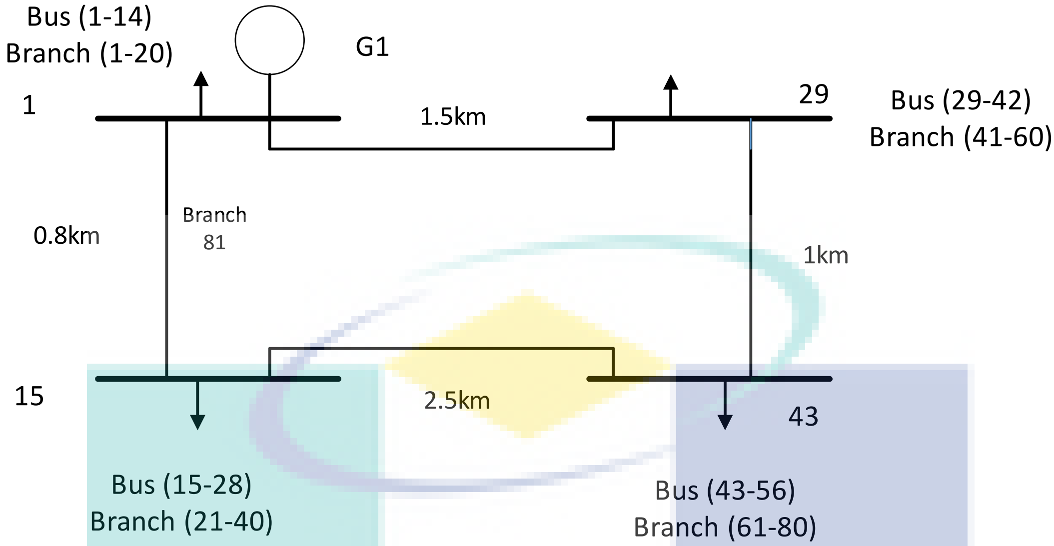

Figure 5. MV Network (case 2)

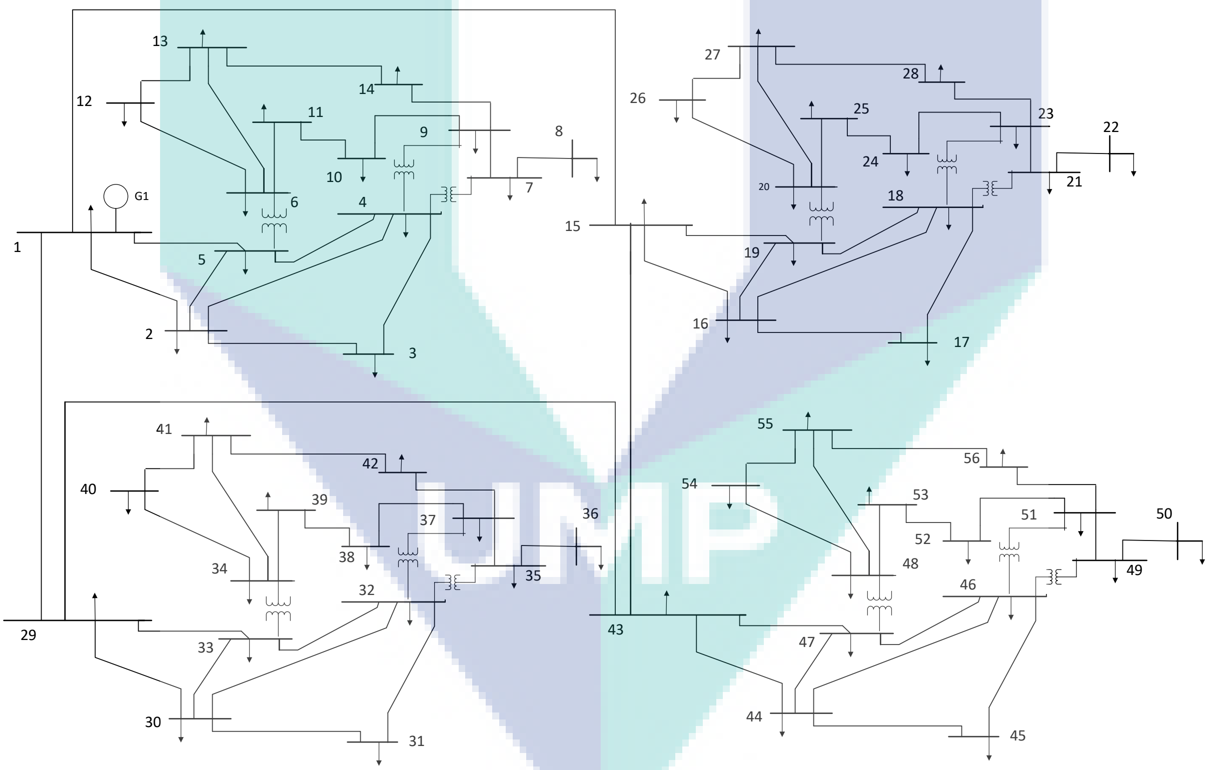

Figure 6. MV and detailed LV Networks (case 3)

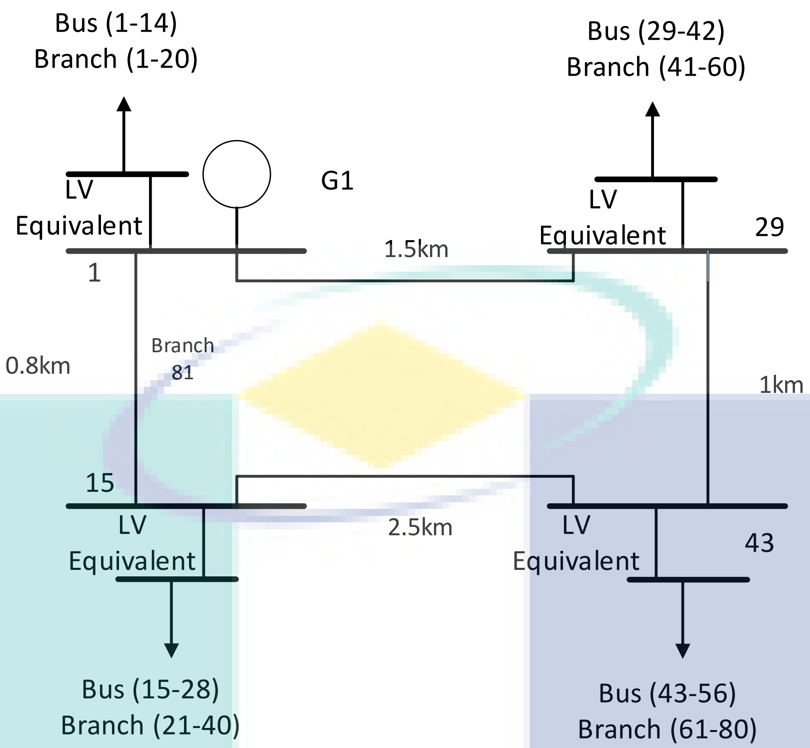

Figure 7. MV and Equivalent LV Networks (case 4)

Single and Three Phase Network Scenario

The next considered network for these analyses is rural LV distribution network for single and three phases diagram. The network consists of a single transformer with a rating of 500 kVA, and the line feeder is mostly overhead lines carrying 230 V for each phases supplying a total of 44 domestic customers. Star connection is used allowing the employment of two different voltages; 230 V and 400 V. The network configuration is radial without normally open network reconfiguration or back-up supply. Figures 8 and 9 present rural LV network in single and three phases diagram respectively.

Table 2. Feeder Parameters (LV Rural)

LV feeder	Id.	Cross section (mm^2)	Maximum Sustained Current (A)	R_{ph}	X_{ph}
Underground Cable Ethylene Propylene Rubber	A	25	110	0.87	0.085
	B	70	190	0.443	0.076
	C	120	250	0.253	0.071
	D	185	320	0.164	0.074
	E	300	400	0.1	0.073
Overhead Lines Aerial Bundle Conductor (ABC)	F	1x16+25	80	2.33	0.139
	G	3x16+25	80	2.33	0.13
	H	3x95+70	190	0.39	0.108
	I	3x185+120	300	0.2	0.103

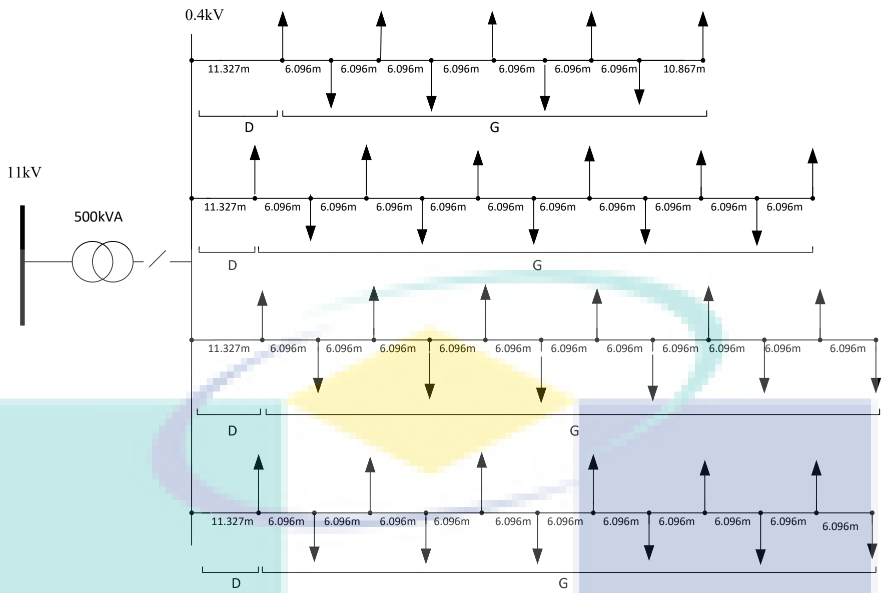

Figure 8. Rural LV Distribution Network (single phase diagram)

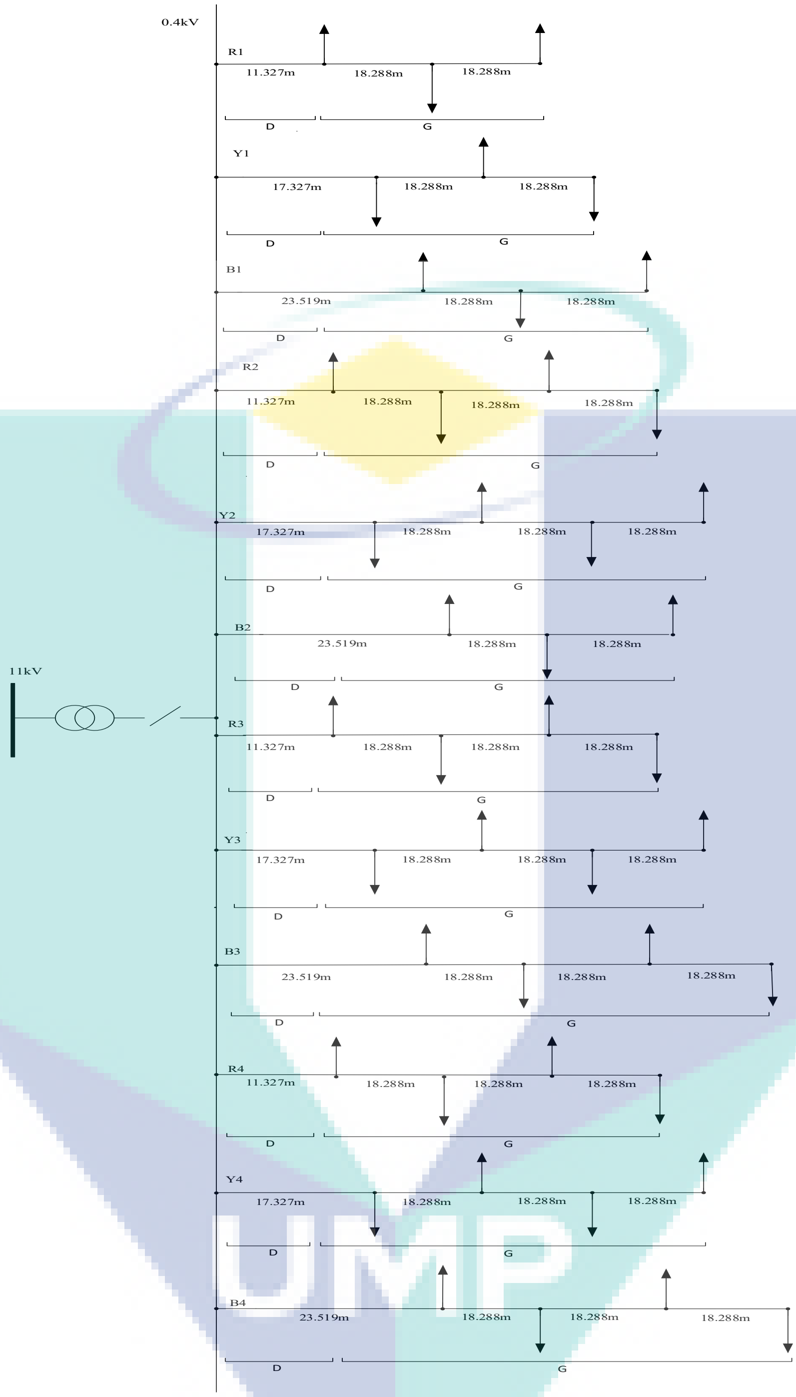

Figure 9. Rural LV Distribution Network (three phase diagram)

Table 3. Transformer parameters (LV Rural)

Rating	**Connection**	**Tapping Range**	**Load Lossess at 75°C (W)**	**No-Load Lossess (W)**	**Impedance (%)**	**Model Parameters (p.u. on 100 MVA)**	
						RLV	XLV
500	Dyn11	± 5% in 2.5% taps	5100	680	4.75	2.04	9.28
315			3420	580	4.75	3.4444	14.6794
200			2900	540	4.75	7.5	22.5

Past recording and statistic data are significant for predicting and assessing future and present reliability performance of distribution network. These data are required for simulation technique to characterise the performance of distribution network under analysis. Two of three (i.e. mean fault rates, MTTR and unavailability) general reliability input are required to perform the simulation. The mean fault rates represent the total number of times in a year the component has to be removed from service for repair due to the failure that occurs while MTTR represents the average times required to repair the components that affected by the failure. Table 4 presents the statistic of mean fault rates and MTTR of network components.

Table 4. Mean Fault Rates and MTTR

Power Component	**Voltage Level (kV)**	**Mean fault rate λ_{mean} (faults/year)**		**MTTR r/μ_{mean} (hours/fault)**	
		[28]	[29]–[36]	[28]	[29]–[36]
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
Transformers	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	<11	0.0004	-	35.3	-

Protection Scenario

Secondary distribution feeders can be in the type of insulated conductor (underground cable) or bare conductor (overhead lines). Underground cables are usually installed in urban area while overhead lines are equipped in 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 into a residential customer premises. Accordingly, the typical network arrangement considered for overhead LV power distribution is illustrated in Fig 10. Based on the fig 10, one cable supplies a number of poles mounted fuse, in which several customers are protected by a single fuse.

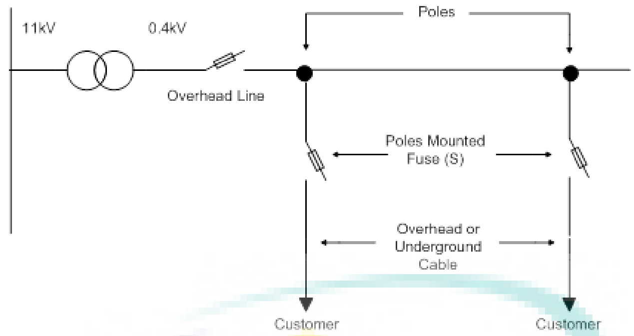

Figure 10. Typical Arrangement for LV overhead distribution systems [37]

Test network used to simulate the reliability analysis are a typical sub-urban (SU) UK LV residential distribution network configuration without and with protection device arrangements, in Fig. 11 and Fig. 12, respectively. Fig. 12 contains more network components (fuses and circuit breakers) within the dashed-rectangle area compare to Fig. 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 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.

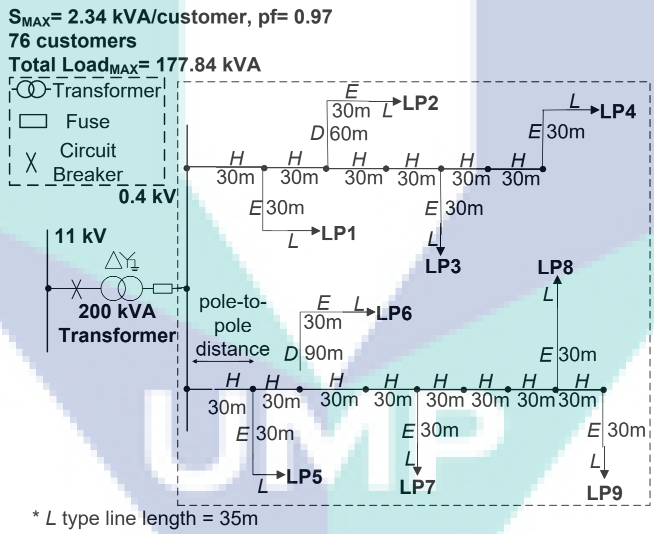

Figure 11: LV SU distribution network without fuse protection [38]–[43]

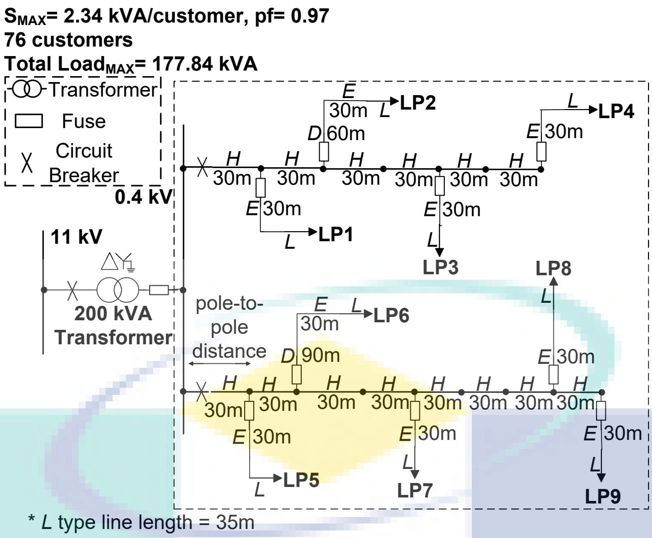

Figure 12: LV SU distribution network with fuse protection [37]–[43]

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 [3]. 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.

Chapter 4 Result and Discussion

LV Equivalent

Figure 13 below illustrates the average indices of 4 different cases. Based on Figure 13, the average of SAIFI in Case 1 network is slightly lower than in Case 2. This is because the total interruption in LV is lower than in MV, which is directly related to failure rates from Table 4. Another contributing factor is the number of component in Case 1 is higher than Case 2. Since the formula of SAIFI is related the total interruption, hence an increase in the occurrence of interruptions in the system will also increase the value of SAIFI. Since LV network is located to the downstream of MV; thus the interruptions in LV will affect the total interruptions in MV for Case 3 and 4. Hence, the interruptions in MV will be higher than in LV. This is one of the reasons why the average of SAIFI is lower than in MV.

The repair time used in Case 1 and Case 2 are 5 hours/fault and 6.44 hours/fault, respectively. Since the average of interruption hours (CAIDI) is inversely proportional to the average failure rate (SAIFI), hence the higher the value of SAIFI, the lower the value of CAIDI. Figure 13 illustrates Case 2, which has higher SAIFI and the lowest CAIDI. While for Case 3 and Case 4, the average values of SAIFI, SAIDI, CAIDI are close to each other. The result of the average reliability indices obtained in both Case 3 and Case 4 are acceptable since these network models need to be the same or almost the same for all the indices. This is because the representation of the equivalent network (Case 4) is to simplify the large/complex network (Case 3) without changing any parameters of the network.

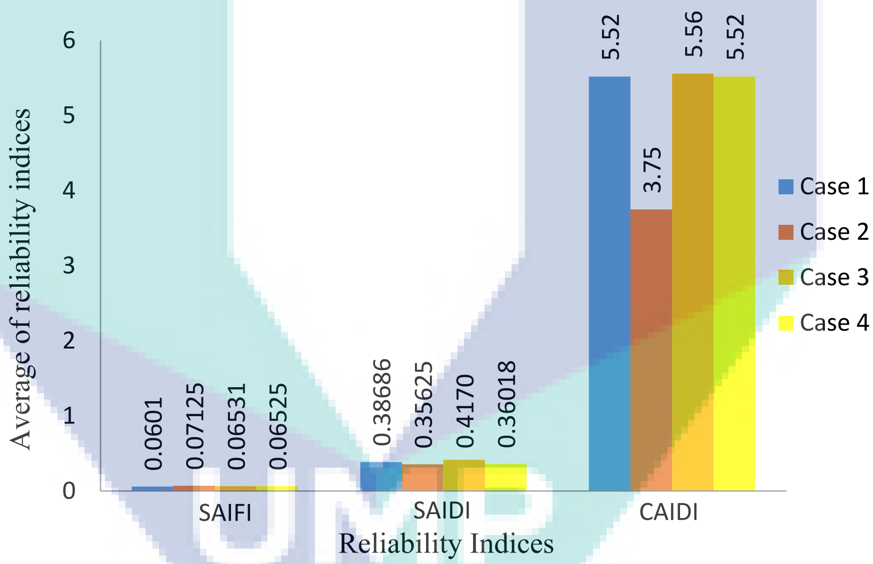

Figure 13. Reliability results for four cases.

Table 5 below shows the percentage error between detailed (Case 3) and equivalent network (Case 4). The average of SAIFI between Case 3 and Case 4 are close to each other. Hence, the percentage error between these two is the lowest. Since Case 3 is the combination of LV and MV networks, therefore, the repair time of the components is different according to the types of networks. Thus, the percentage error in the average of CAIDI between Case 3 and Case 4 is about 0.72 % which is higher than percentage error in SAIFI. Lastly, the percentage of error in SAIDI is the highest compared to the others. The SAIDI index is the total duration of interruption over the total number of customers. The total duration of interruptions is related to the repair time and interruptions of components. Since the interruptions in detailed network varies and there are a few customers who are not interrupted at all, hence it will affect the overall average of SAIDI in detailed network. Thus, the percentage error of SAIDI between these two networks are the highest. This percentage error of SAIDI can be reduced by increasing the simulation time.

Table 5. The percentage error between detailed (Case 3) and equivalent network (Case 4)

Average Index	Case 3	Case 4	Percentage Error (%)
SAIFI	0.06531	0.06525	0.09
SAIDI	0.4170	0.36018	13.63
CAIDI	5.56	5.52	0.72

Detailed Network

The detailed network (Case 3) represents the combination of both MV with LV detailed networks. All the parameters of components in the network must be configured and analysed. These parameters such as resistance, R and reactance, X of components in the network must be represented by equivalent values, which are Req and Xeq. All the information of parameters used in this analysis are obtained from MatPower. In Case 3, detailing the network model required more time to model the network and higher simulation time compared to Case 4. The positive side of Case 4 is it can provide more detailed information, especially on the specific location/component of interruption and duration of interruption in the system.

Since the failure rate of the lines depends on the length of lines, hence increasing the length of the line will increase the failure rate. The data of interruptions of a specific customer will facilitate the service provider to detect the location of failure in a short time, hence reducing the duration of interruptions experienced by the customers. Figure 14 below shows the reliability indices for each of the customers. This graph displays that the reliability indices for every customer varied among them. This means that each of the customer will experience a different total number of interruptions. Based on the graph, for customers 1, 31, 32, 33, 44, 46 and 47, there is no reliability indices recorded. It means that these customers did not experience interruptions at all. This is due to many combinations of electrical path from source to load, which increase the security level for these customers.

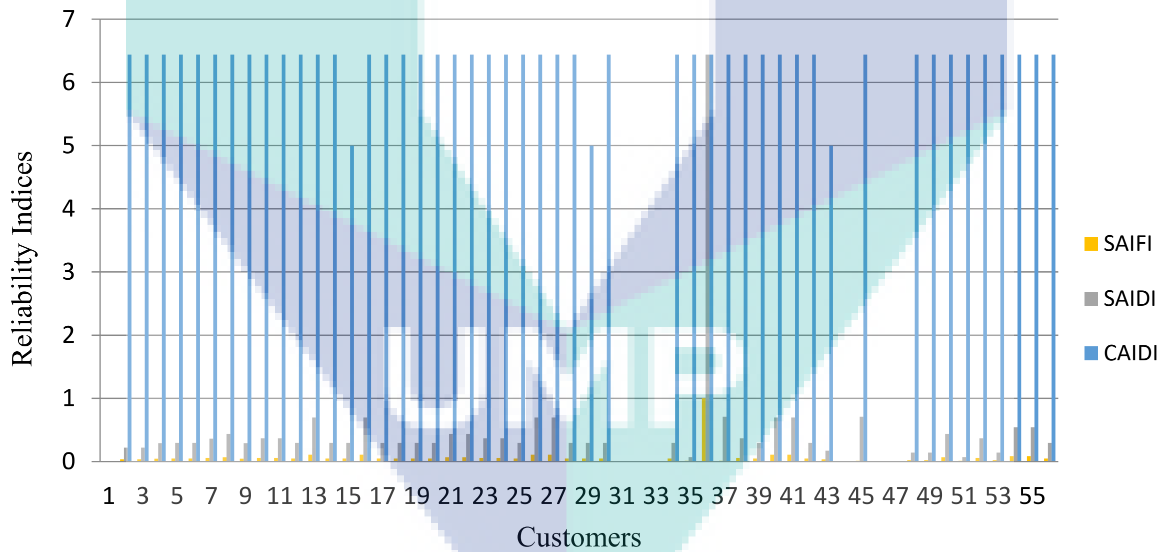

Figure 14. Detail reliability indices for case 3

Equivalent Network

This equivalent representation (Case 4) will not change the parameter of the components in the network because the total number of the same parameter is represented with one equivalent value. There are about 56 customers in the detailed network (Case 3); thus, the parameters of LV network (Case 1) at every 14 customers will be represented with one equivalent customer. In this case, the reliability indices (SAIFI, SAIDI, CAIDI) are used to justify the representation of detailed network (Case 3) with an equivalent network (Case 4).

The equivalent network (Case 4) has benefits, especially in reducing the simulation time, but it is really difficult to detect the interruption and location of interruption occurring in the network. This is because one equivalent value represents a numerous value of components and configurations in the LV network. If the type of fault component and location of fault is detected, the service provider will be able to provide mitigation plan to overcome this interruption by re-routing the electrical path from source to customers. Hence, it is crucial, especially to the service provider to decide, either to detect the specific location of the failure in the network or save detailed network modelling time and simulation time.

Figure 15 shows the reliability indices obtained for each customer in Case 4. Based on the graph, the value of CAIDI obtained is constant for each of the customers. The result is acceptable since the values for Case 3, and Case 4 are almost the same. The value differences between Case 3 and Case 4 are able to be reduced by increasing the simulation value.

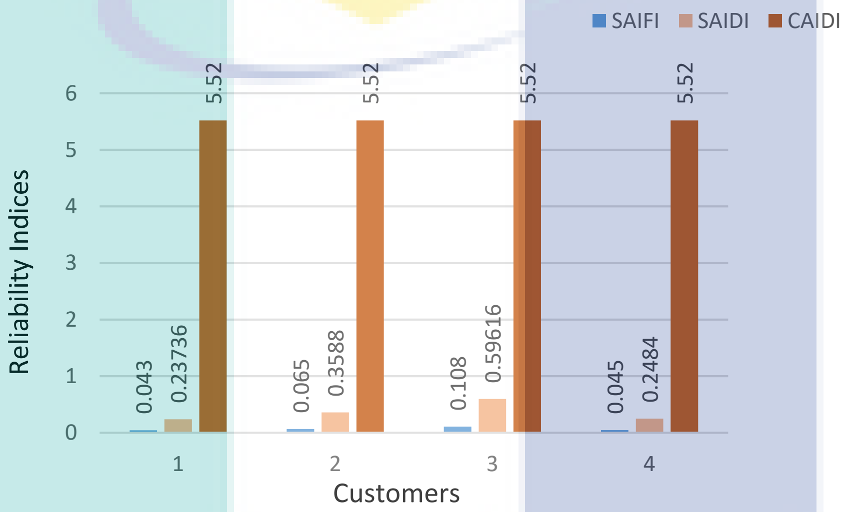

Figure 15. Detail reliability indices for case 4

Single and Three Phase Network

The network area located at the rural residential with about 44 customers. The type of house that related to this study are terrace house with load demand 1.5kW per houses, with a total load of this region is 69.47kVA. Based on Figure 8 (single phase) feeder 1, 2, 3 and 4 consist of 9, 11, 12, 12 loads respectively. For three phase network (Figure 9), it has the same number of load in single phase network, but the connection of the load to the supply is three phase network. For feeder 1, it received supply only from red wire, while feeder 2 received supply from yellow wire and feeder 3 received supply from blue wire.

Table 6. Reliability Indices (average of all customer)

Network	SAIFI	SAIDI
Single phase	0.99363	6.58907
Three phases	0.67881	4.49607

Table 7. Reliability Indices (focus on the type of customer)

Network	Type of Customer	SAIFI (location)	SAIDI (location)
Single phase	Best	0.0157 (1)	0.86309 (1)
	Median	1.0147 (15, 26, 38)	6.67844 (15, 26, 38)
	Worst	2.0227 (44)	12.49379 (44)
Three phases	Best	0.33770 (33)	1.86841 (21)
	Median	0.67370 (19, 23, 26, 30, 35)	4.71299 (19, 26, 30, 35)
	Worst	1.01470 (44)	6.74819 (17)

Table 6 present the average value of indices for all customer. It clearly shows that by the value of SAIFI and SAIDI for LV network of single phase diagram are higher than three phase diagram. It indicates that neglecting the real configuration of LV distribution network should overestimate the reliability performance. Single phase diagram has a higher value compared to three phase diagram due to the fault rates of the main feeder. In single phase diagram, all phases (red, yellow and blue) of main feeders are connected together, although in reality, it doesn't operate in such way. For example, if red phase of the main feeder is faulted, yellow and blue phases also faulted, resulting in more interruption and duration of interruption experience by customers.

Table 7 illustrate the type of customer based on reliability performance; best customer for low-value indices, median customer for average value indices, and worst customer for a high value of indices. The best customer typically located near the source and short in electrical supply path, which directly related to equation (1). Worst customer is opposite factors of the best customer; located further from source and long in electrical supply path. Hence, a better organisation of emergency staff/source plan during fault can be employed to decrease the frequency and duration of interruption.

By knowing the correct reliability performance of each customer, type of network component in the planning phase can be utilized to minimise energy losses. For instance, low core energy losses of conductor or underground cable may be employed for a long feeder supplying a high number of customer. Another suggestion of earlier distribution planning is configuring various network configuration by getting the best reliability performance and lowest energy losses. Reliability performance of every customer is important nowadays due to penalty enforcement by EC (for Malaysia). Each customer has its maximum experience frequency and duration of interruption. If the customer experience interruption/duration exceed the maximum value by EC, DNOs must pay the penalty to the customer. Therefore, distribution network planning is crucial for DNOs to minimise paying the penalty.

Protection

Below are the reliability performance results illustrated in Table 9 and Figs. 16-21.

Table 8. 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

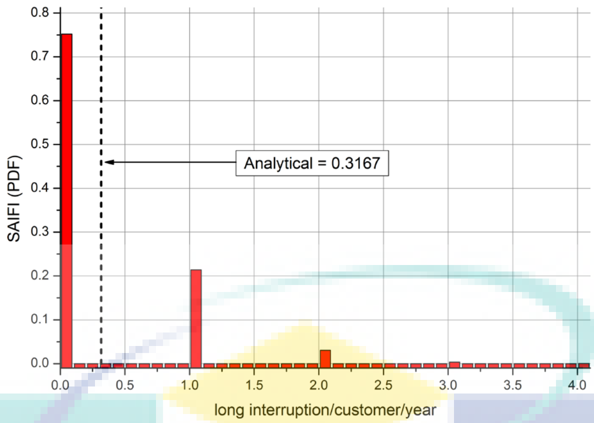

Figure 16: SAIFI (PDF) for LV Network without protection devices

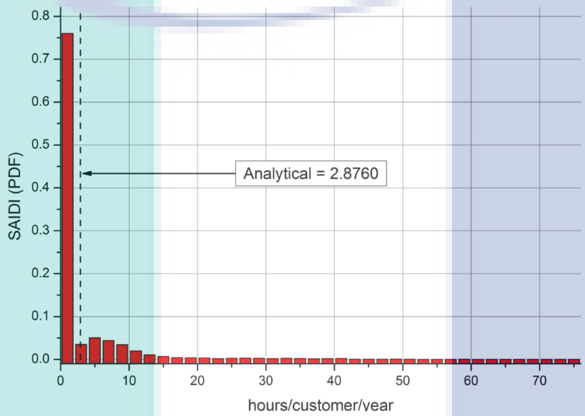

Figure 17: SAIDI (PDF) for LV Network without protection devices

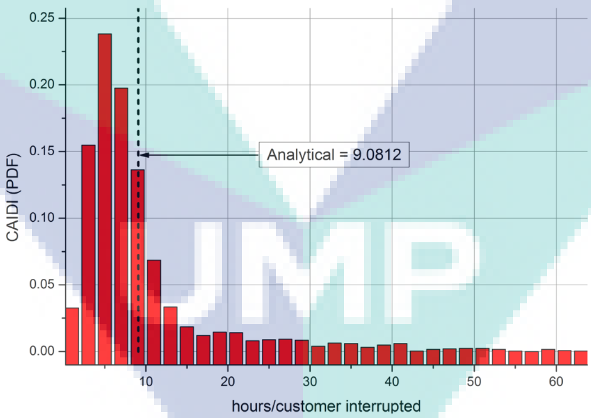

Figure 18: CAIDI (PDF) for LV Network without protection devices

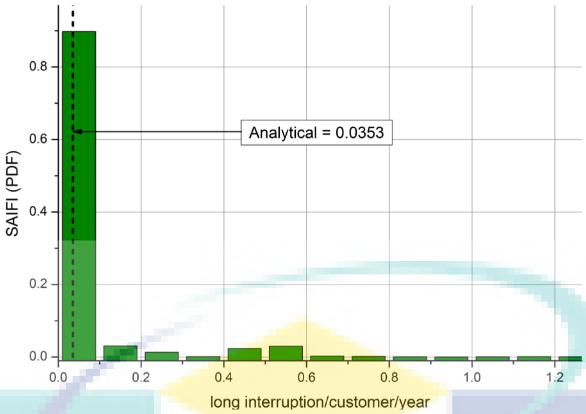

Figure 19: SAIFI (PDF) for LV Network with protection devices

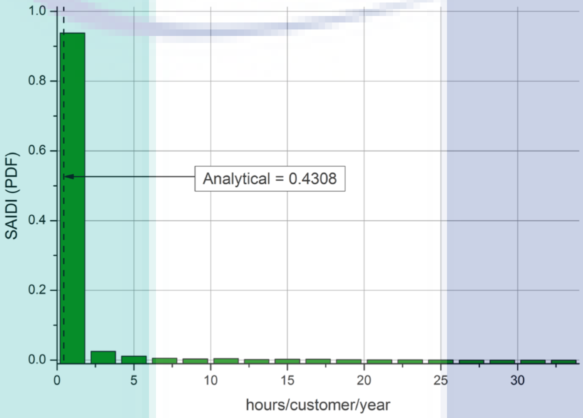

Figure 20: SAIDI (PDF) for LV Network with protection devices

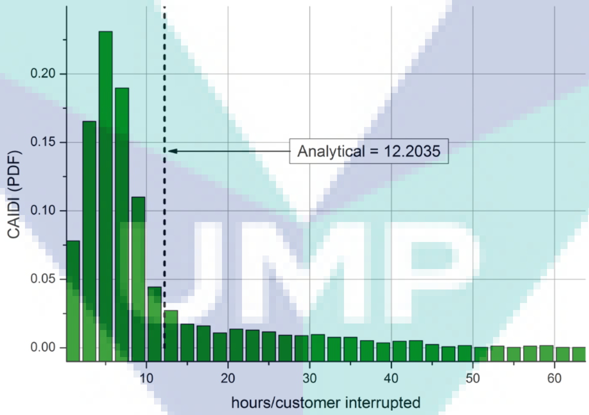

Figure 21: CAIDI (PDF) for LV Network with protection devices

From customer point of view, SAIFI and CAIDI indicate an average of total customer experienced number of 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 9, 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 [44], providing the equivalent fault rate, λ_{eq}, and mean repair time, μ_{eq}, for equation (1) and (2).

Based on Fig. 11, 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}:

$$SAIFI = \frac{\lambda_{eq}}{TC} \tag{4}$$

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 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 by protection device:

$$\lambda_P = \sum_{iP=1}^{NP} \lambda_{iP} \tag{5}$$

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 (4), the value of SAIFI become less. For CAIDI, the trend is otherwise. This is due to the denumerator N, where in 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 effect 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 4, 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 is no ideal, minimum or maximum values of reliability indices, as the values varies from one DNOs to another, depending on the load demand, geographical areas, location, network configuration, size of networks, network components, and etc.

Chapter 5 Conclusion

This work has introduced the methodology of reducing large/complex network into a single equivalent network. The complexity of the network is represented by one equivalent network in which the parameter of reliability indices of these networks will have the same value or close to each other depending on the number of simulations. The percentage error of reliability indices can be reduced by increasing the number of simulations (years). Although the equivalent of a network can simplify the network and reduce simulation time, the disadvantage of this network is the difficulty to determine the location of fault and faulty component.

Next, modelling the correct configuration of the distribution network is important as it affects the overall performance of distribution network; aggregation of all downstream network (LV networks) to the upstream network (MV and HV networks). The modelling of network configuration depending on the operation and protection system of network. For MV and HV networks, the protection system employed in three phases operation, which single, double or three phases fault should lockout (isolate from healthy part) all phase. It differs for LV network, where the protection system employed in single phase operation. If one phase fault, only that phase is lockout, another two phases continue in supply. Another reasons for correct configuration are to minimize losses and penalty. DNOs may utilise low energy losses component for critical feeder and configure optimal network configuration during distribution network planning phase.

Finally, 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 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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Appendix

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*—Reliability, monte-carlo, analytical, distribution network, protection.**

I. Introduction

The evolution and transformation of existing networks into future ‘smart grid’ required comprehensive/detail planning, management and operation of 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 a 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 importance role of disconnecting healthy network with 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 urban area while overhead lines are equipped in 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 are 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 into a residential customer premises. Accordingly, the typical network arrangement considered for overhead LV power distribution is illustrated in Fig 1. Based on the fig 1, one cable supplies a number of poles mounted fuse, in which several customers are protected by a single fuse.

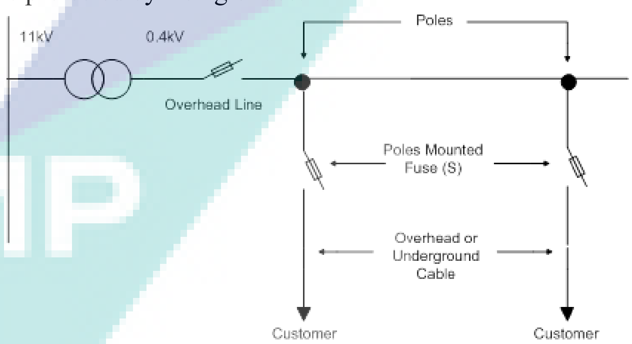

Figure 1: Typical Arrangement for LV overhead distribution systems [1]

III. Generic Test Network Model

Test network used to simulate the reliability analysis are a typical sub-urban (SU) UK LV residential distribution network configuration without and with protection device arrangements, in Fig. 2 and Fig. 3, respectively. Fig. 3 contains more network components (fuses and circuit breakers) within the dashed-rectangle area compare to Fig. 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 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.

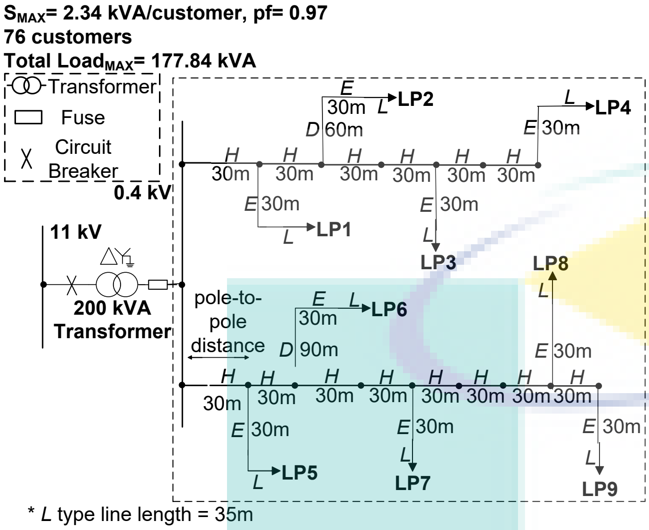

Figure 2: LV SU distribution network without fuse protection [2]–[7]

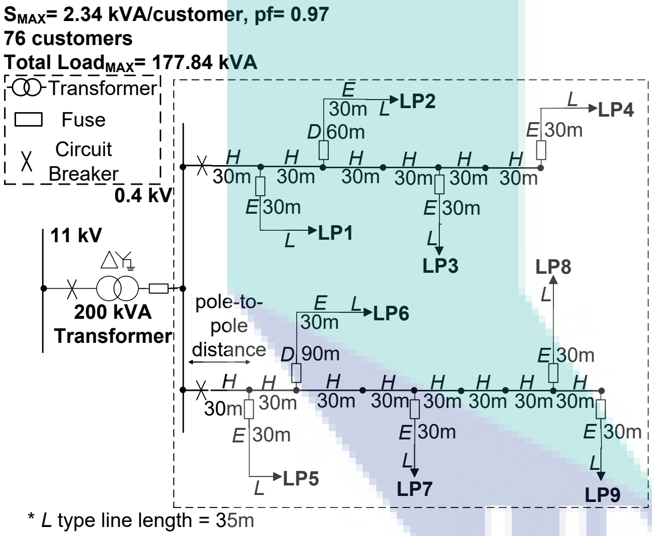

Figure 3: LV SU distribution network with fuse protection [1]–[7]

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 assessment of 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.

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

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

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

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

C. Reliability Data

Correct assessment of reliability performance strongly depends on the availability and accuracy of the required input data, where of 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 mean 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.

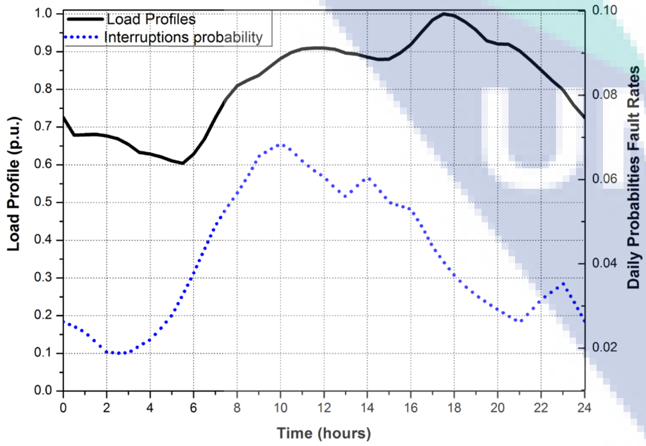

Figure 4: Correlation of daily load profile and daily probability fault rates

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

A. Results

Below is the reliability performance results illustrated in Table 2 and Figs. 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

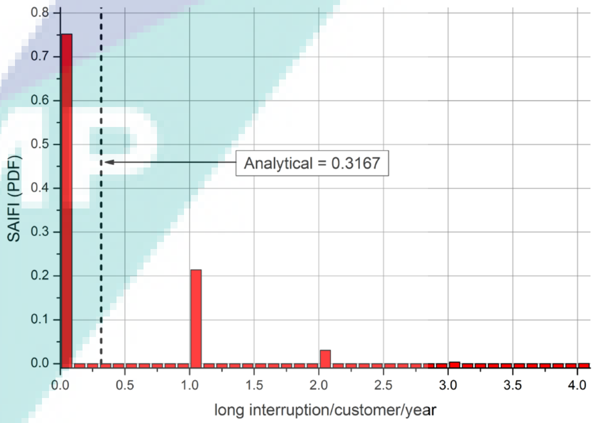

Figure 5: SAIFI (PDF) for LV Network without protection devices

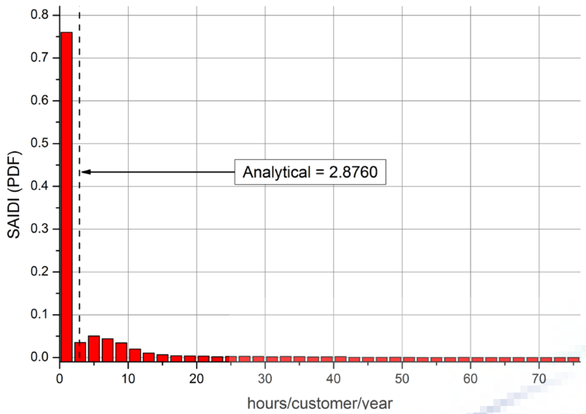

Figure 6: SAIDI (PDF) for LV Network without protection devices

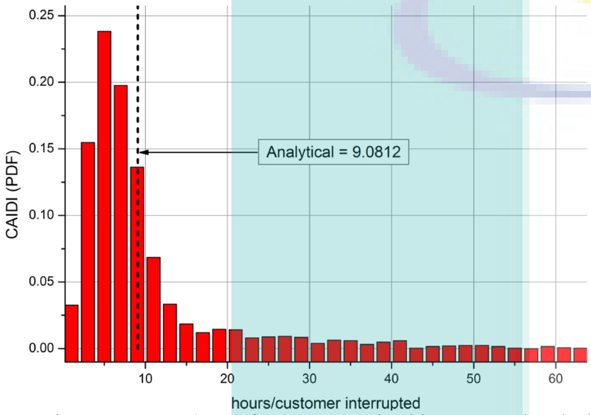

Figure 7: CAIDI (PDF) for LV Network without protection devices

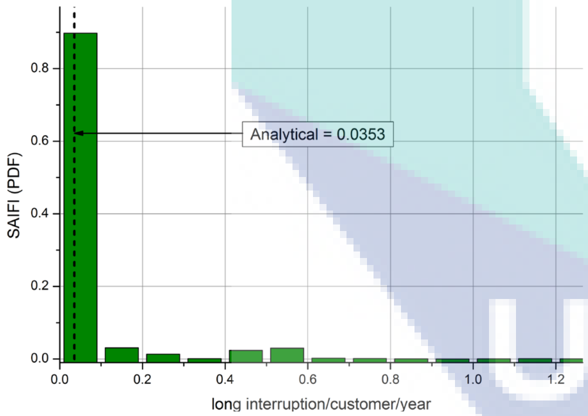

Figure 8: SAIFI (PDF) for LV Network with protection devices

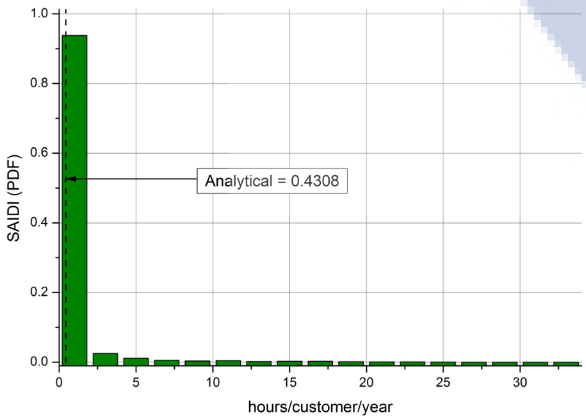

Figure 9: SAIDI (PDF) for LV Network with protection devices

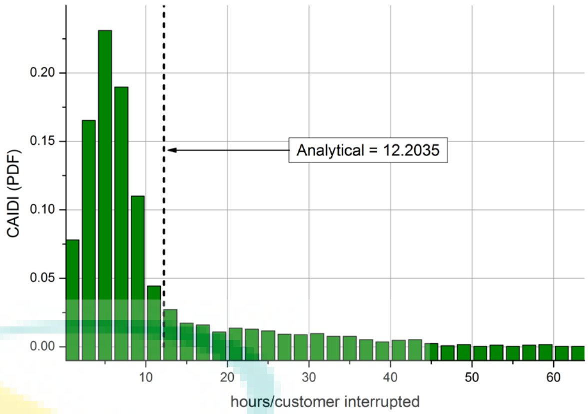

Figure 10: CAIDI (PDF) for LV Network with protection devices

B. Discussion

From customer point of view, SAIFI and CAIDI indicate an average of total customer experienced number of 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 Fig. 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}:

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

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 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 by protection device:

$$\lambda_P = \sum_{iP=1}^{NP} \lambda_{iP} \tag{8}$$

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, where in 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 effect 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 is no ideal, minimum or maximum values of reliability indices, as the values varies from one DNOs to another, depending on the load demand, geographical areas, location, network configuration, size of networks, network components, and etc.

V. Concluding Remarks

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 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.

Acknowledgment

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Low Voltage Reliability Equivalent Using Monte-Carlo Simulation Technique

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Abstract. Reliability is the ability of a system to supply continuous electricity to customer which ends with zero fault that occurs under a specific period of time. Most of the literature focus more on medium voltage (MV) and high voltage (HV) compared to the low voltage (LV) due to the general absence of exact data in LV network and sizing of LV network. Plus, an increase in size, making the LV network becomes complex and difficult to assess. Therefore, in this paper, the performance of reliability in LV network will be evaluated in detailed network model. To reduce simulation time, methodology of reducing detailed network into an equivalent network is introduced. This equivalent network is obtained by simplifying the complex network using Monte-Carlo Simulation technique. The results in this research are quantified and compared between these detailed and equivalent networks in reliability indices; SAIFI, SAIDI and CAIDI..The values of SAIFI ,SAIDI and CAIDI in detailed network are slightly higher than in equivalent network.

1. Introduction

Power systems are perhaps the most complex large-scale engineered systems today, and it is predicted to have the highest level of reliability. The interruption always occurs in the system, yet their customers expect more reliability and affordability [1]. Over decades, the reliability of power system evaluation was focused more on the generation and transmission compared to the distribution system especially on the low-voltage distribution although this low voltage will also affect the performance of power system. The goal of the present planned in distribution system is to ensure that the performance of power system, especially in LV and MV will give better effect to the customers. Thus, it is important to ensure that the customer will get the continuity of supply with minimum interruption occurring. In most of the power system, both MV and LV are represented in a lumped model due to the complexity of calculation and the volumes of LV and MV [2]. Hence, the simulation will take time to compute the result for the reliability analysis in such a complex and large network. Thus, the representation of an equivalent network will simplify the complex network, consequently reducing simulation time.

Since distribution network is currently supplying the most customers, it is tied up by the target or minimum customer satisfaction level imposed by Energy Regular, which in Malaysia is Energy Commission (EC). These targets mostly involve the frequency and duration of interruption. To attain that target, distribution network operators (DNOs) must correctly assess their reliability performance. Therefore, it is critical to have accurate distribution network configurations and parameters. However, due to the size of distribution network, low voltage (LV) network is often represented by aggregate model [3-8].

In this research, the main intention is to represent the whole LV network with a single equivalent component. This simplified equivalent component is implemented in MV system specifically at the downstream of the aggregation of MV point. The performance of reliability in a detailed network should be assessed first before an assessment in an equivalent network can be done. The detailed network will give more details and specific information of the system such as the interruption on the specific location and occurrence of fault while the equivalent network consists of simplified information of the network.

2. Monte-Carlo Simulation Technique

In reliability assessment, there are two types of methods that can be used to evaluate the reliability performance of the network, which are analytical and probability assessment. The analytical method uses a mathematical based approach which evaluates the performance of reliability in power system using mathematical solution while the probability method uses random nature process. In terms of contingency, basically the analytical approach will choose the states in increasing order of which each state is evaluated in just one time. The reliability indices are then calculated using mathematic solution based on the statistical data related to each state [9]. As power system consists of a large and complex network, Monte-Carlo Simulation (MCS) will be used to equivalate and assess the performance of networks [10,12]. The sequential MCS technique is used which simulates the system chronological behaviour by sampling the system state sequences for several period of time. For this method, two basic inputs which are fault rate and repair time, need to be identified first before it can be randomly generated [13,14].

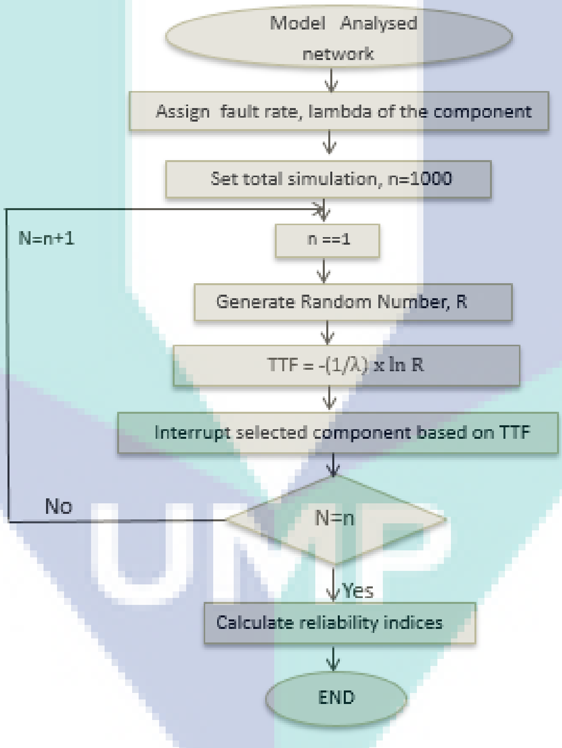

Figure 1. Flowchart of Monte-Carlo Simulation

Table 2. Description of cases

Case	Description
1	LV network consists of 14 buses and 20 branches
2	MV network consists of 4 buses & 4 branches
3	Detailed (a combination of MV and LV) network consists of 56 buses & 84 branches
4	Equivalent network (a combination of MV and LV equivalent) network

Figure 1 above shows the flowchart of how the performance of reliability in the system is being assessed. In this research, two models of bus system, which are Network 14 and Network 4gs (networks from Matpower) are used to represent the distribution network. Network 14 represents LV distribution network (case 1) while Network 4gs represents MV distribution network (case 2). Both of the networks are being modified by only one generator to analyse the reliability performance of the systems. Before an equivalent network can be assessed, a few analysis needs to be done in both LV and MV networks. In distribution system, the LV network is always located to the downstream of MV network. Even though the objective of this research is to evaluate the performance of LV network, the assessment of MV network is also included to quantify and justify the importance of detailing the distribution network. Hence, there are about 4 different networks that need to be analysed.

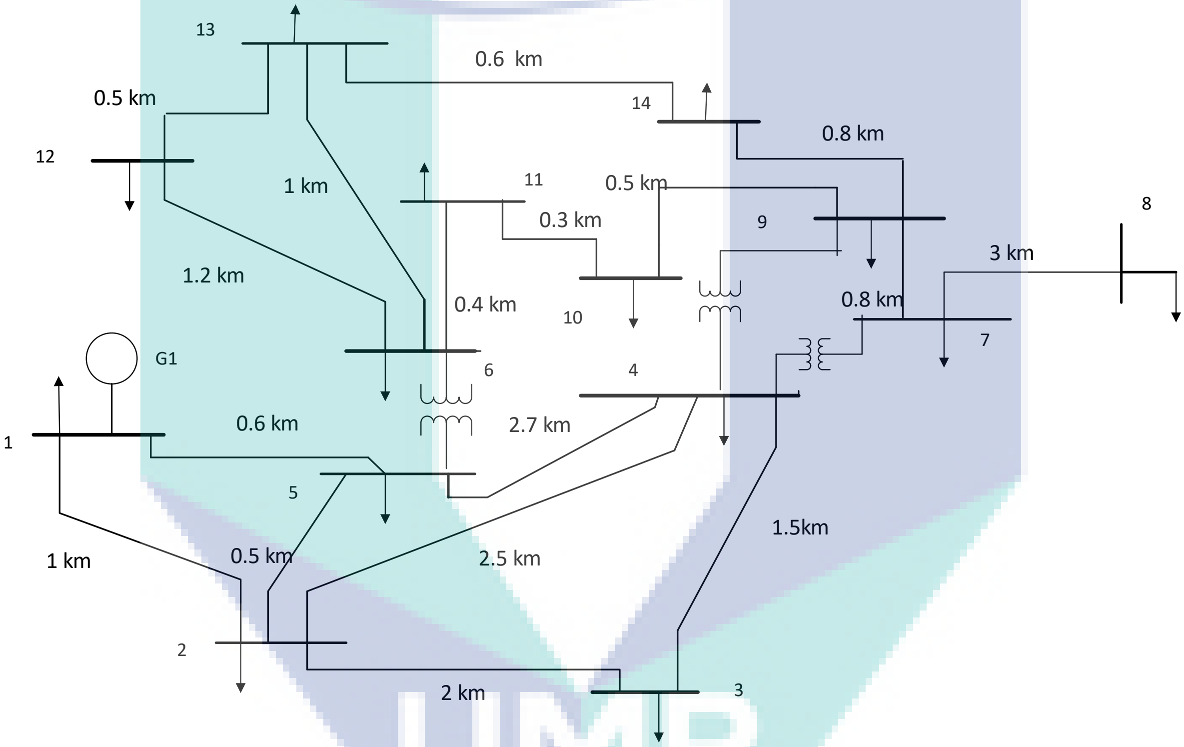

Figure 2. LV Network (case 1)

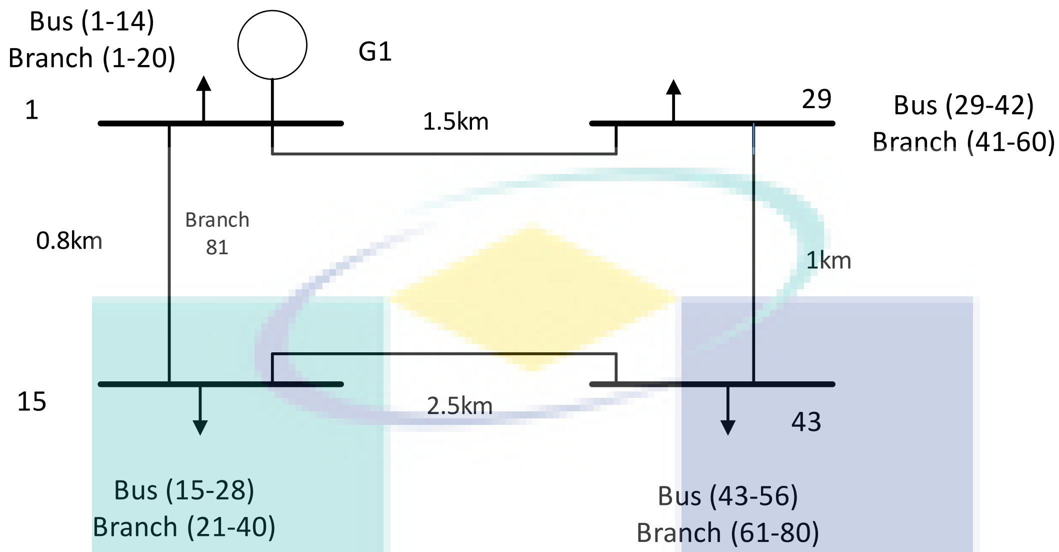

Figure 3. MV Network (case 2)

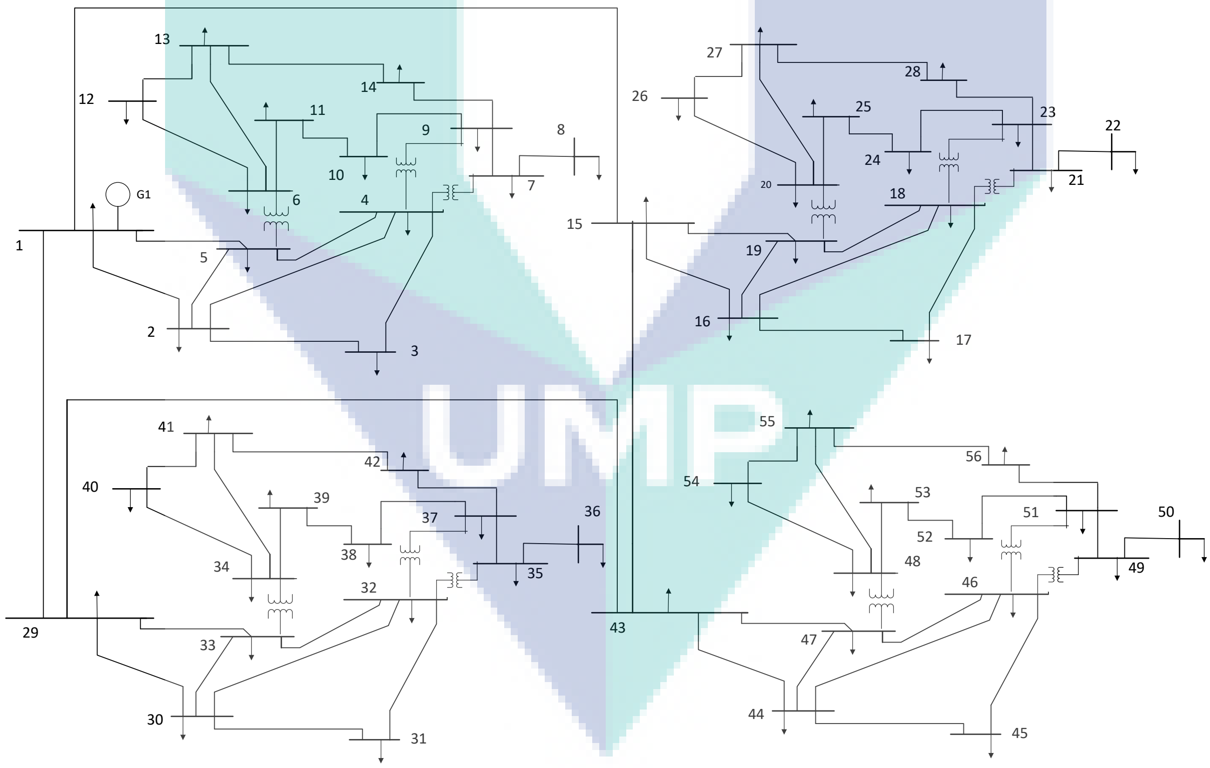

Figure 4. MV and detailed LV Networks (case 3)

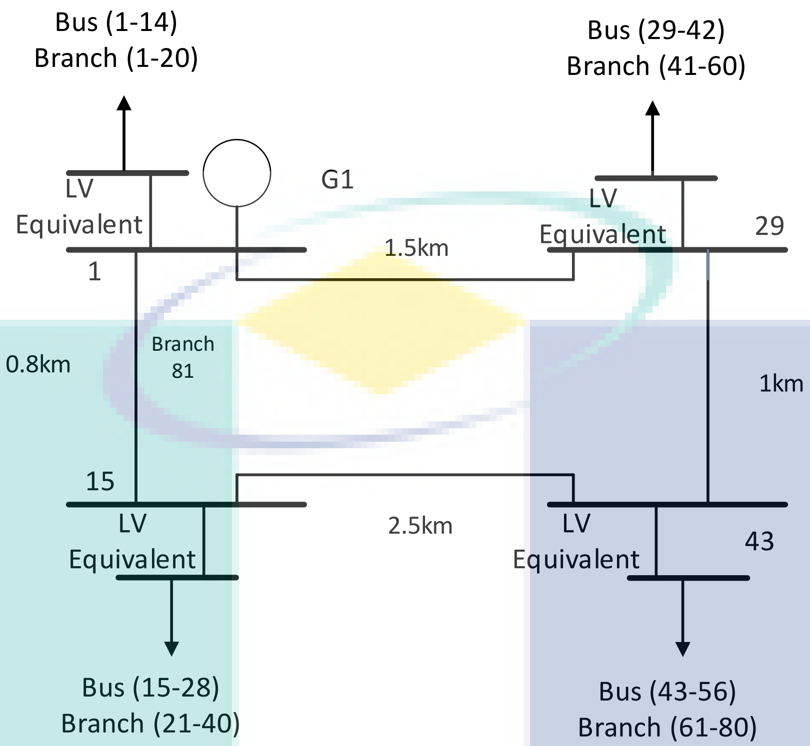

Figure 5. MV and Equivalent LV Networks (case 4)

2.1 Input data, fault rate and repair time

As stated above, two basic inputs in the reliability assessment are fault rate and repair time. It is very important to select the accurate value for both of these inputs since it will indirectly affect reliability performance. For each of failure rate and repair time, it will consider the reliability performance of every component in the network such as transformer, circuit breaker, etc. In this research, two components of power systems are included, but the main focus is overhead line since it is the most dominant component in the network.

Table 3. Parameter for reliability analysis in LV and MV network [15,16]

Component	Voltage (kV)	Fault rates (failure/year)	Repair times (hours/fault)
Overhead lines	11	0.123	5
	0.4	0.168	6.44
Transformer	11/0.4	0.015	5

2.2 Reliability Indices

In distribution system, the assessment of the reliability can be divided into two different groups which are load indices and system indices [17]. There are a few reliability indices used as a parameter to evaluate the performance of reliability in the system which are SAIDI, SAIFI, MAIFI, CAIDI, ENS and AENS [18]. In this analysis, only three common indices are considered, which are SAIDI, SAIFI and CAIDI. These indices are very important especially to the service provider to record the performance of reliability in power system in order to ensure better quality of services received by the customers [19].

SAIFI = Total number of customers interrupted (LI) / Total number of customers served (1)

SAIDI = Total number of interruption durations (by LI) / Total number of customers served (2)

CAIDI = SAIDI / SAIFI = Total number of interruption durations / Total number of customers Interrupted (3)

3. Results and Discussion

Figure 6 below illustrates the average indices of 4 different cases. Based on Figure 6, the average of SAIFI in Case 1 network is slightly lower than in Case 2. This is because the total interruption in LV is lower than in MV, which is directly related to failure rates from Table 2. Another contributing factor is the number of component in Case 1 is higher than Case 2. Since the formula of SAIFI is related the total interruption, hence an increase in the occurrence of interruptions in the system will also increase the value of SAIFI. Since LV network is located to the downstream of MV; thus the interruptions in LV will affect the total interruptions in MV for Case 3 and 4. Hence, the interruptions in MV will be higher than in LV. This is one of the reasons why the average of SAIFI is lower than in MV.

The repair time used in Case 1 and Case 2 are 5 hours/fault and 6.44 hours/fault, respectively. Since the average of interruption hours (CAIDI) is inversely proportional to the average failure rate (SAIFI), hence the higher the value of SAIFI, the lower the value of CAIDI. Figure 6 illustrates Case 2, which has higher SAIFI and the lowest CAIDI. While for Case 3 and Case 4, the average values of SAIFI, SAIDI, CAIDI are close to each other. The result of the average reliability indices obtained in both Case 3 and Case 4 are acceptable since these network models need to be the same or almost the same for all the indices. This is because the representation of the equivalent network (Case 4) is to simplify the large/complex network (Case 3) without changing any parameters of the network.

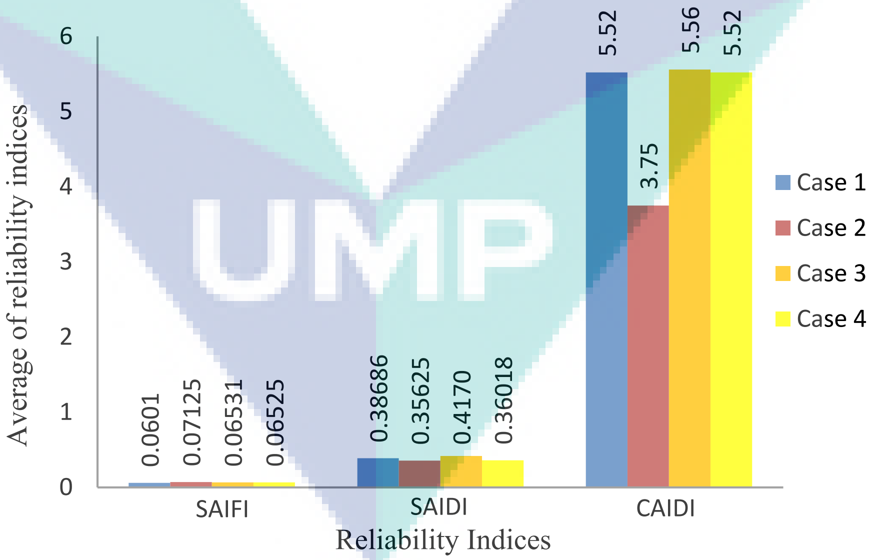

Figure 6. Reliability results for four cases.

Table 4 below shows the percentage error between detailed (Case 3) and equivalent network (Case 4). The average of SAIFI between Case 3 and Case 4 are close to each other. Hence, the percentage error between these two is the lowest. Since Case 3 is the combination of LV and MV networks, therefore, the repair time of the components is different according to the types of networks. Thus, the percentage error in the average of CAIDI between Case 3 and Case 4 is about 0.72 % which is higher than percentage error in SAIFI. Lastly, the percentage of error in SAIDI is the highest compared to the others. The SAIDI index is the total duration of interruption over the total number of customers. The total duration of interruptions is related to the repair time and interruptions of components. Since the interruptions in detailed network varies and there are a few customers who are not interrupted at all, hence it will affect the overall average of SAIDI in detailed network. Thus, the percentage error of SAIDI between these two networks are the highest.This percentage error of SAIDI can be reduced by increasing the simulation time.

Table 4. The percentage error between detailed (Case 3) and equivalent network (Case 4)

Average Index	Case 3	Case 4	Percentage Error (%)
SAIFI	0.06531	0.06525	0.09
SAIDI	0.4170	0.36018	13.63
CAIDI	5.56	5.52	0.72

3.1 Detailed Network

The detailed network (Case 3) represents the combination of both MV with LV detailed networks. All the parameters of components in the network must be configured and analysed. These parameters such as resistance, R and reactance, X of components in the network must be represented by equivalent values, which are Req and Xeq. All the information of parameters used in this analysis are obtained from MatPower. In Case 3, detailing the network model required more time to model the network and higher simulation time compared to Case 4. The positive side of Case 4 is it can provide more detailed information, especially on the specific location/component of interruption and duration of interruption in the system.

Since the failure rate of the lines depends on the length of lines, hence increasing the length of the line will increase the failure rate. The data of interruptions of a specific customer will facilitate the service provider to detect the location of failure in a short time, hence reducing the duration of interruptions experienced by the customers. Figure 7 below shows the reliability indices for each of the customers. This graph displays that the reliability indices for every customer varied among them. This means that each of the customer will experience a different total number of interruptions. Based on the graph, for customers 1, 31, 32, 33, 44, 46 and 47, there is no reliability indices recorded. It means that these customers did not experience interruptions at all. This is due to many combinations of electrical path from source to load, which increase the security level for these customers.

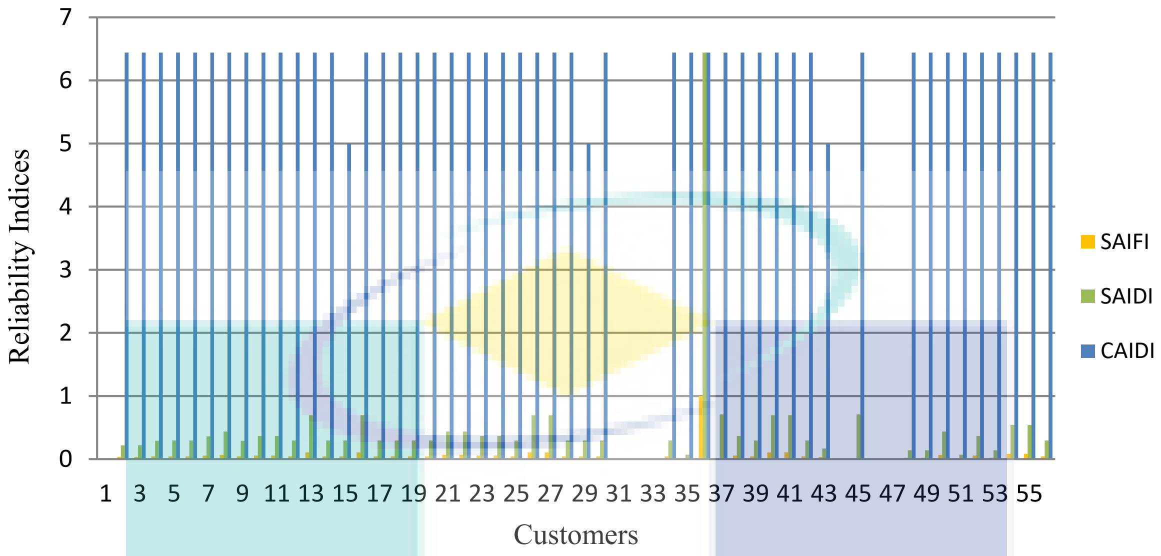

Figure 7. Detail reliability indices for case 3

3.2 Equivalent Network

This equivalent representation (Case 4) will not change the parameter of the components in the network because the total number of the same parameter is represented with one equivalent value. There are about 56 customers in the detailed network (Case 3); thus, the parameters of LV network (Case 1) at every 14 customers will be represented with one equivalent customer. In this case, the reliability indices (SAIFI, SAIDI, CAIDI) are used to justify the representation of detailed network (Case 3) with an equivalent network (Case 4).

The equivalent network (Case 4) has benefits, especially in reducing the simulation time, but it is really difficult to detect the interruption and location of interruption occurring in the network. This is because one equivalent value represents a numerous values of components and configurations in the LV network. If the type of fault component and location of fault is detected, the service provider will be able to provide mitigation plan to overcome this interruption by re-routing the electrical path from source to

customers. Hence, it is crucial, especially to the service provider to decide, either to detect the specific location of the failure in the network or save detailed network modelling time and simulation time.

Figure 8 shows the reliability indices obtained for each customer in Case 4. Based on the graph, the value of CAIDI obtained is constant for each of the customers. The result is acceptable since the values for Case 3, and Case 4 are almost the same. The value differences between Case 3 and Case 4 are able to be reduced by increasing the simulation value.

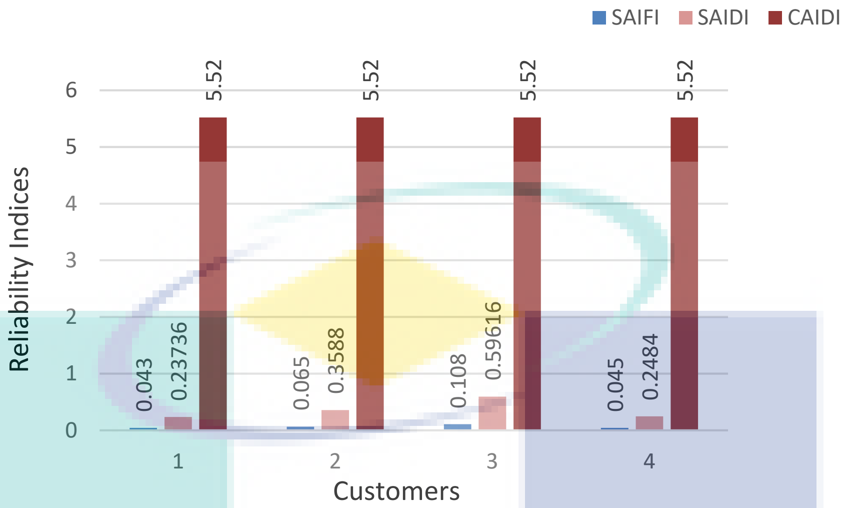

Figure 8. Detail reliability indices for case 4

4. Conclusion

This paper has introduced the methodology of reducing large/complex network into a single equivalent network. The complexity of the network is represented by one equivalent network in which the parameter of reliability indices of these networks will have the same value or close to each other depending on the number of simulations. The percentage error of reliability indices can be reduced by increasing the number of simulations (years). Although the equivalent of a network can simplify the network and reduce simulation time, the disadvantage of this network is the difficulty to determine the location of fault and faulty component.

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Article

Energy Regulator Supply Restoration Time

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Abstract: In conventional reliability analysis, the duration of interruptions relied on the input parameter of mean time to repair (MTTR) values in the network components. For certain criteria without network automation, reconfiguration functionalities and/or energy regulator requirements to protect customers from long excessive duration of interruptions, the use of MTTR input seems reasonable. Since modern distribution networks are shifting towards smart grid, some factors must be considered in the reliability assessment process. For networks that apply reconfiguration functionalities and/or network automation, the duration of interruptions experienced by a customer due to faulty network components should be addressed with an automation switch or manual action time that does not exceed the regulator supply restoration time. Hence, this paper introduces a comprehensive methodology of substituting MTTR with maximum action time required to replace/repair a network component and to restore customer duration of interruption with maximum network reconfiguration time based on energy regulator supply requirements. The Monte Carlo simulation (MCS) technique was applied to medium voltage (MV) suburban networks to estimate system-related reliability indices. In this analysis, the purposed method substitutes all MTTR values with time to supply (TTS), which correspond with the UK Guaranteed Standard of Performance (GSP-UK), by the condition of the MTTR value being higher than TTS value. It is nearly impossible for all components to have a quick repairing time, only components on the main feeder were selected for time substitution. Various scenarios were analysed, and the outcomes reflected the applicability of reconfiguration and the replace/repair time of network component. Theoretically, the network reconfiguration (option 1) and component replacement (option 2) with the same amount of repair time should produce exactly the same outputs. However, in simulation, these two options yield different outputs in terms of number and duration of interruptions. Each scenario has its advantages and disadvantages, in which the distribution network operators (DNOs) were selected based on their operating conditions and requirements. The regulator reliability-based network operation is more applicable than power loss-based network operation in counties that employed energy regulator requirements (e.g., GSP-UK) or areas with many factories that required a reliable continuous supply.

Keywords: reliability; network reconfiguration; time to supply; guaranteed standard of performance

1. Introduction

The reliability performance of distribution networks incorporates all possible contingencies associated with all power components in the network, including distribution feeders and protection systems. Reliability performance of the network is mostly related to maintaining the power supply to the customer. Apart from maintaining the voltage level within permissible limits and minimising the feeder losses, network reconfiguration is able to maintain an adequate level of reliability set by the energy regulator [1,2]. In addition, the network operation must adhere to the P2/6 Engineering

Recommendation [3] that suggests transfer capacity from alternative sources by certain maximum times based on class of group demands.

In general, the structure of a distribution network reflects a meshed configuration that normally operates radially with the support of another supply point, either a primary substation or a reflection centre. A reflection centre resembles a closed-loop arrangement that guarantees the supply of all connected feeders. With the advent of remote control of switches and circuit breakers, distribution network operators (DNOs) are able to control network reconfiguration easily and further boost system automation. Network reconfiguration also relieves the overloading of the network components. Feeder reconfiguration is performed by opening switches/breakers (normally closed) that are closed to the faulty part of the network and closing switches/breakers (normally open) located at the end of the feeder network [4–7]. Switching is performed in such a way that the network radial is maintained and all loads are energised. A normally open switch/breaker is closed to transfer a load from one feeder to another, while an appropriate switch/breaker is opened to restore the radial structure.

Another conventional method of restoring customer interruption is by repairing or replacing the faulty network component [8–11]. The selection of either repairing or replacing a faulty network component depends on the class of group demand outage, types of network components, network component availability, transportation, geographical area of faulty area, and others. For transformer outage in group of demand type class B [3], supply to customer must be restored by maximum 3 h, which can only be performed via replacement. Outage originated from a faulty fuse is typically below 1 MW (class A [3]) and no definite restoration time in [3]. However, the restoration of faulty fuses must be performed within maximum 3 h based on [1].

In the last decade, various objectives have been used for network reconfiguration. The objective or the aim of network reconfiguration can either be single or multiobjective. The varieties of single objectives are minimisation of power losses or energy losses, total network cost, voltage deviation, benefit/cost ratio and voltage sags. Multiobjectives combine two or more single objectives in a network reconfiguration. Power loss minimisation [12–16] and voltage profile [17–20] are conventionally employed for network reconfiguration with less attention towards network reliability [18,21].

The literature pertaining to reliability-based reconfiguration, though in abundance, is not inclined toward energy regulator requirements, which substantially improves interruption frequency and duration. Although reducing interruption frequency and power loss is interrelated, the objective differs. In reliability, the main purpose is to minimise frequency of customer interruption regardless of load demand (maximum, average or minimum), whereas in power loss, saving maximum load demand (to minimise load loss) is the priority than protecting customers with minimum load. In addressing this challenge, this paper proposes an alternative approach in using new restoration times called time to supply (TTS) for realistic evaluation of distribution reliability performance.

2. Input Parameters

2.1. Suburban MV Network

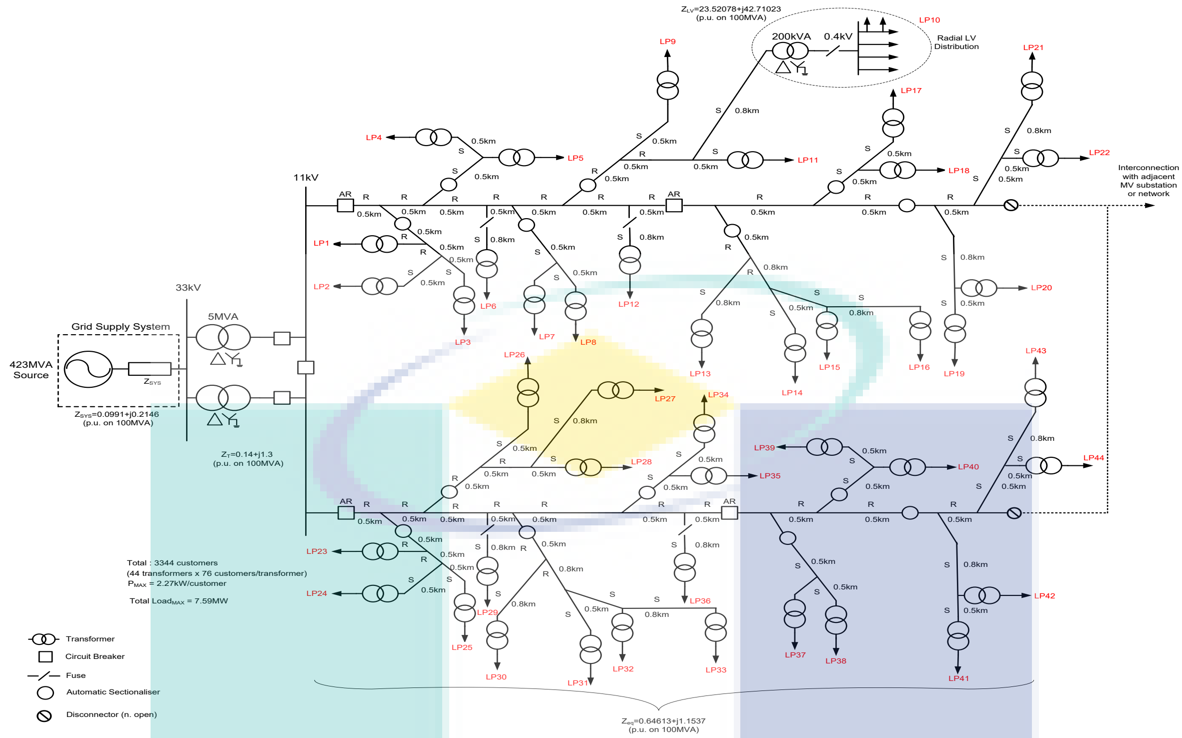


Figure 1. Typical distribution network configuration supplying suburban residential load [22–27].

A typical UK suburban distribution network was considered in the analysis (see Figure 1). The radial type of power distribution network delivers power from the main branch to sub-branches, then splitting out from the sub-branches again. This appears to be the cheapest, but least reliable network configuration. Tables 1 and 2 present the parameters of UK suburban network.

Table 1. Parameters of Typical 11, 0.4, and 0.23 kV Feeders [22,28–30].

Operating Voltage (kV)	Feeder Type	Id.	Cross Section (mm^2)	Resistance/km (p.u. on 100 MVA)	Reactance/km (p.u. on 100 MVA)
11	Overhead Lines or Mixed	R	150	0.11259	0.18363
		S	100	0.14658	0.26189
0.4		D	95	0.32	0.075
		E	50	0.443	0.076
		H	95	0.32	0.085
0.23		L	35	0.851	0.041

Table 2. Parameters of Typical MV/LV Transformers [22,28,30–32].

Operating Voltage (kV)	Vector Group	Rating (MVA)	Resistance (p.u. on 100 MVA)	Reactance (p.u. on 100 MVA)	Tap Range Min	Tap Range Max	Tap Step
33/11	Dyn11	5	0.14	1.3	0.85	1.045	0.0143
11/0.4	Dyn11	0.2	7.5	22.5	0.95	1.05	0.025

2.2. Mean Fault Rates and Mean Time to Repair (MTTR)

Mean fault rates and MTTR are the two basic inputs required for system reliability assessments. In the literature, the reported values of these two input data vary in wide ranges (based on the characteristics and location of network, types and features of power components, as well as their operating conditions). Table 3 presents the statistics of mean fault rates and mean repair times obtained from two main sources: UK-related values reported in [33] and from other sources [34–41].

Table 3. Mean Fault Rates and MTTR of Power Components.

Power Component	Voltage Level (kV)	Mean Fault Rate λ_{mean} (Faults/Year)		MTTR μ_{mean} (Hours/Fault)	
		[33]	[34–41]	[33]	[34–41]
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
Transformers	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	<11	0.0004	-	35.3	-

2.3. Fault Types

The classification of customer interruption into short interruption (SI) and long interruption (LI) is impossible without, for instance, modelling the applied protection systems. One simple way to make a clear distinction between short and long supply interruptions of customers is by defining a uniform distribution and linking it to the system reliability assessment procedure. For that purpose, past recordings collected from 14 UK DNOs between 2005 and 2009 [42] were analysed, in which 54% of supply interruption events were caused by temporary faults (i.e., SI), and 46% were due to permanent faults (i.e., LI).

2.4. Guaranteed Standard of Performance

The energy regulator has specified certain requirements for the duration and the number of interruptions in order to protect domestic (i.e., residential) and non-domestic customers (i.e., customers without special contract or agreement with the DNOs regarding LI) from excessive LI events. References depicted in [1] and [28] refer to the main UK statutory instrument, specifying the permissible supply restoration times for up to 5000 customers and more than 5000 customers, respectively. This is illustrated in Table 4 (normal system operating conditions), along with the corresponding compensations that DNOs pay directly to the customers (and not to the regulator), if the supply is not restored within the specified time [1] and [28].

Table 4. The UK Guaranteed Standard of Performance (GSP-UK).

Supply Restoration Time		Compensation Paid to:	
No. of Customers Interrupted	**Maximum Supply Restoration Time**	**Domestic Customers**	**Non-Domestic Customers**
<5000	18 h	£54	£108
	After each succeeding 12 h	£27	
≥5000	24 h	£54	£108
	After each succeeding 12 h	£27	
	Maximum	£216	
Multiple Interruptions		Compensation (all customers)	

Four or more interruptions (≥4), each lasting at least three hours (≥3 h)	£54

3. Reliability Methodologies

Probabilistic reliability assessment procedures seem to suit the analysis of system reliability performance, particularly in terms of their ability to model stochastic and inherently unpredictable variations of input parameters and data (e.g., fault rates and repair times) with their assumed probability distributions. The approaches of the probabilistic reliability assessment model provide a wide range of variations of practically all input parameters and data in one or a few simulation/calculation setups, without repeating the calculation after an input data is modified.

Although the probabilistic reliability assessment procedures are more difficult to implement (particularly in complex large-scale systems), they provide accurate and detailed outputs. The most frequently used probabilistic reliability assessment approach is the Monte Carlo simulation (MCS) [43–47]. Aside from network modelling, conventional MCS analysis requires statistical information on fault rates and MTTR of faulted power components as input data. Network models and fault rates of power components are used to establish customers experiencing interruptions (and the frequency), whereas MTTR of faulted components and network protection, reconfiguration, switching and alternative supply functionalities are used to estimate the duration of corresponding supply interruptions. The outputs of MCS analysis are reliability indices that reflect probability distributions with the corresponding mean values.

3.1. Monte Carlo Simulation (MCS) Procedures

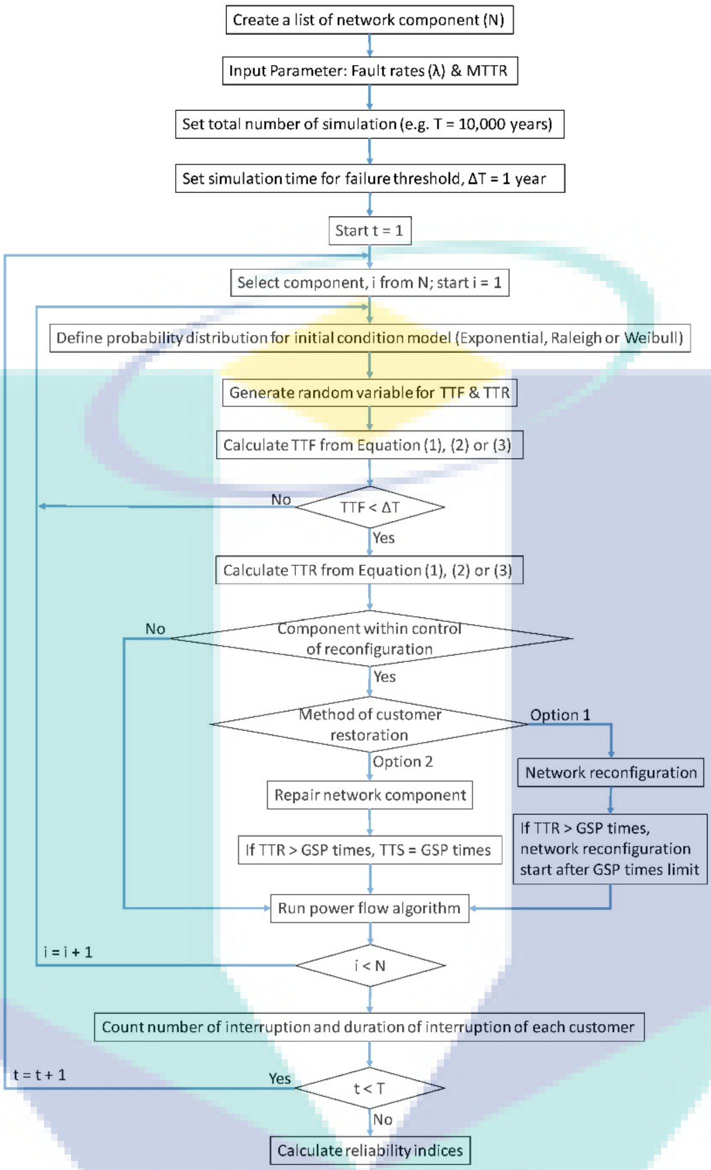


Figure 2. Monte Carlo simulation (MCS) procedures.

In any power system reliability procedures, MTTR is used to define the restoration times of network components that directly have an impact on the duration of interruption. In some cases, where network automation is unavailable (network reconfiguration) or in the absence of regulatory supply requirements (in some nations) on distribution networks, it is indeed realistic to use MTTR values. Nevertheless, in a country that applies regulatory supply requirements, the function of MTTR as input data may result in significant overestimation of reliability performance. Thus, DNOs should consider a new method to assess the duration of interruption by correlating with regulatory supply requirement time. Accordingly, this section presents a new methodology (see Figure 2) of assessing duration of interruption realistically, based on GSP-UK restoration times.

Based on the methods in MCS, a random variable (generated by a random generator) is assigned to an inverse cumulative distribution function to convert fault rates and MTTR (see Table 3) into system states, time to fail (TTF) and time to repair (TTR). The system states of the network component can be modelled with a series of distribution functions: Exponential, Weibull and Rayleigh. The parameters of distribution function are available in [48–50]

$$\text{Exponential: TTF/TTR} = \ inverse\{1-\exp(-\lambda t)\}\,, \tag{1}$$

$$\text{Weibull: TTF/TTR} = inverse\left\{1-\exp(-t/\delta)^{\beta}\right\}, \quad (2)$$

$$\text{Rayleigh: TTF/TTR} = inverse\left\{1-\exp(-0.5(t/\sigma)^{2})\right\}. \quad (3)$$

Generally, the proposed method substitutes MTTR values of intended network component with new time to supply (TTS) of GSP-UK values only if MTTR value > TTS value. Literally, the TTS value indicates a fast time response (compared to the MTTR value) either by replacing with a new component or quick repairing the existing component. Since it is nearly impossible to have a fast response time to all network components and cause under-utilisation of network automation (network reconfiguration), only components on the main feeder (carrying a high current that may affect many customers) are selected to replace MTTR values with TTR values (option 2). To compare the practicality of option 2 with complete network automation, option 1, network reconfiguration, was generated. In option 1, the network component fault/interruption time adheres to the exact values of MTTR, while the customer restoration time is shorted by the GSP-UK duration limit via network reconfiguration. In other word, customers experience outages through the normal path of electrical supply and the duration of outage experienced by the same customer is shortened by rerouting the electrical supply through the network reconfiguration until the faulty component is repaired/replaced.

3.1. Considered Scenarios

In Table 5, scenario SC-1 is a base case that quantifies the benefits of network reconfiguration and repair/replace network component with TTS value. Scenario SC-2 represents the existing network reconfigurations and functionalities (option 1) in accordance with GSP requirements. This means that the network should have switching functionalities to transfer to an alternative supply and for reconfiguration, since, otherwise, many customers would face excessively long supply interruptions (determined by MTTR network components). Next, scenario SC-3 (option 2) has the same purpose in scenario SC-2, but without any transfer to an alternative supply and reconfiguration, as it only substitutes the MTTR of each power component into TTS in accordance with GSP. Scenario SC-3 determines the variance between network reconfiguration and the replacement time of MTTR in adherence to GSP. The purpose of scenario SC-4 is to list the benefits of minimising time window of fault via network reconfiguration. Finally, scenario SC-5 embeds "smart grid", wherein automatic remote-controlled switching may be implemented in future for a suburban distribution network.

Table 5. Description of the Analysed Scenarios.

Description of Scenarios
Scenario SC-1: No reconfiguration and repair/replace network component in accordance with GSP (time to supply—TTS) in the network
Scenario SC-2: All long interruption (LI) (including transfer to alternative supplies and reconfiguration) up to maximum 18 h (in accordance to GSP)—OPTION 1
SC-2A: Reconfiguration at random hours up to 18 h
SC-2B: Reconfiguration at exactly maximum 18 h
Scenario SC-3: Replacement of all LI repair time with TTS (within the control of reconfiguration, as in scenario SC-2) up to maximum 18 h (in accordance GSP)—OPTION 2
SC-3A: Replacement of all LI repair time with random hours up to 18 h
SC-3B: Replacement of all LI repair time with exactly 18 h
Scenario SC-4: All LIs (including transfer to alternative supplies and reconfiguration) up to maximum 3 h
SC-4A: Reconfiguration at random hours up to 3 h
SC-4B: Reconfiguration at exactly 3 h
Scenario SC-5: Time for transfer to alternative supply and reconfiguration are exactly 3 min

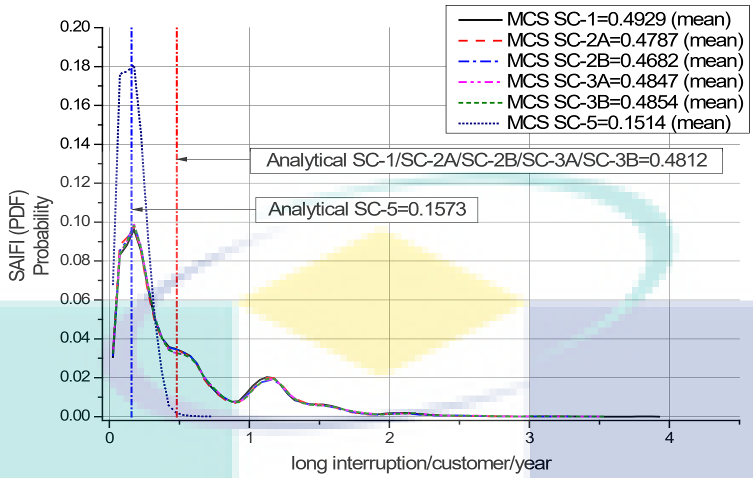
4. Reliability Performance Results

Table 6 presents the values of reliability indices; System Average Interruption Frequency Index (SAIFI), Momentary Average Interruption Frequency Index (MAIFI), System Average Interruption Duration Index (SAIDI), Customer Average Interruption Duration Index (CAIDI) and Energy Not Supplied (ENS) calculated using the MCS technique with a total simulation of 10,000 years for suburban distribution network. MATLAB (R2018a, MathWorks, Natick, MA, US) is used to implement MCS and PSSE software (33, Siemens, Schenectady, NY, US) to model the analysed network and solve the power flows.

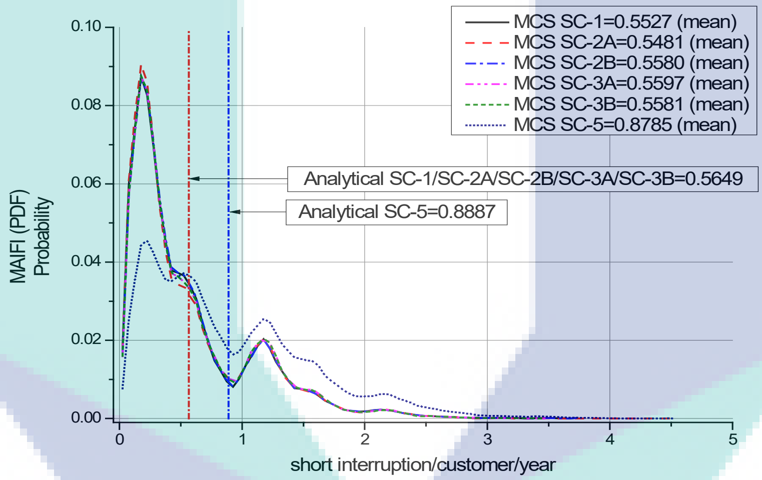
Table 6. Scenario SC-1 to SC-5.

Scenario	Indices	Probabilistic (Mean Values)
SC-1	SAIFI	0.4929
	MAIFI	0.5527
	SAIDI	33.7625
	CAIDI	68.4914
	ENS	3539.4823
SC-2A	SAIFI	0.4787
	MAIFI	0.5481
	SAIDI	6.5735
	CAIDI	13.7321
	ENS	669.5330
SC-2B	SAIFI	0.4682
	MAIFI	0.5580
	SAIDI	8.4968
	CAIDI	18.1494
	ENS	842.8723
SC-3A	SAIFI	0.4847
	MAIFI	0.5597
	SAIDI	6.1732
	CAIDI	12.7374
	ENS	625.1351
SC-3B	SAIFI	0.4854
	MAIFI	0.5581
	SAIDI	8.1339
	CAIDI	17.6588
	ENS	831.2357
SC-4A	SAIFI	0.4733
	MAIFI	0.5569
	SAIDI	4.0005
	CAIDI	8.4526
	ENS	397.6056
SC-4B	SAIFI	0.4734
	MAIFI	0.5569
	SAIDI	4.3145
	CAIDI	9.1138
	ENS	430.6348
SC-5	SAIFI	0.1514
	MAIFI	0.8785
	SAIDI	3.3554
	CAIDI	22.1576

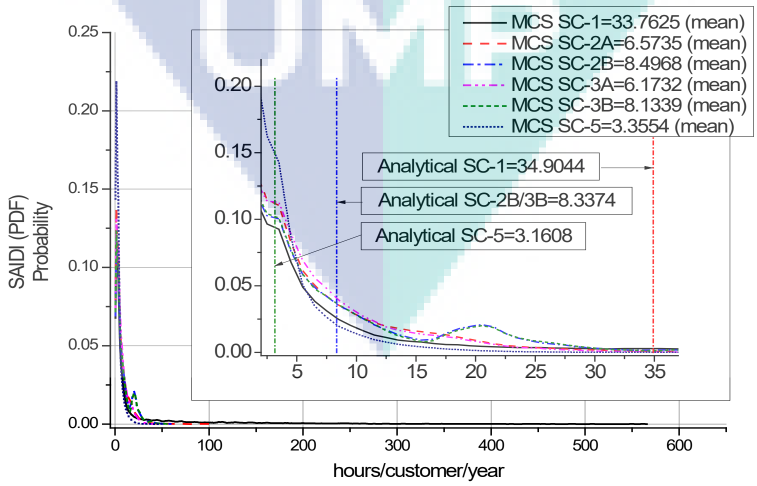
ENS	346.5313



(**a**)



(**b**)



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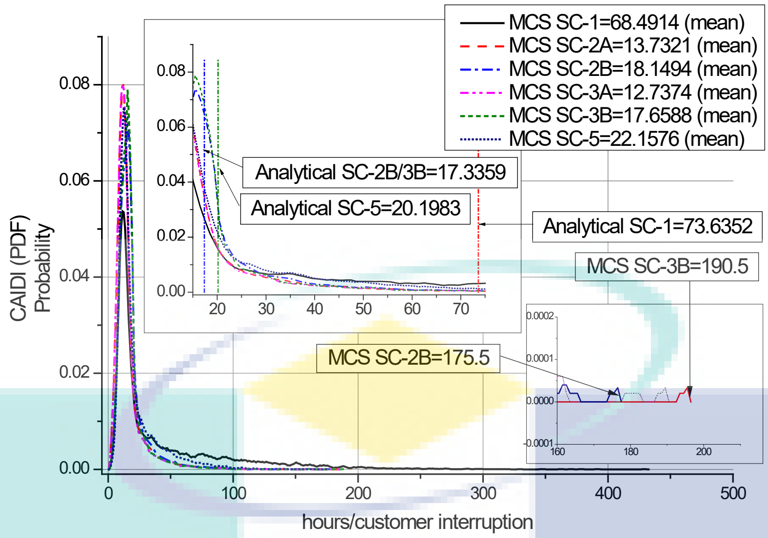
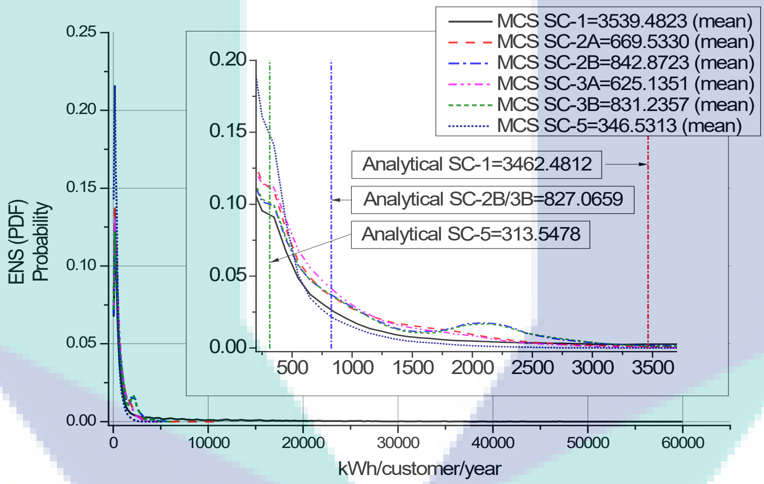
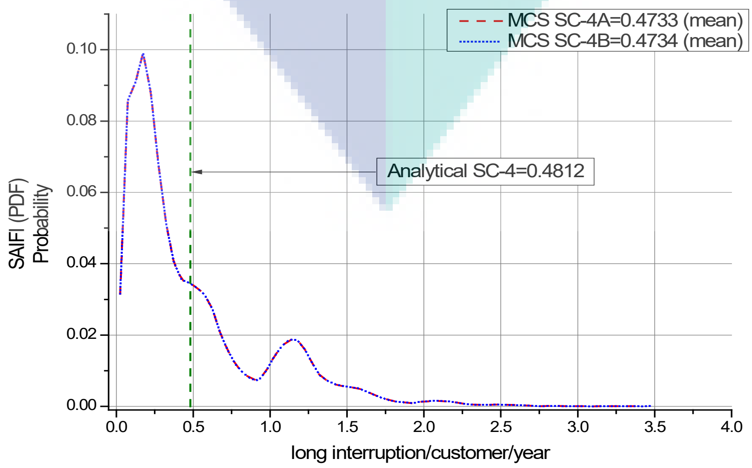


(**d**)

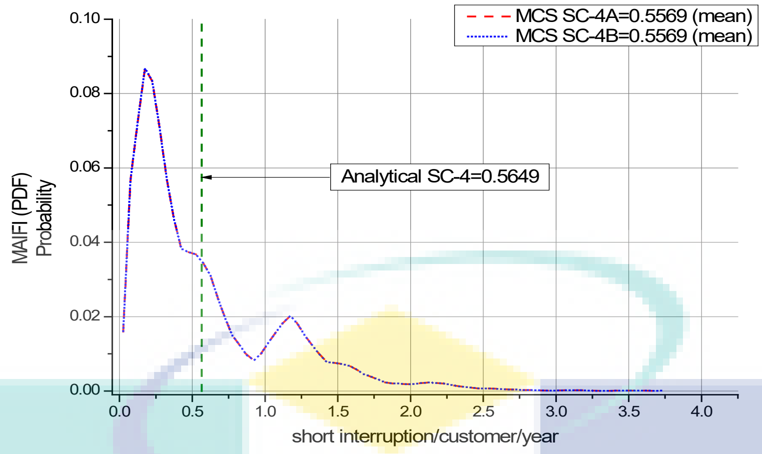


(**e**)

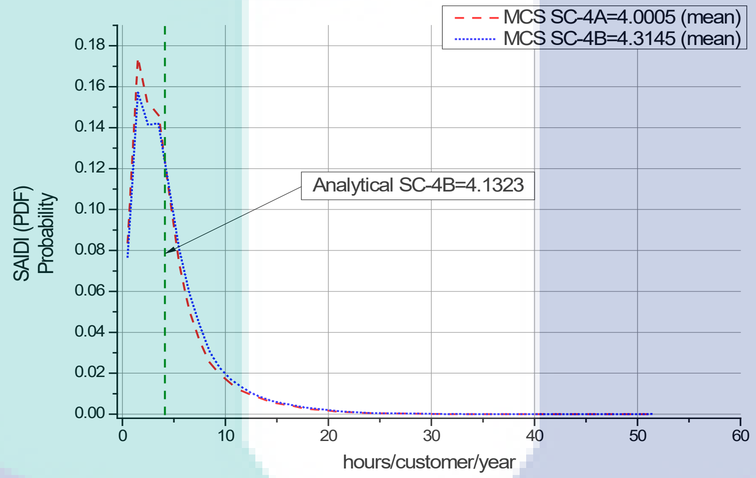
Figure 3. Indices for scenario SC-1, SC-2A/2B, SC-3A/3B and SC-5. (**a**) SAIFI index; (**b**) MAIFI index; (**c**) SAIDI index; (**d**) CAIDI index; and (**e**) ENS index.



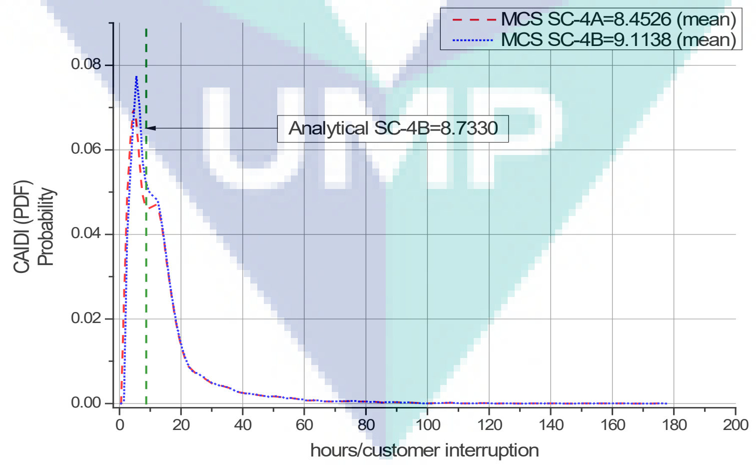
(**a**)


MCS SC-4A=0.5569 (mean)
MCS SC-4B=0.5569 (mean)
Analytical SC-4=0.5649
MAIFI (PDF)
Probability
short interruption/customer/year

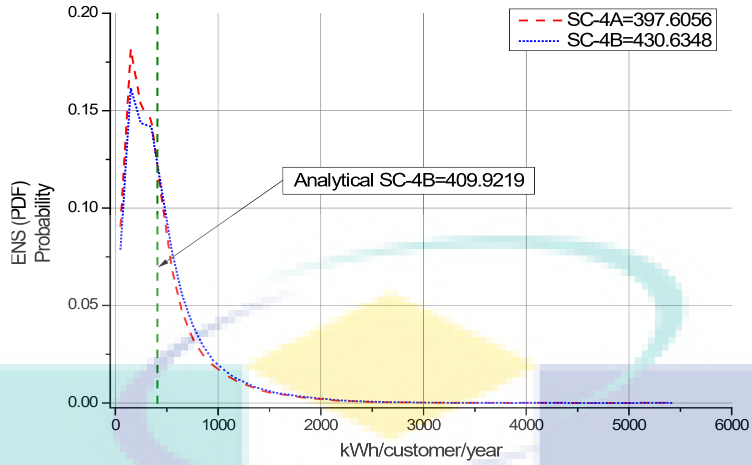
(**b**)


MCS SC-4A=4.0005 (mean)
MCS SC-4B=4.3145 (mean)
Analytical SC-4B=4.1323
SAIDI (PDF)
Probability
hours/customer/year

(**c**)


MCS SC-4A=8.4526 (mean)
MCS SC-4B=9.1138 (mean)
Analytical SC-4B=8.7330
CAIDI (PDF)
Probability
hours/customer interruption

(**d**)



(**e**)

Figure 4. Indices for scenario SC-4A/4B; (**a**) SAIFI index; (**b**) MAIFI index; (**c**) SAIDI index; (**d**) CAIDI index; and (**e**) ENS index.

5. Discussion

The results of scenarios SC-1, SC-2A/2B, and SC-3A/3B suggest that network reconfiguration and repair/replace with TTS can successfully reduce long supply interruptions. Figure 3d illustrates that the MCS outputs displayed a greater reduction in hours, from 68.4914 to 13.7321/18.1494, for scenarios SC-1 and SC-2B/3B, respectively.

In scenarios SC-2A/2B and SC-3A/3B, although the methods (options 1 and 2) of restoration supply differed, both scenarios shared almost similar values. In detail, Figure 3d shows that the line graph of scenario SC-2B is up to 175.5 h, while that for scenario SC-3B is up to 190.5 h. This signifies that for scenario SC-2B, two separate durations of interruptions occurred, and they overlapped with the reconfiguration duration time causing the tail of scenario SC-2B to be smaller than scenario SC-3B.

Between scenarios SC-2A and SC-2B, or SC-3A and SC-3B, huge variances were noted in the values based on Figure 3d (CAIDI index). This is because the repair time in scenario SC-2B/3B was always exactly 18 h, while in scenario SC-2A/3A, although the repair time window was up to 18 h, it was not always exactly 18 h. This led the values of CAIDI in Figure 3d for scenario SC-2A/3A to be lower than scenario SC-2B/3B. As long as the duration of interruption is within the permissible limit (scenario SC-2A/3A), the values are acceptable.

There are possibilities that the values for scenarios SC-2A and SC-2B, or SC-3A and SC-3B share almost similar values. In scenario SC-2A/3A, the time window of repair time/reconfiguration is bigger (up to 18 h), with multiple choices for selecting the hour for repair time or reconfiguration time. For a smaller window of reconfiguration/repair time, as in scenarios SC-4A (repair time up to 3 h) and SC-4B (repair time exactly 3 h), the values of CAIDI for both scenarios in Figure 4d were almost identical.

In Figure 3a, the MCS mean value of SAIFI scenario SC-2B was slightly lower than SC-3B because in scenario SC-2B (see Figure 5), the frequency of interruptions was lower than that in scenario SC-3B (see Figure 6). In Figure 5, customers only experienced single interruption, while double interruptions are shown in Figure 6. Thus, scenario SC-3B exhibited higher values of average duration of interruption than those recorded for scenario SC-2B.

Figures 5 and 6 portray the tail graphs of scenarios SC-2B and SC-3B for better understanding. In Figures 5 and 6, the same customers experienced LIs with varied average duration of interruption. In Figure 5, no second duration of interruption was noted, while in Figure 6, the customer experienced a second interruption within a 3 h duration. Thus, as displayed in Figure 6, the duration of interruption was 21 h, which is longer than that in Figure 5, 18 h.

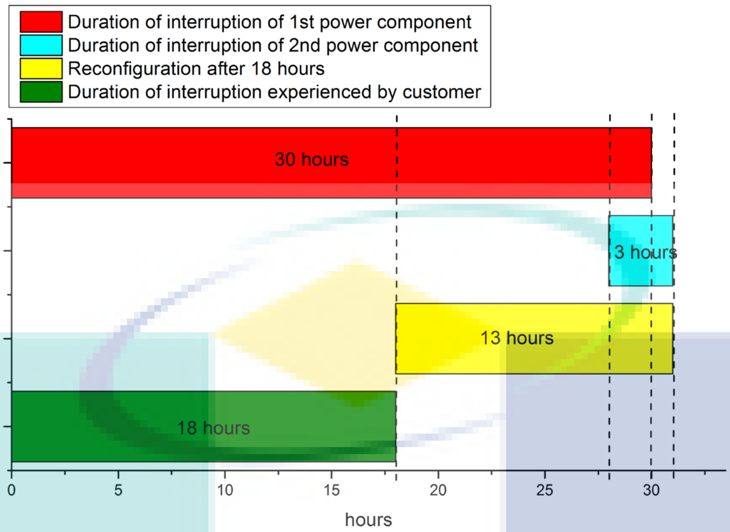


Figure 5. Example of scenario SC-2B tail graph.

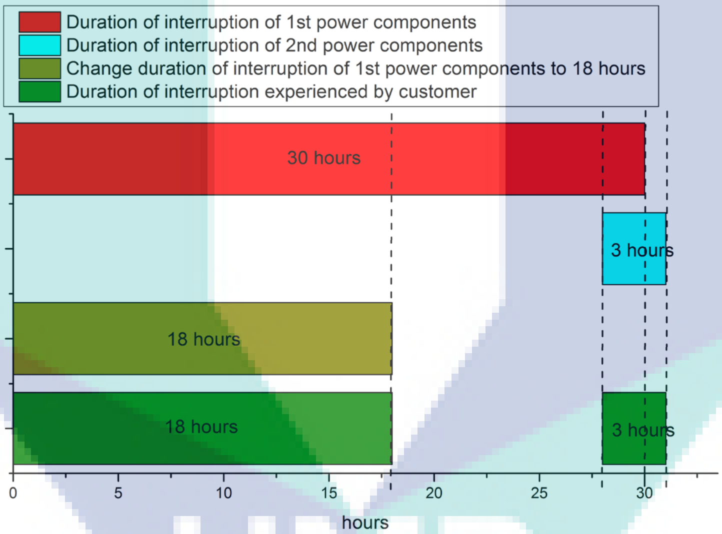


Figure 6. Example of scenario SC-3B tail graph.

As for scenario SC-5, when "smart grid" automatic switching was applied to the network reconfiguration, the CAIDI values (i.e., average duration of LIs) increased after all faults were addressed within 18 h, to turn into Sis, due to less than 3 min of automatic switching. In detail, the shorter duration of LI no longer contributes to the average values, causing the average values of CAIDI of scenario SC-5 to be higher. This also indicates that automatic switching reduced the number of LIs but increased the average duration of interruptions and the number of SIs.

6. Conclusions

This paper presents the reliability performance under various reconfigurations and replacement repair times based on regulator supply requirements. Each presented scenario has its own pros and cons. It is possible and realistic to change the mode of operation from a power loss-based to a regulator reliability-based network reconfiguration or repair/replace network component by adhering to GSP requirements on the existing network, so as to meet the target set by the energy regulator. In option 1 (network reconfiguration), the selection of restoration time (either 3 min, or 3 or 18 h) was unrestricted by human activity and weather, as DNOs may operate switches/breakers manually or automatically, rerouting the electrical supply. As for option 2 (repair/replace network component with TTS value), it is practical to completely clear the fault within 18 h, but optional (either feasible or otherwise) for 3 h or below 3 h. The 3 h replacement/repairing of network component depends on the definition, by including or excluding travelling time, locating fault area, weather condition, and others. Hence, several scenarios bring about extra flexibility to DNOs. DNOs may choose the most appropriate methods/options or scenario in accordance with their operation conditions and the requirements of the network system so as to meet their own reliability target, as well as the target fixed by the energy regulator.

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Reliability Performance of Low Voltage (LV) Network Configuration

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Abstract. Networks are typically modelled in single phase diagram especially for medium voltage (MV) and high voltage (HV) networks. For low voltage (LV) networks, it is not suitable to model it in a single phase diagram. The reliability performance of LV network may be overestimated or underestimated if the network is modelled in a single phase diagram. Analytical technique is used to quantify the performance of LV network in single and three phase network diagrams. Three phase LV network diagram illustrates the true reliability performance compared to single phase LV network diagram in term of the best, median and worst location of customers. Accurate network configuration may benefit in minimizing energy core losses and reducing paying penalty to the customer by distribution network operators (DNOs).

Keywords: reliability, distribution network, single phase diagram, three phase diagram

1 Introduction

Typically, the importance of reliability in distribution system has received less attention compared to generation and transmission systems. The main reason of these two systems are significant due to these two systems carries high current that affects a vast number of customer (indirectly) and considers as a backbone of electrical supply (especially transmission network). However, the importance of distribution network should not be neglected as it directly connected to the end customer.

Since distribution network supplying the most customer, it ties up by the target or minimum customer satisfaction level imposed by Energy Regular, which in Malaysia is Energy Commission (EC). These targets mostly involved the frequency and duration of interruption. To attain that target, distribution network operators (DNOs) must correctly assess their reliability performance. Therefore, it is critical to have accurate distribution network configurations and parameters. However, due to the size of distribution network, low voltage (LV) network often represented by aggregate model [1]–[6].

Typically, the aggregate model of LV network is represented by active and reactive power downstream from the point of aggregation. For certain steady-state analysis, the LV representation of active and reactive powers are enough, but in term of reliability perspective, additional information is required especially in fault rates and mean time to repair (MTTR) input. The detail reliability input from LV representation may decide the performance level of distribution network.

Furthermore, in the EC report [7], a vast number of customer interruption is originated from LV network, compared to medium voltage (MV) and high voltage (HV) networks as in Figure 1. Customer Average Interruption Duration Index (CAIDI) is defined as average interruption time per customer affected by the interruption. In the same report, CAIDI from LV network is higher than MV and HV networks as in Figure 2. From these statements, the distribution network should include reliability input of LV network for analyses of MV or HV/MV networks. Therefore, by properly illustrating the configuration of LV networks in MV or HV/MV networks, no components will be neglected in regards to the load aggregation from lower to higher voltage.

Another concern related with LV network is modelling of network diagram. Typically, most of the network is modelled as a single line diagram, where all customer of each phases (red, yellow and blue phases) are connected to single conductor. In another word, if the blue phase is faulty/interrupted, other phases (red and blue) also interrupted. The modelling of LV network in single line diagram is incorrect as the protection devices in LV network operate in individual phase. For MV and HV networks, the modelling of network as single line diagram is correct as the protection devices are operating in three phases system [8]–[13]. Hence, ignoring the design of LV network in three phases diagram will underestimate the reliability performance of network.

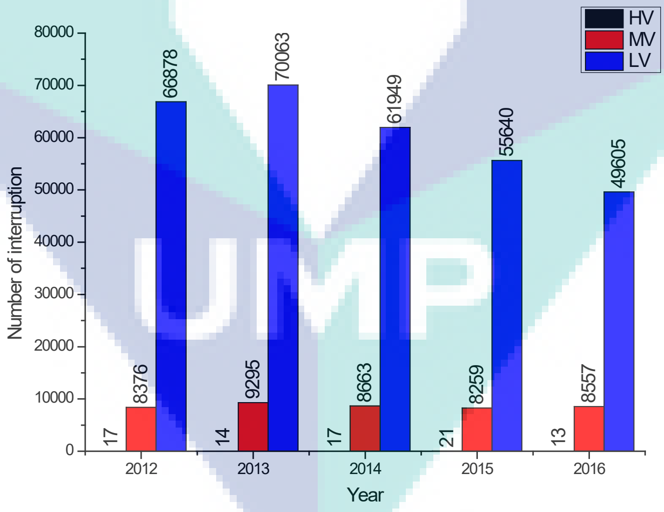

Fig. 1. Number of interruption by voltage variation

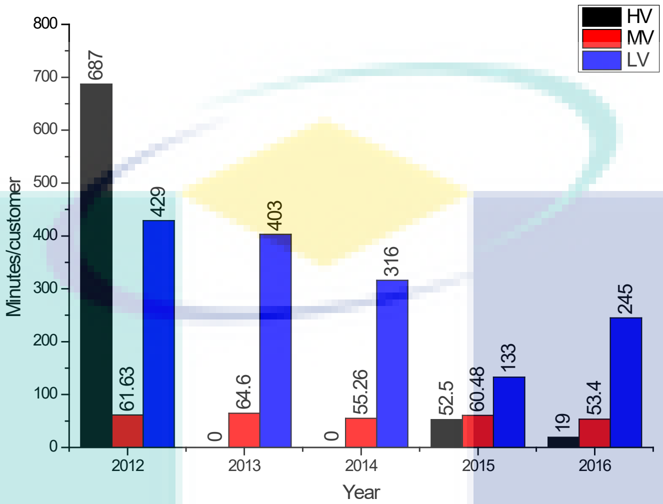

Fig. 2. Duration of interruption by voltage variation

Therefore, accurate reliability performance can be obtained with detail and correct design of LV network for analyses of MV or HV/MV networks. Concerning this matter, the paper aims to present the methodology of formulating accurate LV distribution network model based on reliability inputs of network component, component parameters and network configuration.

2 Reliability Input

The reliability assessment of distribution system required distribution network complete with its configurations and parameters and reliability input in term of fault rates and mean times to repair (MTTR) of network components.

2.1 LV Distribution Network

The considered network for these analyses is rural LV distribution network. The network consists of a single transformer with a rating of 500 kVA, and the line feeder is mostly overhead lines carrying 230 V for each phases supplying a total of 44 domestic customers. Star connection is used allowing the employment of two different voltages; 230 V and 400 V. The network configuration is radial without normally open network reconfiguration or back-up supply. Figures 3 and 4 present rural LV network in single and three phases diagram respectively. Tables 1 and 2 provide more details for the network components.

Table 1. Feeder parameters

LV feeder	Id.	Cross section (mm^2)	Maximum Sustained Current (A)	R_{ph}	X_{ph}
Underground Cable	A	25	110	0.87	0.085
	B	70	190	0.443	0.076
Ethylene Propylene Rubber	C	120	250	0.253	0.071
	D	185	320	0.164	0.074
	E	300	400	0.1	0.073
Overhead Lines	F	1x16+25	80	2.33	0.139
	G	3x16+25	80	2.33	0.13
Aerial Bundle Conductor (ABC)	H	3x95+70	190	0.39	0.108
	I	3x185+120	300	0.2	0.103

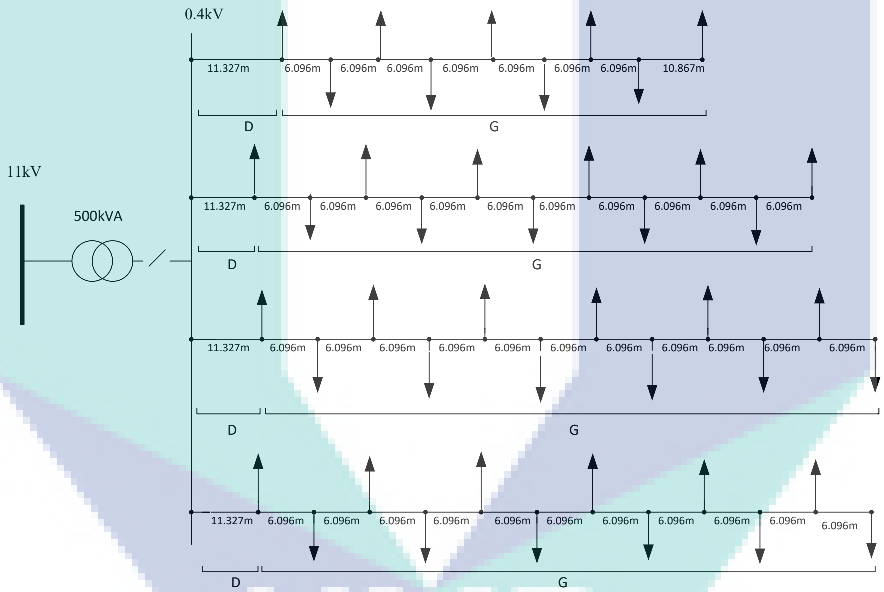

Fig. 3. Rural LV Distribution Network (single phase diagram)

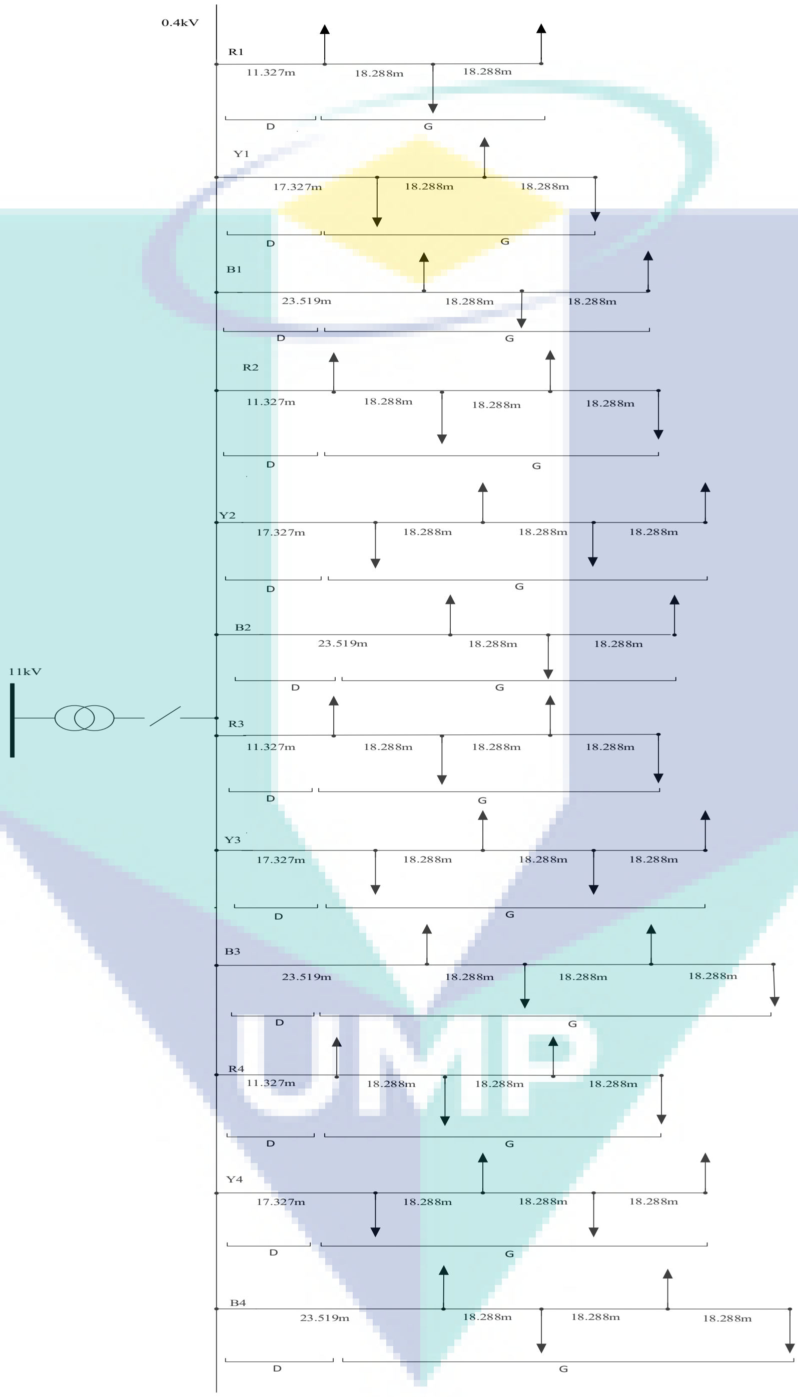

Fig. 4. Rural LV Distribution Network (three phase diagram)

Table 2. Transformer parameters

Rating	Connection	Tapping Range	Load Lossess at 75°C (W)	No-Load Lossess (W)	Impedance (%)	Model Parameters (p.u. on 100 MVA)	
						RLV	XLV
500	Dyn11	± 5% in 2.5% taps	5100	680	4.75	2.04	9.28
315			3420	580	4.75	3.4444	14.6794
200			2900	540	4.75	7.5	22.5

2.2 Mean Fault Rates and Repair Times

Past recording and statistic data are significant for predicting and assessing future and present reliability performance of distribution network. These data are required for simulation technique to characterise the performance of distribution network under analysis. Two of three (i.e. mean fault rates, MTTR and unavailability) general reliability input are required to perform the simulation. The mean fault rates represent the total number of times in a year the component has to be removed from service for repair due to the failure that occurs while MTTR represents the average times required to repair the components that affected by the failure. Table 3 presents the statistic of mean fault rates and MTTR of network components.

Table 3. Mean Fault Rates and MTTR

Power Component	Voltage Level (kV)	Mean fault rate λ_{mean} (faults/year)		MTTR μ_{mean} (hours/fault)	
		[14]	[15]–[22]	[14]	[15]–[22]
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
Transformers	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	<11	0.0004	-	35.3	-

3 Reliability Assessment

The Analytical technique is used to assess the performance of LV networks. Typical indices are used to assess the performance of distribution networks.

3.1 Reliability Method

The technique that used to determine power system reliability is a classical method which is an analytical method [23]. In this paper, the analytical method is used to measure reliability performance. The reliability indices that have been evaluated using classical concept are the three primary ones of average failure rate λ_s, average outage duration r_s, and average annual unavailability or average annual outage time u_s. These indices are expected average values of total customers of the LV distribution system [23], [24]. This term of reliability indices is used to determine the number and duration of interruption.

Average failure rate;

$$\lambda_S = \sum_i \lambda_i \tag{1}$$

Average outage time;

$$U_S = \sum_i \lambda_i r_i \tag{2}$$

Average annual outage time;

$$r_S = \frac{U_S}{\lambda_S} = \frac{\sum_i \lambda_i r_i}{\sum_i \lambda_i} \tag{3}$$

Analytical method has numerous attractive features which a precise method and computationally well-organised and possibly most important, it offers the developer with understanding of the relationship between input variables and final results. Also, analytical model and techniques have been necessary to provide planners and designers with the results necessary to conclude reliability performance. Analytical techniques denote the system by mathematical model and evaluation of the reliability indices from this model using direct numerical. Besides, they provided expectation indices in relatively short computing time.

3.2 Reliability Indices

The reliability performance of rural LV distribution networks are assessed through the calculation of a set of reliability indices. The System Average Interruption Frequency Index (SAIFI), and System Average Interruption Duration Index (SAIDI) are typical set of indices used by most countries [24]. These set of indices also used by Tenaga Nasional Berhad (TNB) for reporting the performance of distribution network in most area in Malaysia to EC.

System average interruption frequency index, SAIFI. It indicates how frequent an average customer is subjected to sustained interruption over a predefined time interval.

$$SAIFI = \frac{Total\ number\ of\ customer\ interruptions}{Total\ nmber\ of\ customers\ served}$$

$$= \frac{\sum \lambda_i N_i}{N_i} \tag{4}$$

System average interruption duration index, SAIDI. The interruption index of power supply is indicated in minutes per customers.

$$SAIDI = \frac{Sum\ of\ customer\ interruption\ durations}{Total\ number\ of\ customers}$$

$$= \frac{\sum U_i N_i}{\lambda_i N_i} \tag{5}$$

4 Result

The network area located at the rural residential with about 44 customers. The type of house that related to this study are terrace house with load demand 1.5kW per houses, with a total load of this region is 69.47kVA. Based on Figure 3 (single phase) feeder 1, 2, 3 and 4 consist of 9, 11, 12, 12 loads respectively. For three phase network (Figure 4), it has the same number of load in single phase network, but the connection of the load to the supply is three phase network. For feeder 1, it received supply only from red wire, while feeder 2 received supply from yellow wire and feeder 3 received supply from blue wire.

Table 4. Reliability Indices (average of all customer)

Network	SAIFI	SAIDI
Single phase	0.99363	6.58907
Three phases	0.67881	4.49607

Table 5. Reliability Indices (focus on the type of customer)

Network	Type of Customer	SAIFI (location)	SAIDI (location)
Single phase	Best	0.0157 (1)	0.86309 (1)
	Median	1.0147 (15, 26, 38)	6.67844 (15, 26, 38)
	Worst	2.0227 (44)	12.49379 (44)
Three phases	Best	0.33770 (33)	1.86841 (21)
	Median	0.67370 (19, 23, 26, 30, 35)	4.71299 (19, 26, 30, 35)
	Worst	1.01470 (44)	6.74819 (17)

5 Discussion

Table 4 present the average value of indices for all customer. It clearly shows that by the value of SAIFI and SAIDI for LV network of single phase diagram are higher than three phase diagram. It indicates that neglecting the real configuration of LV distribution network should overestimate the reliability performance. Single phase diagram has a higher value compared to three phase diagram due to the fault rates of the main feeder. In single phase diagram, all phases (red, yellow and blue) of main feeders are connected together, although in reality, it doesn't operate in such way. For example, if red phase of the main feeder is faulted, yellow and blue phases also faulted, resulting in more interruption and duration of interruption experience by customers.

Table 5 illustrate the type of customer based on reliability performance; best customer for low-value indices, median customer for average value indices, and worst customer for a high value of indices. The best customer typically located near the source and short in electrical supply path, which directly related to equation (1). Worst customer is opposite factors of the best customer; located further from source and long in electrical supply path. Hence, a better organisation of emergency staff/source plan during fault can be employed to decrease the frequency and duration of interruption.

By knowing the correct reliability performance of each customer, type of network component in the planning phase can be utilized to minimise energy losses. For instance, low core energy losses of conductor or underground cable may be employed for a long feeder supplying a high number of customer. Another suggestion of earlier distribution planning is configuring various network configuration by getting the best reliability performance and lowest energy losses. Reliability performance of every customer is important nowadays due to penalty enforcement by EC (for Malaysia). Each customer has its maximum experience frequency and duration of interruption. If the customer experience interruption/duration exceed the maximum value by EC, DNOs must pay the penalty to the customer. Therefore, distribution network planning is crucial for DNOs to minimise paying the penalty.

6 Conclusion

Modelling the correct configuration of the distribution network is important as it affects the overall performance of distribution network; aggregation of all downstream network (LV networks) to the upstream network (MV and HV networks). The modelling of network configuration depending on the operation and protection system of network. For MV and HV networks, the protection system employed in three phases operation, which single, double or three phases fault should lockout (isolate from healthy part) all phase. It differs for LV network, where the protection system employed in single phase operation. If one phase fault, only that phase is lockout, another two phases continue in supply. Another reasons for correct configuration are to minimize losses and penalty. DNOs may utilise low energy losses component for critical feeder and configure optimal network configuration during distribution network planning phase.

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