Research Article

Reliability-based DG location using Monte-Carlo simulation technique

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Abstract
Reliability targets have become essential to distribution network operator since Energy Regulator set minimum targets of reliability performance of the network and penalise if the targets not achieved. Thus, placement of distributed generation (DG) into network offers improvement in reliability performance. Typically, less attention is given to DG reliability-based placement compared to voltage- and loss-based placement. Therefore, this paper presents the placement of DG based on reliability performance, which applied to medium voltage (MV) and low voltage (LV) sub-urban distribution network. The typical Monte-Carlo simulation technique is used to assess both system and customer-related reliability performance. The placement of DG into MV and LV networks show improvement in terms of reliability performance.

Keywords Reliability · Low voltage network · Medium voltage network · Monte-Carlo simulation · Distributed generation

1 Introduction

System reliability defines the distribution network operators (DNOs) performance of existing electricity networks and indicators for the improvement of future 'smart grids'. One of the objectives of DNOs is to expand the electricity supply services by providing reliability performance within limit/target and at the same time, lowering the operational and maintenance cost to provide affordable tariff to the customers. However, present distribution systems (traditional energy flow from generation system to distribution system) designed that the performance of medium voltage (MV) and low voltage (LV) networks have a significant impact on the frequency and duration of interruption since most of the customer connected at these networks.

Thus, by incorporating distributed generation (DG) into the distribution network will minimise capital investment for the weakest or reinforcement-required network, especially upgrading network component. There are many types of technologies for DG such conventional DG, which is powered by fossil fuel (e.g. natural gas or diesel fuel) and renewable DG, such as solar cells and wind-powered generation. DG typically defines the production of electricity at or near the load demand/customer. Examples of DG include solar panel on residential rooftops, small size wind-generation on the top of building and backup generators at hospital.

DG connected at some network locations will have a higher impact than the same DG connected at the other network locations. This opens the question of the "placement of DG", but it should be noted that the DNOs have little to no impact on DG placement, as DG units are owned, installed and operated by individual customers/users, based on, e.g. their investment plans, availability of land, etc. However, DNOs can incentivise or subsidise certain network locations to DG developers, and therefore, at least to some extent, influence the selection of the locations of DG systems in their networks.

Regardless whether it optimally located or not, DG and Energy Storage (ES) can help to (significantly) improve

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network voltage regulation (particularly in weak networks), to reduce system losses (unless there are excessive reversed power flows) and to improve overall network performance, including system reliability levels. Several numbers of studies have developed various methodologies of incorporating DG, which typically applied to the weakest point in the networks. Most of the related literature implements voltage sensitivity [1–7], or loss sensitivity [6, 8–13] as the main factors in deciding on (optimal) placing and sizing of DG.

Although most of existing literature states or documents that selection of DG based on these criteria (voltage, or loss) will improve network reliability performance, this was a secondary effect of some other main criteria used for the DG placement. Accordingly, a very few studies have previously concentrated on the problem of (optimal) placement and operation of DG and ES systems with a primary function to improve reliability performance of the network, e.g. [14–16]. To fill this gap, the analysis in this section applies improvement of reliability performance as one of the criteria for studying the impact of DG location and tries to identify these load points where connected DG will have the most beneficial impact.

2 Monte-Carlo simulation

The main reliability parameters used for input of MCS are fault rates and mean time to repair (MTTR). These inputs are not static average values but vary over time after been represented using probability density function (PDF). Thus, reliability input with fault rates (λ) and mean repair times (μ) used in this analysis presented in [17]. Accordingly, a random number (generated by random generator) is linked to inverse cumulative distribution function (CDF) to convert fault rates and MTTR into two main states, Time to Fail (TTF) and Time to Repair (TTR) for each network component. The states of the network component can model with a series of distribution function; Exponential, Raleigh, and Weibull.

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

$$\text{Weibull;TTF/TTR} = \mathit{inverse}\left\{1 - \exp(-t/\delta)^{\beta}\right\} \tag{2}$$

$$\text{Raleigh;TTF/TTR} = \mathit{inverse}\left\{1 - \exp(-0.5(t/\sigma)^2)\right\} \tag{3}$$

Each iteration is simulated yearly in 40 years (typical network component's lifetime) and stop at 10,000 years of simulation. The general resolution of simulation is 30-min step, which is relatively low, but enough to differentiate the type of interruption either long or short interruption. In each simulation, whether there is network component failure or not, the power flow calculation assesses the number and demands of interrupted loads. The simulation is employed with the combination of Matlab and PSS/E softwares, and automated by Python. The methodology of MCS approach used in this paper illustrated in Fig. 1.

3 Sub-urban distribution networks

3.1 MV sub-urban distribution network

The MV sub-urban distribution network in Fig. 2 shows two main feeder lines with tree-like structure. In normal condition, the two main feeder lines operate radially, and during fault condition, the network becomes meshed through closing the switch of a normally open circuit breaker. The network also provided with alternative supply at the end of main feeders with unrestricted electricity supply. Due to the radial configuration, the impact of locating DG will be more significant according to its placements, more or less remote from the mains supply. The parameters for all components can found in [15].

3.2 LV sub-urban distribution network

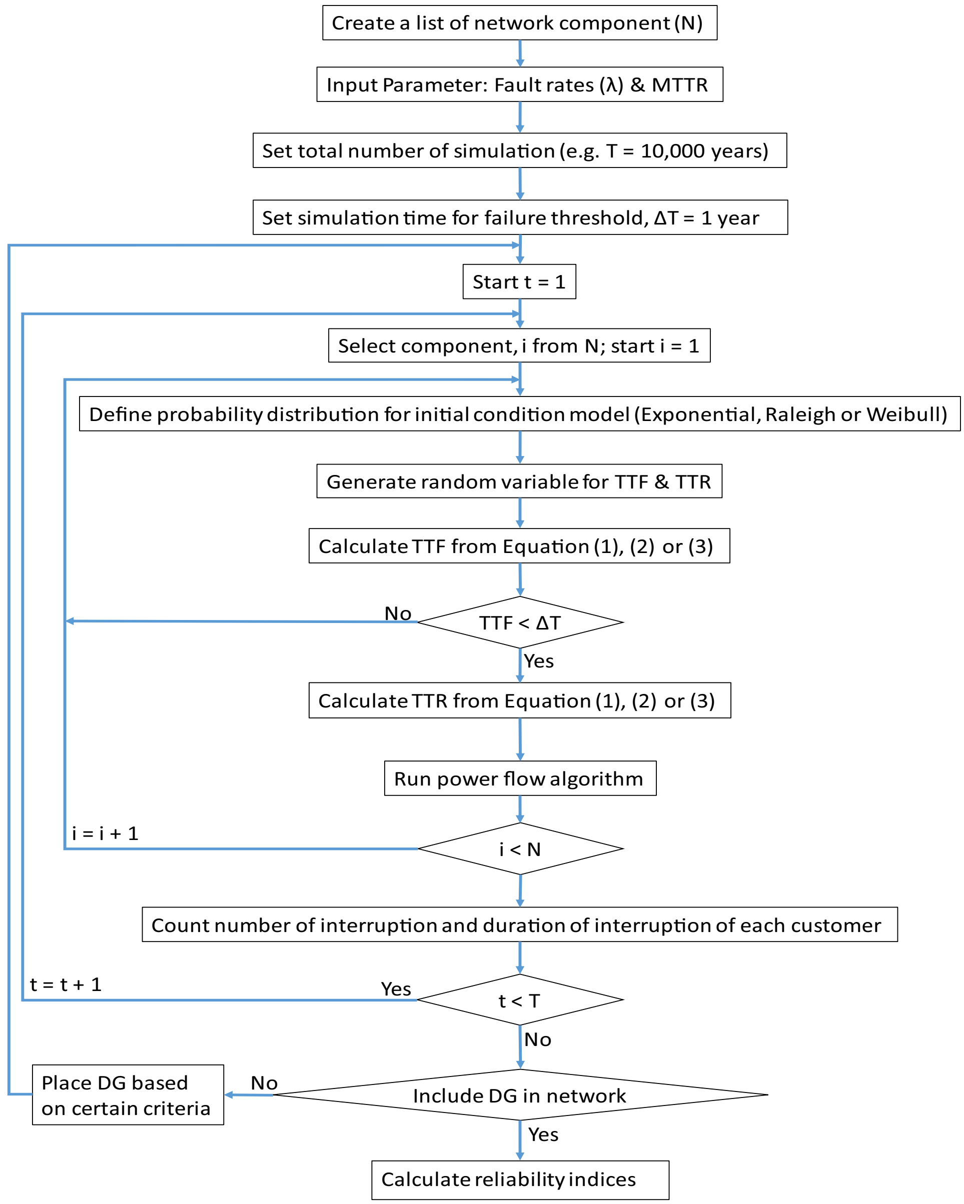
Each of the 44 LV bulk load supply point connected through a 200kVA 11/0.4 kV transformer supplies in identical LV sub-urban network with 76 individual LV customers. The network has two main feeder lines which operate radially and no network reconfiguration system within this network.

3.3 Distributed generations (DGs)

DGs categorised into two different technologies: conventional and renewable energy technologies. The main difference between conventional and renewable DG is the steadiness output of the DG. Renewable DG depends on variable inputs, such as solar and wind energy, which may fluctuate, making it difficult to forecast and control. In a case where renewable DG is connected to the load demand to supply during interruptions, the supply and demand may not match, resulting in load shedding for some of the customers.

Since the primary objective of this study is to find the location of DG, the DG used in this study is non-renewable and non-intermittence source such as fuel cell or CHP. This study assumes DG operates with 0.95 (leading power factor) and able to supply active power and reactive power to the local network. The operations of DG not only serve as backup supply during fault, which serve the healthy part of the network but also injects power to network during

Fig. 1 Monte-Carlo simulation (MCS) algorithm



normal condition. The penetration of DG in the network is assumed 5% of maximum residential demand.

4 Reliability performance assessment

The protection system is used to segregate the faulty part from the healthy part of the distribution network. By the objective of supplying electricity to a large number of customer, DNOs will apply corrective action through network reconfiguration. In Fig. 2, the only reconfiguration is only for two main feeder lines and others branch feeders, due to economy-design limitations, are typically not modelled with 'n-1' security factor. As a result, several customers will have disconnected from the supply, resulting in a long duration of interruption. Therefore, by incorporating of DG into the distribution network, may provide an alternative solution for providing continuous electrical supply to customers (Fig. 3).

4.1 Identification of DG location

The interruption duration from Fig. 4 is calculated using MCS technique for the base case, which no DG connected in the network. Figure 4 shows reliability performance of MV sub-urban network with operation of alternative supply at the end of main feeder lines, which operate after faults longer than 3 h or 18 h accordance with Security and Quality of Supply (SQS) and Guaranteed Standard of Performance (GSP) [24, 25], respectively.

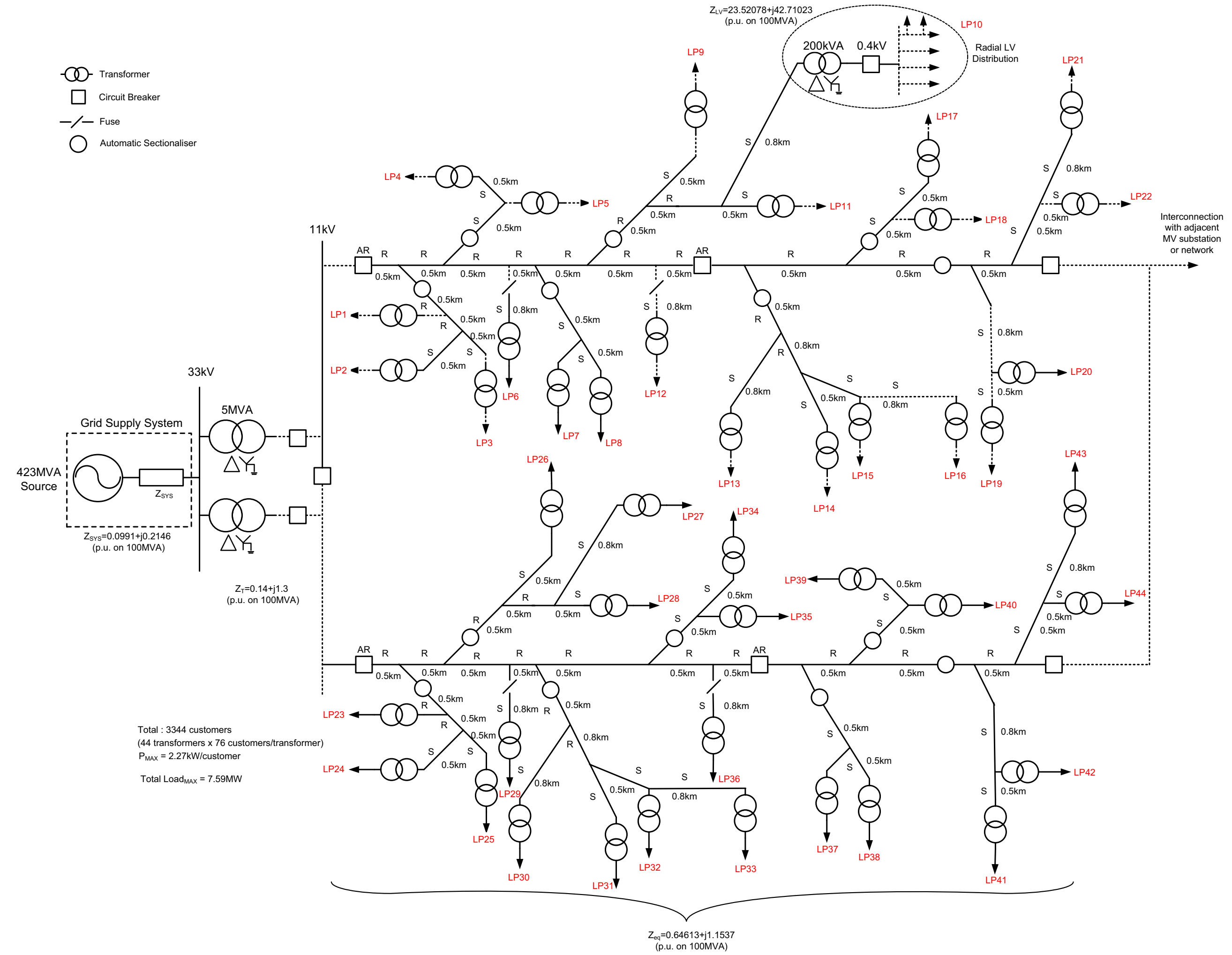


Fig. 2 Typical MV sub-urban distribution network [15, 18–21]

As expected, the customers that experience longer interruptions are at load point 19 (for MV main feeder 1) and load point 43 (for MV main feeder 2) in Fig. 2 which located farther from the source. These customers also define less than 1 MW [24, 25] in which is support with alternative supply after 18 h of fault. Thus, their probability of experiencing a shorter duration of interruption (known as the best-served customers) who are at load point 6 (for MV main feeder 1) and load point 29 (for MV main feeder 2). Based on cumulative of active power from downstream to upstream of the main feeder, load point 6 and 29 are customers that define in category B based on Table 1 in which are supported with alternative supply after experienced 3 h or more of long interruption.

4.2 Reliability analysis with DG(s)

To have an accurate estimation of impact of DG towards system reliability, a lot of factors need to consider. In this study, the analysis correlates all network components fault rates with the probability of fault rates while residential loads simulated with residential load profiles. For example, if one of the 33/11 kV transformer from the Fig. 2 fails when load demand at the downstream of network is greater than the power rating of the other transformer, a large number of customer may be able to have continuous supply if the DNOs apply suitable corrective action. Figures 5 and 6 show the daily probabilities of long/short interruption and typical residential load profiles, respectively.

Therefore, the connection of DG able to provide a continuous supply until normal supply established. In this case, the faulted part of the network will operate in islanded mode. After an interruption, some or all loads instantly transferred to the DG, depends on DG size capabilities. By providing energy into the network, the number and duration of interruption experienced by the customer may be reduced. To avoid applying load shedding at a single load point (where the placement of DG),

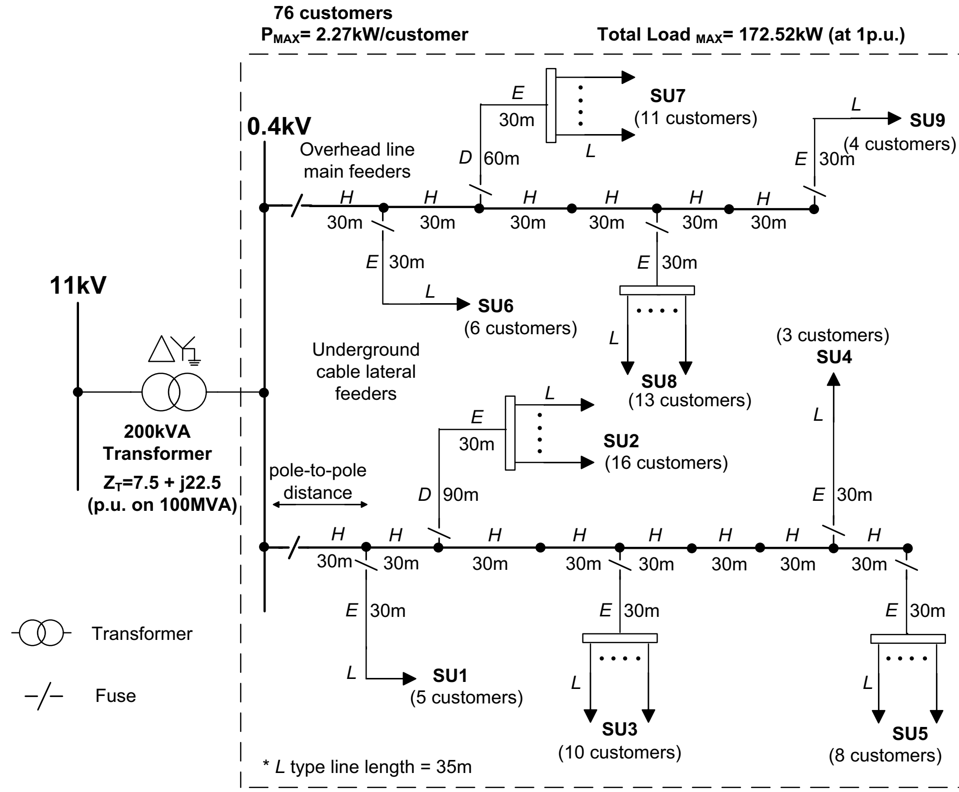


Fig. 3 Sub-urban LV distribution network [22, 23]

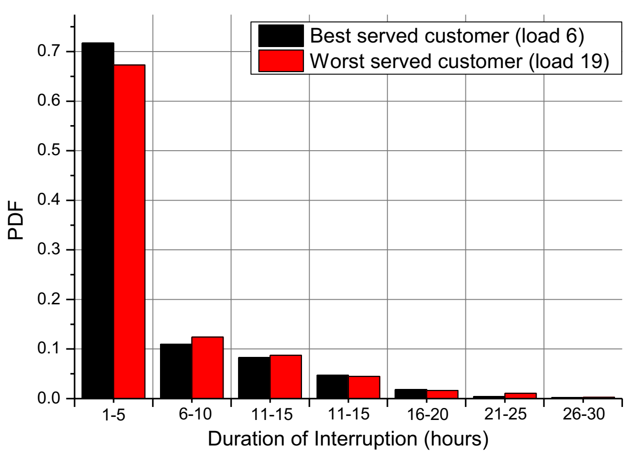


Fig. 4 Interruption duration experienced by the best- and worst-served customer for main feeder 1

Table 1 Average values of reliability indices (MCS)

Indices	SAIFI	SAIDI	MAIFI	CAIDI	ENS
Base case	0.4414	2.7888	0.5263	9.3870	273.0411
DG-LV	0.4186	2.6440	0.5108	9.2635	255.0656
DG-MV	0.4381	2.7754	0.5297	9.2001	255.2354

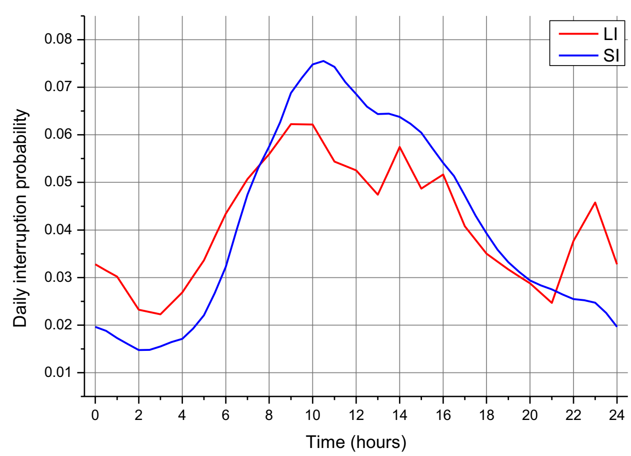


Fig. 5 Probabilities of long/short interruption (LI/SI) in 24 h [26]

the size of DG used in this analysis is a more or match the maximum load demand for a single load point. Since the location of DG has decided, possible implementation of DG is either at MV side (Fig. 7) or LV side (Fig. 8). Therefore, two scenarios with DG are analysed:

- DG placement at MV side of load point (DG-MV)—a single unit of DG with a size of 180 kW.

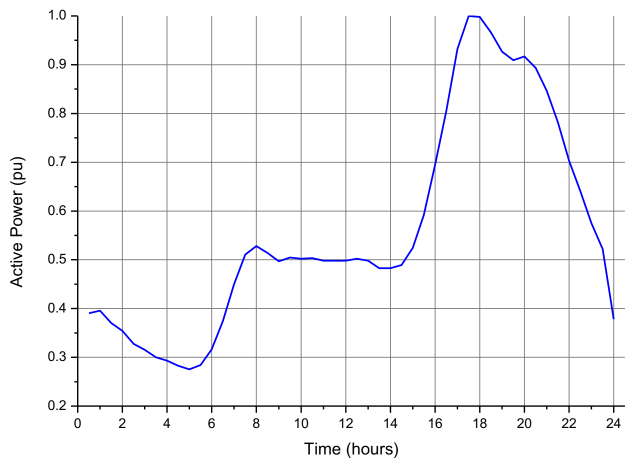


Fig. 6 Typical residential load profiles (day of maximum demand) [17]

- DG placement at LV side of load point (DG-LV)—Two units of DGs with the size of 80 kW (locate at LV feeder 1) and another 100 kW (locate at LV feeder 2).

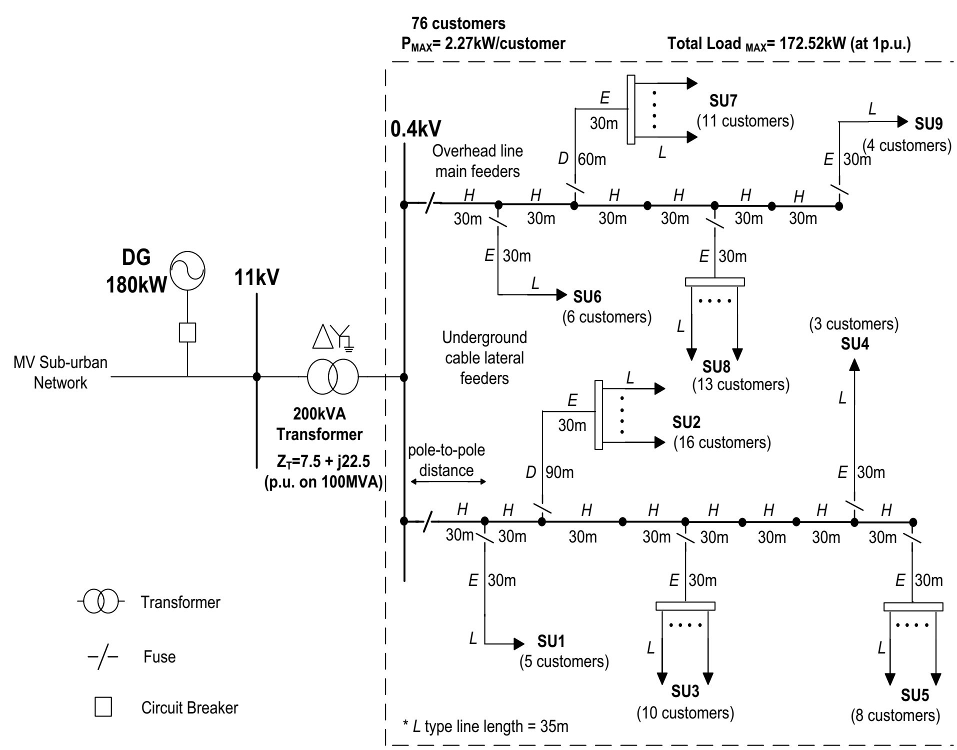
5 Results and discussion

The reliability performance of MV sub-urban distribution network is analysed for the two different cases and compared with the base case, which no DG connected in the network. System-related indices (SAIFI, SAIDI and MAIFI, CAIDI and ENS) are used to verify the impact of DG placement into the sub-urban distribution network. To any claim benefits from the reliability perspective, there should be some reasonable improvement in reliability indices. Otherwise, DNOs will get no benefit or credit for the investment of DG that they make in the network.

By penetration of DG about 5%, the improvement of reliability performance is low since the connection of DG only at load point with the highest duration of interruption. Thus, the reliability indices normalised by a large number of served customers, dilute any quantifiable benefits of DG on the distribution network. Figure 9 shows the reliability indices for the base case, and two considered DG cases simulated for a total duration of 10,000 years. All DG scenarios decrease the probability of the customer's number and duration of interruptions. Average values of reliability shown in Table 1 to illustrate the positive effects from one case to another (Table 2).

To confirm the suitable approach for assessing reliability performance with inclusion of DG in network, analytical approach is applied and compared with MCS approach. The analytical approach is typically related to mathematical equations, which characterise the network in terms of the specified input data, typically limiting output to one set of results, e.g. mean values of reliability indices, corresponding to specified input mean data (i.e. fault rates and mean repair time). In other words, analytical approach is a non-time sequence method while MCS is a time sequence method. For example, if fault happens at initial-lines in

Fig. 7 Connection of DG at the MV side (primary side of 11/0.4 kV distribution transformer) [22, 23]



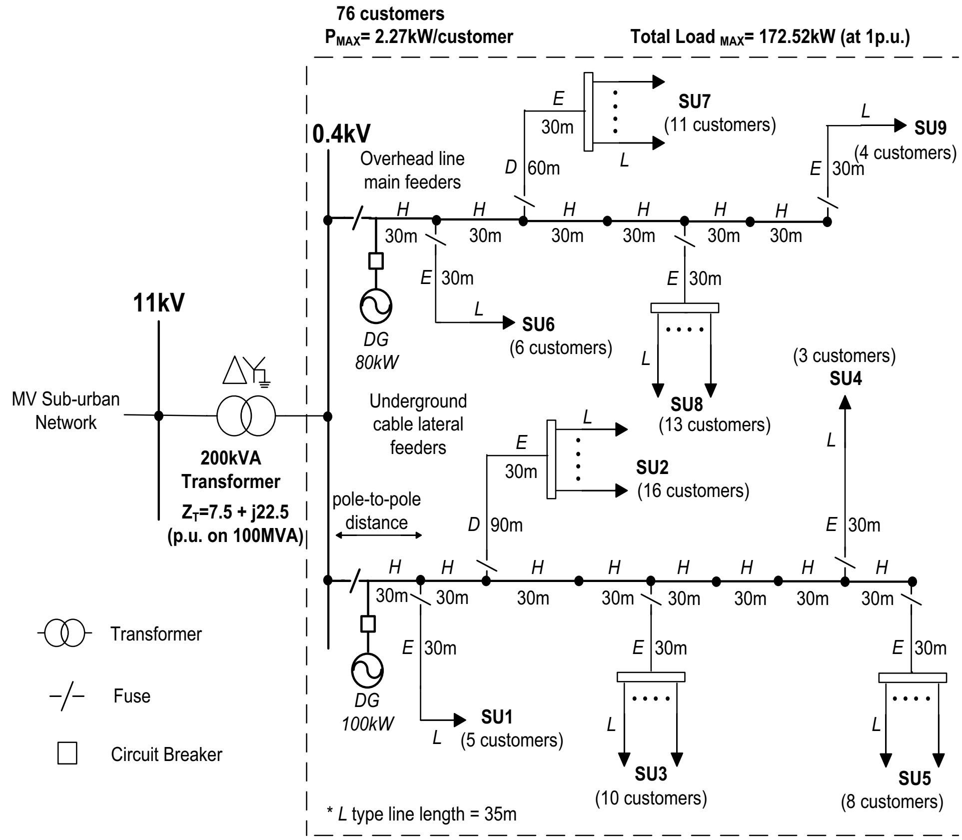


Fig. 8 Connection of DG at the LV side (secondary side of 11/0.4 kV distribution transformer) [22, 23]

Fig. 2, the end-lines unable to reconfigure due to limitation of analytical approach. Thus, causing an increment in all reliability indices values. Since the calculation of network performance of base case for analytical approach is incorrect, there is no reason to proceed with DG-LV and DG-MV cases for analytical approach.

From Table 2, it is possible to identify the improvement of reliability indices. The outputs are as expected, where the most improvement case is DG-LV. This is due to the placement of DG nearer towards customer for case DG-LV compared to DG-MV; which the energy supply to the customer from DG is shorter. Thus, the aggregation number of component of case DG-LV less based on Eqs. (1) and (2). Another contribution that improves case DG-LV than DG-MV is the number of DG. In this research, the DG is assuming to operate without any failure. For case DG-MV, the number of DG is one, while in DG-LV, the number of DG is two; which increase the security level of the network. The improvement for DG-LV are about 5.2%, 5.2%, 3.0%, 1.3%, and 6.6%, and for DG-MV are 0.7%, 0.5%, 0.0%, 2.0% and 6.5% in SAIFI, SAIDI, MAIFI, CAIDI and ENS indices, respectively.

By DG penetration only with 5%, the benefits of DG location either MV or LV side, resulting in the overall improvement of 4.3% for DG-LV and 1.9% for DG-MV. Although the improvement of case DG-LV is greater than DG-MV, the difference is small; 3%. In prise-wise perspective, installing and operating a single unit of DG is cheaper than installing two units of DG. Unless if the failure rate and repair time of DG unit are included in the assessment, from a reliability point of view, installing two units of DG is better than a single unit of DG.

The assessment of distribution network not only limited to well-defined reliability indices which is system-related indices (SAIFI, SAIDI, MAIFI, etc.), but it should assess with individual customer-related which focus on certain define customer. In this next assessment, the load points that choose to assess is the load point with the highest duration of interruptions (load point 19 and 43). Figure 10 illustrates the long interruptions and duration of interruption for load point 19 only.

Table 3 shows the average values of LIs, durations and average duration of interruptions for load point 19 and 43. By comparing the reduction of average values from Table III for DG-MV and DG-LV with the base case, a greater reduction is from the DG-LV case. Thus, with greater reduction of average values for DG-LV case, resulting in more improvement of system-related indices compare to DG-MV case results. Therefore, locating of DG at the LV side gives more benefits in term of reliability point of view.

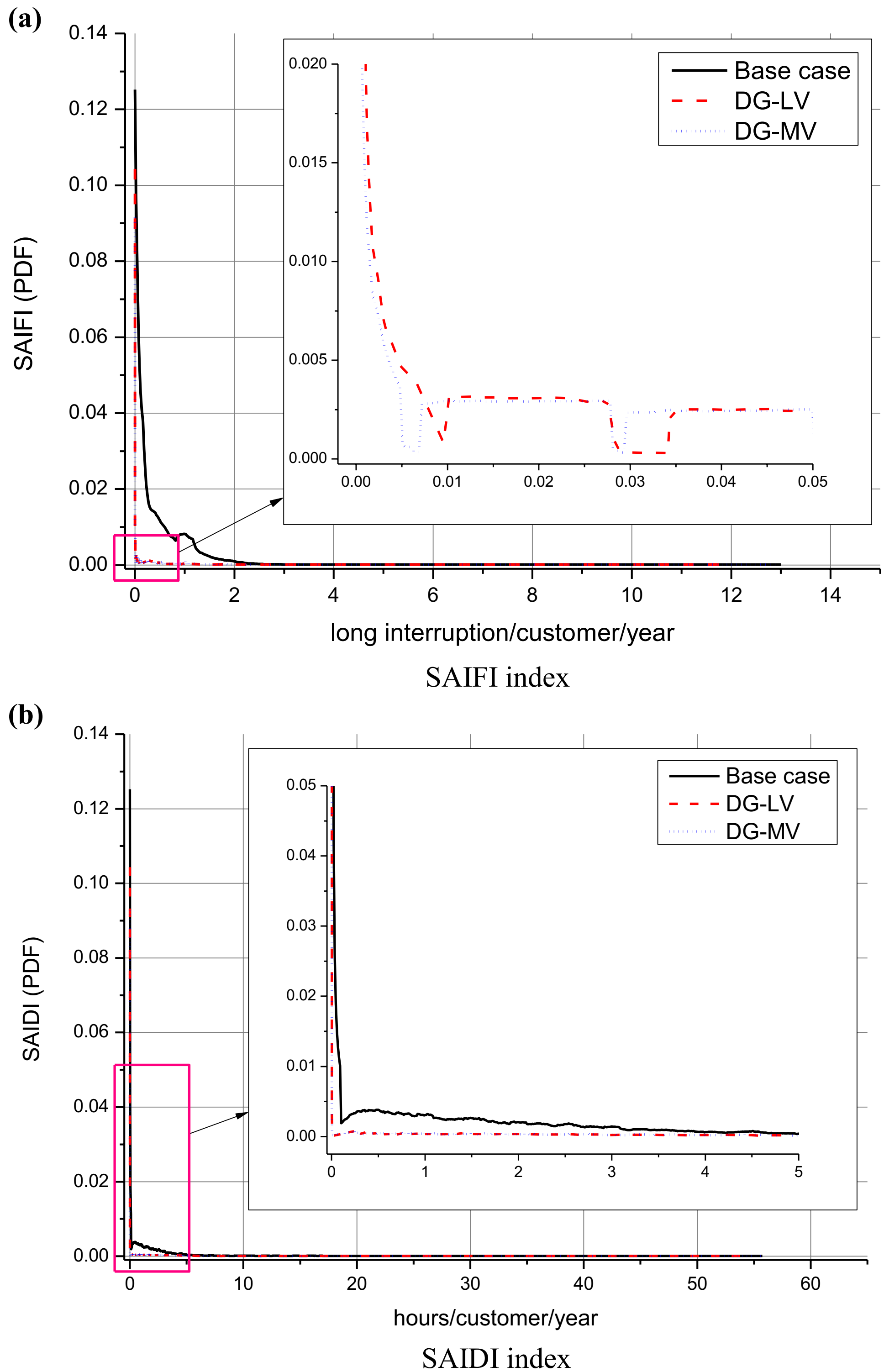


Fig. 9 Reliability indices for the base case and two considered DG cases

Table 2 Average values of reliability indices (analytical)

Indices	SAIFI	SAIDI	MAIFI	CAIDI	ENS
Base case	0.7284	20.4112	0.9043	28.7541	2025.1890

6 Concluding remarks

The presented analysis demonstrated the benefits of DG placement on network reliability performance. The present work has implemented a probability of fault rate, the operation of network according to SQS and

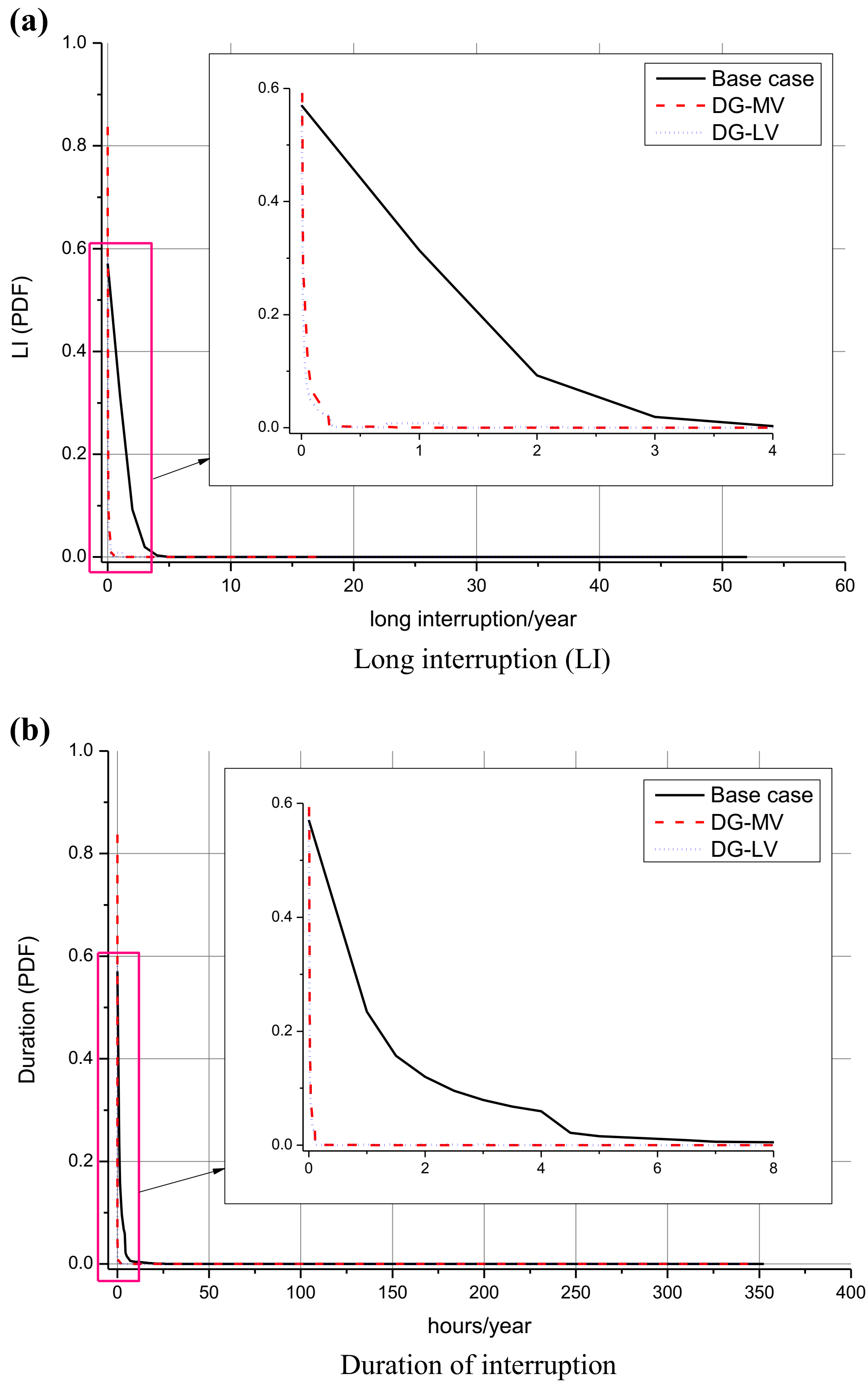


Fig. 10 Average values of LI, and durations interruptions for load point 19 only

GSP, and load profiles into the analysis, which results in more accurate simulation and calculation of system and customer-based indices for residential customers. The reliability results suggest that proper location of DG connection emphasise the positive impacts on system and customer-related reliability.

Although the better improvement is for DG-LV case compares to DG-MV case, from the real perspective with

Table 3 Average values of LI, duration and average duration of interruptions

Indices	LI	Duration	Average duration	LI	Duration	Average duration
Load point	19			43		
Base case	0.5769	4.2392	3.038	0.6083	3.8400	2.8125
DG-LV	0.1281	0.7855	0.9737	0.0547	0.9236	1.8370
DG-MV	0.5082	3.8169	2.4725	0.53375	3.6764	3.3344

limitation of transformer size, it is better to locate DG at MV side (DG-MG case). For this study, DG penetration is only 5%. For example the DG penetration is 60%, and DG is located in LV side, there will be excess energy in the local network (e.g. LV network). Thus, there will be reverse flow of energy from LV to MV in the transformer itself (e.g. 11/0.4 kV). If the transformer size is small, less reverse energy will be flow in the transformer.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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