# Resiliency-oriented dynamic expansion planning of MG-based distribution networks

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Manuscript received 05 February, 2021; revised 05 August, 2021, accepted 24 August, 2021. Paper no. JEMT-2102-1280.

**High-Impact Low-Probability (HILP) events are the ever-increasing threats against distribution networks (DNs). Boosting DN resilience can be achieved by such measures as redundancy increment by substation allocation, feeder routing from less affected area, design of reconfigurable multi-MicroGrid based (MGs) DN and deployment of different distributed generation sources (DGs). This paper proposes an approach for designing resilient DNs by posing the problem as a dynamic modeling of bi-level resilient DN expansion planning (RDEP) program. In the upper level of the RDEP, distribution company (DisCo) identifies the optimal eco-reliable planning and operation of different assets, while in the lower level, DisCo determines the optimal operation point of the expanded DN against the specified HILP. The uncertainties of renewable energy resources, electric load and its market price and ZIP modeling, well incorporate into the problem. To evaluate the effectiveness of RDEP, computer simulation is done on a large scale 138-bus DN and the results are discussed.** 

***keywords:*** *Distribution network, expansion planning, resilience, microGrid, DisPOS*

http://dx.doi.org/10.22109/jemt.2021.271864.1280

## 1. INTRODUCTION

Distribution network expansion planning (DEP) is commonly executed to find the suited solutions to the set of variable including the time, size and site of any equipment to be installed or to be replaced/reinforced. This is done to optimally meet the yearly increasing electricity load demand, in a timely and cost-effective procedure, while responding to all the technical, operational and reliability constraints and requirements. Among the programming strategies, a dynamic scheme is about DEP decisions for multiple years in a single time snapshot resulting lower costs [1]. The known concepts namely security and adequacy are the basis of common DEP, so, the expanded DNs are not capable of meeting renewed duties and upcoming challenges like a situation when facing with HILPs. This inability is mainly referred to the nature if HILPs which can damage multiple components, simultaneously [2]. Extension of the severe effects of HILPs on DN implies that the design, planning and operation of DNs by utilization of the current techniques are faced with serious challenges. So, in such instances, even reliable DNs may encounter with widespread equipment damage causing extensive blackouts. However, today's advanced society with high level of digitalization expect continuity of power supply with higher power quality. Hence, recently, the resilience concept as a complement to the former concepts is developed with the purpose of ensuring the optimal functionality of the DN against HILPs. A resilient DN is the one, can withstand such a major disruption with restricted degradation and able to recover within a finite time frame with constricted expenses. A common idea is that DNs require to bend rather than break [2]-[4]. The lack of resilience on distribution level of power system is the source of about 80% of all outages. Redundancy increment by substation allocation, feeder routing from less affected area, design of reconfigurable MMG based DN, utilization of different distributed generation units and paying attention to human resilience are such the resilience measures which the effectiveness of each one depends on the type of the HILP threating a specific DN. On the other hand, natural disasters are the most common HILPs in many countries in recent years which the number and intensity of them are significantly ever-increasing due to the climatic changes, and so, the share of DN in power outages will be increased, especially if the required financial budget has not been paid on resilience [1]-[4]. Recently, an ever-increasing attention is gained towards the resilience by the researchers which their efforts are towards design, planning and operation of resilient DNs against extreme and unpredictable HILP incidents. In reliable DEP, switch allocation accompanied by installing new branches can increased the redundancy degree of DN resulting several routes for power flow supplying the loads. As a famous principle, when a fault occurs in a section of the DN, by changing the status of the sectionalizing switches and tie-lines, the faulty section is isolated from the entire system and the power flow reroute to maintain the supply to the un-faulted sections. In [6] resilient DN is configured by applying such measures as hardening, back-up generators installation and allocation of switching devices. In [7], DN reconfiguration (DNR) and simultaneously, distributed energy resources (DERs) scheduling are considered as the basis of the proposed outage management scheme aims to increase the DN resilience. MG is a small-scale DN with at least one DER and one load with clearly defined electrical and geographical boundaries. According to the IEEE standard 1547.4, building DNs as multi-MGs with islanding capability is an efficient way to enhance network reliability and resilience. For this purpose, DGs are utilized in DNs to form MGs that can supply power to the loads considering eco-reliability cost function, power quality enhancement and emission reduction [8]. Reconfigurable MG can empower much more flexibility in operation of DN [9]. Ref [10] proposes a framework to generate resilient designs of DERs to enhance the resilience of MGs. A MG-based service restoration procedure aims to boost the preparedness of MGs during unfolding extreme events is proposed in [11]. Transformation of traditional DN into resilient autonomous multi-MGs by optimal allocation of DGs is studied in [12]. In [13] self-adequate MG formation by optimally allocation of DERs in DN is studied from the robustness and resilience points of view. In [5] a resilient DN design model is proposed incorporating hardening, redundancy and multi-MGs, simultaneously. Strengthen the DN resilience by optimization of line hardening while considering provisional multi-MGs is studied in [14]. Dynamic modeling of MG formation and simultaneously, optimal operation of different DERs to resilience improvement is proposed in [15]. Ref [16] presents a novel planning strategy for DN planners to enhance the resilience of the pre-existed DNs confronting emergencies. Optimal formation of dynamic MGs, their service areas, and the optimal operation of various DER technologies are investigated in [17]. In [18] a framework to generate resilient designs of DERs for disaster impact mitigation and hence maximizing the resilience of MGs is proposed.

Survey of the recently published papers, shows that, most of the reported literatures are focused on the resilience enhancements of the pre-existed DNs without any expansion plan for the future even despite the growing load demand; while, resilient expansion planning of DNs can prevent from the exorbitant cost of resilience enhancements of the pre-existed DNs and also prevents from unreasonable unavailability of electrical power due to unpreparedness of the pre-existed DNs against HILPs. Also, the existing papers, are based on static modeling's of the problem focusing on a single horizon year and do not have any plan for the middle years, why so, the limited budget of DisCo, does not permit to put all the investments in a year and the investments must be applied in different years till horizon year using dynamic modeling of the planning problem. Clearly, accurate solutions require realistic power system modeling. In this regards, considering the socio-economic priority of end-user customers is an appropriate strategy for resilient power supply, lowering the unwanted load shedding in the case of an outage occurrence. Moreover, in the practical situation, dependency of power consumption to voltage amplitude and also the uncertainties related to the power generation of renewable DGs, electric load demand and price are the crucial factors on approaching power system realistically. So, the main contributions of this paper can be summarized as follows:

• Timing, sitting and sizing of the new equipment's e.g. HV substation, multi-type Distributed Generations, and the annual expansion of them;
• Multi-Microgrid based planning of distribution network;
• Timing and sitting of multi-type Switching Devices;
• Annual feeders' routing and conductor sizing
• Annual power distpach of Distributed Generation units;
• Distribution network reconfiguration;
• The mentioned problem is modeled as bi-level problem, normal operating condition and resilience improvement is considered;
• Voltage-sensitive loads and load priority in power supply are considered;
• Uncertainties related to the renewable DGs, the electric load demand and price have been applied;

## 2. THE CONCEPTUAL MODEL OF THE PROPOSED APPROACH

The DN is commonly designed as meshed loop but operates in radial. So, DN is like a forest containing at least one tree (feeder) supposed as a connected graph without any loops. There are switching devices (commonly, circuit breaker and sectionlizers) on some of the branches of each feeder and maybe a switch between two nearby feeders. In MG-based DN, there would be MG(s) on some of the feeders, which each MG's electric boundaries are determined by the points called point-of-common coupling (PCC) where a MG connects to a main grid or another MG. PCC is equipped by a switching device commonly a circuit breaker. Also, each MG may have some switches, commonly sectionlizers, in its configuration. The switches empower a DN or a MG to be reconfigured, also a feeder section or a MG can be isolated from the rest via these switches; for many reasons, e.g. resilience, reliability, power flow necessities, power quality or etc. Conceptually, any MG consists of one Disapatchable DG and several load points and may have different DERs, which all of them working together to generate power for a local area in isolated mode or parallel to the grid or connected with other MG(s). Note that, the boundaries of a MG can be expanded during the years with addition of new load buses. A generalized representation of the MG-based meshed DN targeted at the proposed RDEP is provided in Fig. 1.

The flowchart of the proposed approach, modeled as a bi-level optimization problem is clearly defined in Fig. 2. The defined procedure is based on two principals; reliability and resilience. Reliable power supply of the ever increasing demand for electricity, requires installing new equipment or replacement/reinforcement the pre-existed facilities of DN. On the other hand, the DN is highly capital intensive, and the investments have long lead times and multi-decade economic lifetimes. So, the DN must be designed cost-effective, while responding to all the technical, operational and reliability constraints and requirements. However, even the reliable DN is threaten by destructive effects of the HILPs which to withstand against such a major disruption with restricted degradation and being able to recover within a finite time frame with constricted expenses, the DN must be resilient. So, in the upper level of the proposed scheme, DisCo identifies the optimal eco-reliable planning and

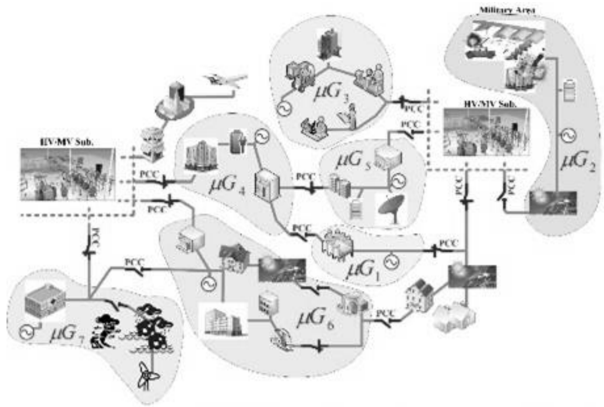


**Fig. 1.** A generalized representation of the MG-based DN targeted at the proposed RDEP

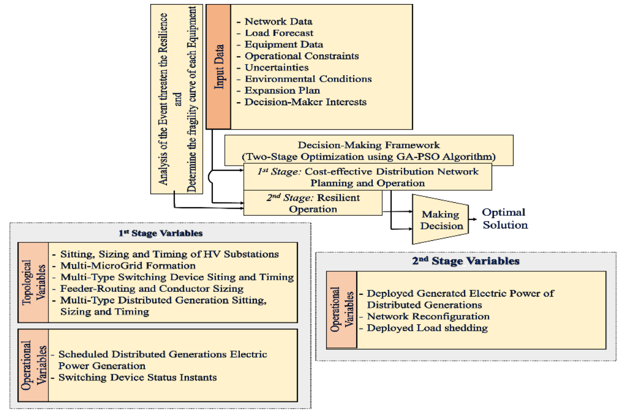


**Fig. 2.** The flowchart of the proposed DREP

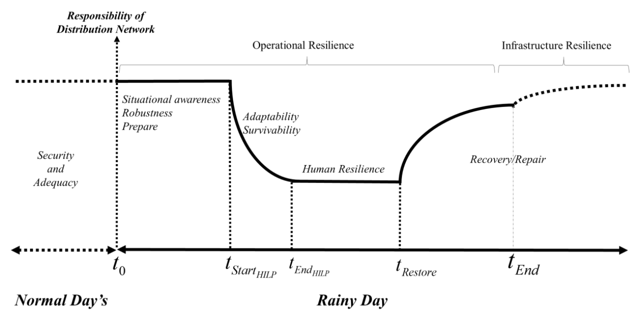


**Fig. 3.** The conceptual model of the proposed RDEP

operation of different equipment of DN (see Fig. 3. normal day), while in the lower level, the DN operator determines the optimal operation point of the expanded DN against the specified HILP (see Fig. 3. rainy day). Note that, the objective function of the lower level is treated as the penalty factor summed with the cost objective of the upper level. Moreover, the proposed dynamic scheme is about RDEP decisions for multiple years in a single time snapshot, meaning that, the proposed scheme determines that in what place and in what year and in what size, is an asset be installed or expanded in DN and specifies the annual multi-MG based DN configuration. It also offers a specific program for all the DN assets operation over the years.

Known that, the electricity consumption varies at different times for different reasons resulting different prices. Also, the power generation of renewable DGs e.g. wind- and solar-based DGs is dependent to the weather condition varies even during a day. So, the uncertainties of load demand, market price and renewable DGs must be considered to accurate decision making. For this purpose, a year is modeled as a day which is further divided into 24 hours (time segments), each referring to a particular hourly interval for the entire year. For a given time segment, the mean value of such parameters as load, renewable power generation (wind speed and solar irradiation) and electricity price are calculated using the historical data of the recent years [19]. Moreover, in the practical situation, loads are not explicitly residential, industrial and commercial; rather, load class mix maybe seen by DN depending on the nature of the area being supplied. So, appropriate load modeling is crucial factor on approaching power system realistically which the voltage dependent load models are adopted from [20].

## A. DREP Problem Formulations

The nature of the bi-level modeling of DREP requires adequate classification of the formulations between these levels which the required descriptions and the corresponding mathematical formulations are provided in the followings:

### A.1. Reliable operating mode as the basis of the upper-level

DREP comprises simultaneous design and economic attentions of numerous parameters and constraints aims to achieve the best layout of DN with lowest possible costs while all technical, operational and reliability options are taken into consideration. System operations and constraints contain the ones commonly used in DNs, i.e., line and voltage limits. Cost-based objective function is the sum of installation, expansion and operation and maintenance costs of different equipment, operation cost of the DN and technical dissatisfaction cost. So, the proposed objective function of the upper level is as follows:

$$\begin{aligned} &Cost-based\,Objective\,Function:\\ &Cost = TC_{HVSub} + TC_{Feeder} + TC_{SD} + ...\\ &\quad TC_{DG} + TC_{Loss} + TC_{PurTrnasCo} + TDC \end{aligned} \quad (1)$$

Since the proposed approach determines the amount of annual investments, so the net present value (NPV) of the annual spent money must be calculated using the following equation:

$$NPV^{y} = \left(\frac{1 + Inflation\ Rate}{1 + Interest\ Rate}\right)^{y} \quad (2)$$

Different terms affecting the implemented objective functions and the related constraints are detailed in the followings;

#### A.1.1 NPV of HV/MV Substation Costs

Substations must be allocated in such a way that all the load points will be supplied. New HV substations(s) will be installed in pre-determined candidate locations and the annual capacity of both the new substations and the pre-existed ones will optimally be specified. The NPV of substation cost is detailed in equation (3). The equation (4) refers to the expansion cost of substation, assumed as the difference of the substation installation cost of different capacities. In (6), safety margin is considered in substation loading. Moreover, the limitations on urban area, financial resources and technical ability are the reasons for defining eq. (7), a maximum annual substation expansion, and eq. (8), maximum substation capacity can be installed in a certain bus.

$$TC_{HVSub} = \sum_{y\in\Psi^{Year}} NPV^y \times \sum_{b\in\Psi^{Bus}} (IC_{(sub,b,y)} + EC_{(sub,b,y)} + OMC_{(sub,b,y)}) \quad (3)$$

Where:

$$EC_{(sub,b,y)} = IC_{(sub,b,y)} - IC_{Sub_{(sub,b,y-1)}} \quad (4)$$

$$OMC_{(sub,\,b,y)} = S_{Rated_{(sub,\,b,y)}} \times C_{OM_{HVSub}} \quad (5)$$

Subject to:

$$S_{Loading_{(sub,y)}} \leq ML_{HVSub} \times S_{Rated_{(sub,y)}} \quad (6)$$

$$S_{Rated_{(sub,b,y)}} \leq S_{Rated_{(sub,b,y-1)}} + AME_{(sub,b)} \quad (7)$$

$$S_{Rated_{(sub,b)}} \leq ME_{(sub,b)} \quad (8)$$

#### A.1.2 NPV of MV Feeder Costs

The proposed approach optimizes the feeder route and conductor sizing. The installation cost of $f$-th feeder with a conductor size is directly dependent to the length of $(L_{(f)})$ it.

$$TC_{Feeder} = \sum_{y\in\Psi^{Year}} NPV^y \times \sum_{f\in\Psi^{Feeder}} (IC_{(f,y)} + EC_{(f,y)}) \quad (9)$$

Where:

$$EC_{(f,y)} = IC_{(f,y)} - IC_{(f,y-1)} \quad (10)$$

Subject to:

$$S_{Loading_{(f,y)}} \leq ML_{Feeder} \times S_{Rated_{(f,y)}} \quad (11)$$

#### A.1.3 NPV of Meshed loop design of distribution network accompanied by MG forming

The principle of mesh design and radial operation of DN requires allocation of both normally open/close switching devices. Switch placement is the basis of MG based planning of DN which MG is a small DN with one dispatchable DG which its boundaries are defined by PCCs. The used switches are either a circuit breaker, designed to immediately isolate the MG/feeder section from the rest of the network, or a sectionalizing switch, enables network reconfiguration in both normal and abnormal conditions. Although the existence of switching devices is helpful for enhancing the resilience of DN, but these switches possess a substantial costs. The number of installable switches is limited by a maximum number, detailed in eq.(12)-(14).

$$TC_{SD} = \sum_{y\in\Psi^{Year}} NPV^y \times \sum_{f\in\Psi^{Feeder}} (IC_{(cbs,f,y)} + IC_{(secs,f,y)}) \quad (12)$$

Subject to:

$$IN_{(cbs)} \leq MN_{CircuitBreaker} \quad (13)$$

$$IN_{(secs)} \leq MN_{Sectionalizer} \quad (14)$$

#### A.1.4 NPV of Distributed Generation Costs

The proposed approach determines optimal siting, sizing and timing of distpachable, wind-based and solar-based DGs in DN and also the hourly power generation of them. Mathematical formulation of the cost calculation and the executed constraints are listed in bellow. Note that, cost evaluation process of these types of DGs is as same and the only difference is the value of the parameters related to each DG type. Maximum generation capacity ($MP_{DG}$) and the maximum number (($MN_{DG}$), of DGs can be installed are limited by eqs. (18)-(19), respectively. Because of great effect of reactive power on the outcomes of the load flow analysis, it's assumed that, these DGs, also generate reactive power, eq. (22). The hourly increase/decrease of DGs power generation is limited by ramp down/up rate ($R_{\mathrm{U/D}_{DDG}}$), in eq. (23). Moreover, due to the high cost and time consuming process of distpachable DG start-up, in normal operating condition, these units will never be shut down and their generation is set to be more than $MG_{DDG}$, eq. (24). The active and reactive power generation of $d$-th DG at $h$-th hour of $y$-th year installed in $b$-th bus, are represented by $P_{Gen_{(dg,b,y,h)}}$ and $Q_{Gen_{(dg,b,y,h)}}$, respectively.

$$TC_{DG} = \sum_{y\in\Psi^{Year}} NPV^y \times \sum_{b\in\Psi^{Bus}} (IC_{(dg,b,y)} + EC_{(dg,b,y)} + N_{Day} \times \sum_{h\in\Psi^{Hour}} OMC_{(dg,b,y,h)}) \quad (15)$$

Where:

$$EC_{(dg,b,y)} = IC_{(dg,b,y)} - IC_{(dg,b,y-1)} \quad (16)$$

$$OMC_{(dg,b,y,h)} = P_{Gen_{(dg,b,y,h)}} \times Cost_{OM_{DG}} \quad (17)$$

Subject to:

$$\sum_{b\in\Psi^{Bus}} P_{Rated_{(dg,b)}} \leq MP_{DG} \quad (18)$$

$$\sum_{b\in\Psi^{Bus}} \frac{P_{Rated_{(dg,b)}}}{max(1, P_{Rated_{(dg,b)}})} \leq MN_{DG} \quad (19)$$

$$P_{Rated_{(dg,b,y)}} \leq P_{Rated_{(dg,b,y-1)}} + AME_{(dg,b)} \quad (20)$$

$$P_{Rated_{(dg,b)}} \leq ME_{(dg,b)} \quad (21)$$

$$PF_{DG} = cte \quad (22)$$

$$|P_{Gen_{(dg,b,y,h)}} - P_{Gen_{(dg,b,y,h-1)}}| \leq R_{\mathrm{U/D}_{DDG}} \quad (23)$$

$$P_{Gen_{(dg,b,y,h)}} \gg MG_{DDG} \quad (24)$$

#### A.1.5 NPV of Power Losses

The considerable share of power losses in a power system is in widespread DN. To evaluate the cost of power losses, the following equations are used:

$$P_{Loss_{(y,h)}} + jQ_{Loss_{(y,h)}} = \sum_{f\in\Psi^{Feeder}} \sum_{y\in\Psi^{Year}} \sum_{h\in\Psi^{Hour}} I^2_{(f,y,h)} \times (R_f + jX_f) \quad (25)$$

$$NC_{Loss} = \sum_{y\in\Psi^{Year}} NPV^{y} \times N_{Day} \times \sum_{h\in\Psi^{Hour}} (Cost_{P_{Loss_{(h)}}} \times P_{Loss_{(y,h)}} + Cost_{Q_{Loss_{(h)}}} \times Q_{Loss_{(y,h)}}) \quad (26)$$

Where, $I_{(f,y,h)}$ is the current flow in $f$-th feeder at $h$-th hour of the $y$-th year.

#### A.1.6 NPV of Power Purchased from transmission network

DisCo purchases electricity via upstream network as the final process in the delivery of electricity to end-user customers. The amount of purchased power and the cost of it, are calculated using eqs. (27)-(28), respectively.

$$P_{PurTrnasCo_{(y,h)}} = \sum_{b\in\Psi^{Bus}} \sum_{y\in\Psi^{Year}} \sum_{h\in\Psi^{Hour}} (P_{Load_{(b,y,h)}} - P_{Gen_{(dg,b,y,h)}}) + \sum_{y\in\Psi^{Year}} \sum_{h\in\Psi^{Hour}} P_{Loss_{(y,h)}} \quad (27)$$

$$NC_{PurTrnasCo} = \sum_{y\in\Psi^{Year}} NPV^{y} \times N_{Day} \times \sum_{h\in\Psi^{Hour}} Cost_{PurTrnasCo_{(h)}} \times P_{PurTrnasCo_{(y,h)}} \quad (28)$$

#### A.1.7 Technical Dissatisfaction Cost attained by load flow analysis

Bus voltage and current flow of a feeder are the essential operational parameters must be kept in acceptable range. So, the load flow analysis is executed to calculate the range of these parameters. Voltage and thermal limit constraint satisfaction can be mathematically represented by a penalization function namely technical dissatisfaction cost (TDC), as follows:

$$TDC = dc \times \max\{(1-\mu^{V}), (1-\mu^{I})\} \quad (29)$$

where, dc is the dissatisfaction cost. The load flow analysis is based on the power balance in each bus of the network, formulated in eqs. (30)-(31):

$$P_{Load_{(b_0,y,h)}} - P_{Gen_{(dg,b_0,y,h)}} = ... \; V_{(b_0,y,h)} \times \sum_{b\in\Psi^{Bus}} V_{(b,y,h)} \times Y_{(b,b_0)} \times cos(\delta_{(b,y,h)} - \delta_{(b_0,y,h)} - \theta_{(b,b_0)}) \quad (30)$$

$$Q_{Load_{(b_0,y,h)}} - Q_{Gen_{(dg,b_0,y,h)}} = ... \; -V_{(b_0,y,h)} \times \sum_{b\in\Psi^{Bus}} V_{(b,y,h)} \times Y_{(b,b_0)} \times \sin(\delta_{(b,y,h)} - \delta_{(b_0,y,h)} - \theta_{(b,b_0)}) \quad (31)$$

Where, $V_{(b,y,h)}$ is the voltage amplitude of $b$-th bus at $h$-th hour of the $y$-th year.

#### A.1.7.1 Voltage limitation

Below equation shows the voltage constraint satisfaction for $b$-th bus at $h$-th hour of the $y$-th year.

$$\mu^{V}_{(b,y,h)} = \begin{cases} \frac{V_{(b,y,h)} - V_{Crit}{}^{\min}}{V_{Safe}{}^{\min} - V_{Crit}{}^{\min}} & V_{Crit}{}^{\min} \le V_{(b,y,h)} \le V_{Safe}{}^{\min} \\ 1 & V_{Safe}{}^{\min} \le V_{(b,y,h)} \le V_{Safe}{}^{\max} \\ \frac{V_{(b,y,h)} - V_{Crit}{}^{\max}}{V_{Safe}{}^{\max} - V_{Crit}{}^{\max}} & V_{Safe}{}^{\max} \le V_{(b,y,h)} \le V_{Crit}{}^{\max} \\ 0 & else \end{cases} \quad (32)$$

Finally, this index for whole network is calculated as:

$$\mu^{V} = \frac{1}{N_{Year} \times N_{Hour} \times N_{Bus}} \sum_{b\in\Psi^{Bus}} \sum_{y\in\Psi^{Year}} \sum_{h\in\Psi^{Hour}} \mu^{V}_{(b,y,h)} \quad (33)$$

#### A.1.7.2 Feeders' thermal limits

The same process has been done for evaluating the satisfaction value of feeders' currents ($\mu^{I}$). The difference is that for the feeders' current, only upper limit is considered.

### A.2. Resilient operating mode as the basis of the lower-level

Integration of the unforeseeable HILP events into DEP process is not an easy and straightforward task. Therefore, the study of resilience enhancement measures of DN is so important and will contribute to the safe and reliable operation of DNs in the presence of adverse, extreme events [21]. The extent of damage caused by the extreme weather events to DN components, is dependent to the nature of the event, its severity, as well as the fragility/strength of the DN components. So, due to the dependence of resilience enhancement measures on the type of the HILP threaten a specific DN, that HILP must be analyzed and adequately applied into the modeling. One of the most common HILPs is about wind hazard which considered in this paper. In [22] the wind hazard was analyzed in extreme wind speed with the weibull distribution, noting that the function parameters are specific to each location with local data, as discussed in IEC 61400-1. Then, the fragility of different components under extreme wind is calculated with the incremented wind speed [23]. By extreme wind speed, wind turbines will stop, overhead transformers fall down, weak poles break and etc. So, feeder routing from less affected area would be beneficial for resilience enhancement. Also, as soon as receiving alerts for the forecasted disruptive events, DisCo performs some proactive operational approaches to diminish the system risk, such as DNR, DG redispatch, resilience-oriented proactive MG management and etc [24]. Such severe disturbances may result multiple equipment faults, which may take several hours to be repaired or replaced. During this period, DisCo tries to lower the penalty cost for load shedding by serving as much load as possible [25]. Conceptually, the responsibility of distribution network curve is detailed in Fig. 3. Normal day refers to the reliability-oriented planning of DN (upper level of RDEP) and the rainy day is a day when DN faces with HILP and to overcome emerging troubles the DN must be resilient (lower level of DREP).

According to the defined goal for the upper-level of the proposed RDEP, all the load demand is supplied in normal days, so, the maximum value in the above curve, happens till . At , it's predicted that the HILP will occur at . So, to enhance the resilience, the integral of the area under this curve at rainy day must be maximized. So, by normalizing the mentioned curve, minimization of the eq. (34) leads to higher resilience. So, this equation is treated as the objective function of the lower level of the proposed RDEP.

$$\textit{Minimize Resilience Index}$$

$$RI_{(y)} = 1 - \frac{\int_{t_0}^{t_{End}} \int_{y \in \Psi^{Years}} \int_{b \in \Psi^{Bus}} P_{r_{(b)}} \times {P'}_{Load_{(b,y,h)}}}{\int_{t_0}^{t_{End}} \int_{y \in \Psi^{Years}} \int_{b \in \Psi^{Bus}} P_{r_{(b)}} \times P_{Load_{(b,y,h)}}} \tag{34}$$

Where $P'_{Load_{(b,y,h)}}$ is the supplied active power in rainy day and $P_{r_{(b)}}$ represents the load supply priority. In this regards, the buses with higher importance in power supply, receive more attention. By executing the resilience roadmap of the proposed RDEP, $RI$ will be minimized. As discussed earlier, $t \leq t_0$ is referred to the upper level of the proposed RDEP, which the done optimized investments will be contributed towards resilience improvement. However, as seen in Fig. 3, it's clear that, the severe spatio-temporal impact of the HILP event makes that the restoration of all the load points in the DN would be almost impossible. Furthermore, the optimum value for both of the decision variable sets, i.e., the set of switches status and the set of distpach levels of DGs, should be simultaneously evaluated to maximize the resilience index. At $t \geq t_0$ , the operational measures are in focus. So, DisCo must proactively implement the strategies aims to reduce the damages on DN and minimize the power outages. At $t = t_0$ the DNR is implemented to find the backbone of the DN which the resilience enhancement will be based on it. DNR is the changing of switching devices status, performing in case of fault (or equipment damaged) to enhance the continuity of power supply. In this regards, the faulty section(s) is isolated and simultaneously, the rest of the mesh designed DN is reconfigured. Actually, DNR is based on the following principles:

✓The reconfigured DN must be tree-liked network.

✓All the end-user consumers existing in unfaulted areas must be supplied.

✓The network constraints, e.g. bus voltages and thermal limits of feeders, must be maintained.

This DN has better technical parameters during the rainy day, would be the less affected one by the HILP, an efficient collaboration between the available resources is obtainable, can supply more loads and the restoration process will be continued rapidly. Noting that, at post-HILP times, the damaged equipment as the out-of-service equipment will be omitted from the DN structure. At, $t > t_{Start_{HILP}}$ supplying high priority loads gets more attention. So, any MG can be connected/disconnected to (from) DN or other MGs. In this regards, the hourly operative multi-MG based DN will be found by determining the status of the switches installed on PCCs. Considering the HILP as a temporary situation, DN operating can be succeed by violating an acceptable range on voltage and current constraints, compared to the normal days. At $t \geq t_0$ , the DG re-distpach, is another measure, has a substantial effect on preparing the DN configuration towards HILP as well as increasing the ability of DN in supplying the required power of consumers as much as possible. In this regards, the hourly output power of DGs are determined. Moreover, according to the priority of the customers in power supply, some of their consumption will be shed. In this regards, each customer has defined a range of a load consumption which its shedding will not offend him/her. So, load shedding is started from the low important consumption of low important customers and if necessary, last to the high important ones. In the post-disaster state, the rapid and efficient decision making is the key requirement for the system restoration process. In the proposed DREP, it's assumed that, the crew will start to work in the damaged area at $t_{Restore}$. Repair/replace of the damaged equipment starts from the most important one which speeds up the restoration of the loads. For example, a line segment in upper stream of the feeder has higher priority. Accurate modeling requires an acceptable estimation on repair/replace time of each damaged equipment and the trip time of crew between damaged areas.

## 3. SIMULATION STUDY

### A. Input data

The destructive effect of weather events such as wind hazard on DN components can be modeled by fragility curve, illustrating the components strength against weather event. The typical fragility curve shown in Fig. 4 (a), represents the vulnerability or failure probability of an electrical component versus wind speed. Note that, the values of $v_{Critical}$, $v_{Threshold}$, and $v_{Collapse}$ vary for different components. Vulnerability assessment requires estimating the future scenario of wind speed. The typical profile of the hourly maximum wind speed considering all the geographic area of the where DN is extended in it, is represented in Fig. 4 (b). Due to the dependence of wind speed to the climatic and environmental variables, and also, in urban areas buildings act as barriers (windbreaks), the maximum wind speed will not flow in various sites. For an example, a colorful rectangle with the same size of the area host the DN is provided. This rectangle is for $t = t_{Start_{HILP}} + 1$ and each color indicates the wind speed (% of maximum speed indicated by red-highlighted circle) in that colored site. Finally, the faulted components at any hour will be determined. In this regards, vulnerable equipment of DN must be found by calculating the component failure probability of each equipment considering the wind speed in the area host that equipment at a specific hour [2, 26-27]. Assumed that, any component faces with $v \geq v_{Threshold}$, is vulnerable enough to be considered as a faulted component. In order to show the feasibility of the proposed RDEP, the simulation study is done on a large scale 138-bus distribution test system, shown in Fig. 5. Nod 201 and 202 are the pre-existed HV/MV substations and the 203 is the candidate one. Black lines are the pre-existed feeders and the dashed lines are the candidate routes. Two candidate locations for installing support center are determined. The simulated DN is the modified version of the one described in [28], which all the necessary characteristics can be found in the [29].

The system simulation is executed using self-composed software namely DisPOS (Distribution Planning and Operation Software) based on MATLAB. DisPOS uses two different optimization algorithms, here, the upper level is solved using genetic algorithm (GA) and the lower level is optimized by particle swarm optimization (PSO). The practicality and accuracy of DisPOS are validated in different industrial projects and scientific papers.

### B. Numerical results, analysis and discussion

Fig. 6 details the annual multi-MG based DN configuration. This Fig. validates the ability of the proposed RDEP to configure a forest-liked network where the location and type of installed switches are clear. The status of these switches are for normal operating condition. Also, the sites of the installed DGs at each year with their types are specified in the related figures. As seen, there are three MGs in the network which their boundaries are expanded during the years.

One of the goals of RDEP is to specify the annual sizing of

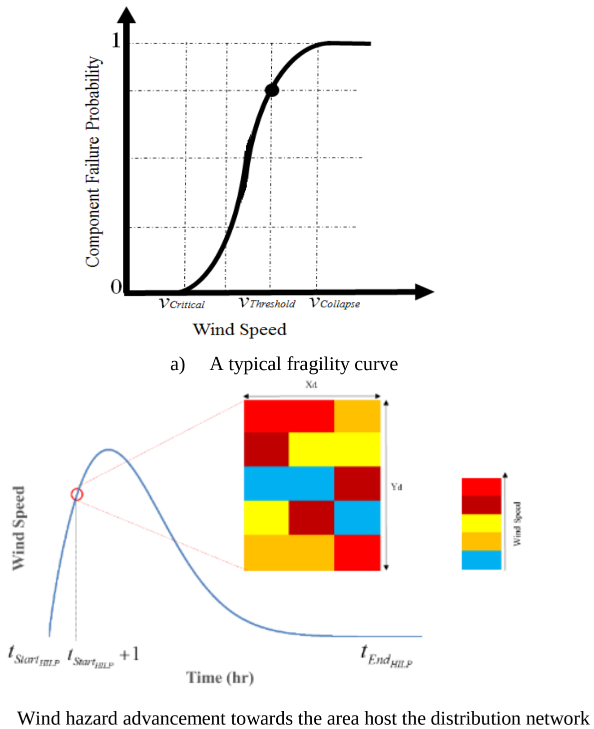


**Fig. 4.** Vulnerability analysis versus wind speed

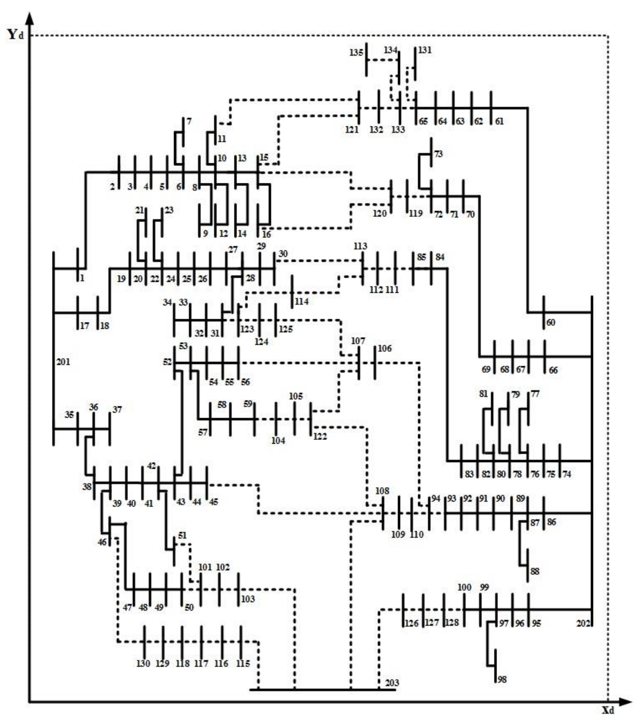

**Fig. 5.** 138-bus distribution test system

substations installed in the network. Table 1 details the capacity of the installed substations in different years of planning period. Cable sizing is another goal of expansion planning of DN aimed

**Table 1.** Cost coefficients of thermal units

| Sub ID | MVA | | | |
|---|---|---|---|---|
| | $1^{st.}$ Year | $2^{nd.}$ Year | $3^{rd.}$ Year | $4^{th.}$ Year |
| 201 | 12 | 18 | 24 | 24 |
| 202 | 12 | 18 | 18 | 18 |
| 203 | 0 | 0 | 6 | 6 |

at RDEP. The used conductors are 637A (0.127+J0.201), 435A (0.161+J0.122) and 376A (0.211+J0.127). The length of these conductors are 119km, 314km and 13km, respectively. It must be mentioned that, the cost-effective solution for DN configuration is the one which has the lowest possible costs. On the other hand, the defined constraints may cause some extra costs, e.g. voltage drop on long feeder's forces to use conductors with higher thermal limits with lower impedance. In Table 2, the site, size and timing of the installed DGs are provided. Also, the power generation of these DGs at $4^{th}$ year are represented in Fig. 7.

**Table 2.** Distributed Generation siting, sizing and timing

| | (Time(Year), Site(Bus No.), Size(kW)) |
|---|---|
| DDG | (1, 1, 50); (1, 19, 100); (1, 47, 200); (1, 69, 50); (1, 95, 50); (2, 1, 50); (2, 21, 400); (2, 57, 400); (2, 67,20 0); (2, 97, 150); (2, 105, 200); (2,105,200); (3, 1, 50); (3, 22, 100); (3, 43,30 0); (3, 67,10 0); (3, 97, 100); (3,104,300); (4, 1, 100); (4, 20, 50); (4, 40, 50); (4, 69, 50); (4, 97, 250); (4,104,150); (4,126,50); |
| WDG | (1, 13, 100); (1, 34,50); (1, 35, 150); (1, 51, 150); (1, 63,200); (2,70,50); (1,74,50); (1,75,150); (1,87,200); (2, 7, 100); (2, 17, 100); (2, 25, 50); (2, 34,50); (3, 70, 150); (3, 117, 50); |
| SDG | (1, 4, 50); (1, 5, 50); (1, 42, 50); (1, 62, 150); (1, 64, 100); (1, 77,200); (1, 83, 100); (1, 103, 100); |

Voltage magnitude is regarded as an important index which affects DN in the case of power flow, power losses, power quality, voltage stability and etc. So, voltage amplitude is considered as the constraints which any solution had have to preserve the buses voltages in standard range. With the aim of validating the fact that the voltage amplitude has maintained in acceptable range, Fig. 8 is provided by taking into account all the scenarios in the planning period.

According to the aims of the proposed RDEP, the expanded DN, must be resilient against the specified HILP. In this paper, occurrence of the wind hazard has been investigated. The duration of the event is considered to be 2 h (between 5:00 and 7:00). By applying the fragility curves for the power distribution poles, transformers and overhead lines, the equipment's in failure state will be determined. According to the operative solutions for resilience enhancement, a multi-MG based DN network must be reconfigured and the generation of DGs must be re-dispatch. This is done by considering the load-generation balance, priority of the loads and power flow necessities. The status of different breakers in different times of a rainy day is provided in Table. 3.

The load-generation balance is provided by considering the amount of load shedding, power generation of DGs and purchasing power from transmission lines. Also, the defined constraints as voltage and thermal limits, are the essential factors in providing load-generation balance. Fig. 9 represents the hourly power generation of different DGs.
It obvious that the responsibility of DN at the time of facing with HILPs is minimized and will be continued and also gets worse, if no action is done. In this regards, the proposed RDEP determines an efficient solution to restore the required power of consumers as much as possible. Fig. 10 depicts the responsibility of distribution network curve for the expanded network at the rainy day. Before HILP, all the loads are supplied, but as the HILP occurs at 5:00, the responsibility is reduced. At 8:00 the repair/restore crew arrives to the area affected by HILP and starts to repair/replace the faulted sections. So, at 8:00, the positive slope of the curve starts and continued. Noting that, repair/restore is time consuming and restoration of all the required loads in a day may be impossible which is clear in the curve.

## 4. CONCLUSION

The number and intensity of natural disasters as the main reason of power outages are significantly ever-increasing due to the climatic changes. Nevertheless, the existing distribution networks are designed according to the familiar concepts of security and adequacy, which cannot prevent from considerable power outages when facing with HILPs. So, cost effective expansion planning of distribution network by judicious employment of switching devices, different distributed generations, besides microgrid forming is essential to ensure the resilience, e.g. rapid load restoration and override the outages. In this regards, the proposed scheme, converges to the best layout of resilient DN with lowest possible costs. As detailed, the obtained solution gives a roadmap of DisCo's measures till horizon year, these measures includes the installation of new equipment or replacement/reinforcement the pre-existed facilities and also the operation of different assets in normal operating condition and when facing with HILPs. The proposed approach plans a cost effective resilient DN. The redundancy of the planned DN is acceptable which has 3-substations with totally 48MVA capacity which their feeders are routed from the less affected area. The penetration of DGs in the planned DN, increases from 15% to 20% in planning period. DN layout and installation of DGs ensures the security of power supply in normal operating condition. However, it's clear that, the responsibility of DN is reduced as soon as HILP occurs. Optimal daily operation of the planned multi-MG based DN can retrieve the 12% of the reduction in system functionality.

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**Table 3.** Distributed Generation siting, sizing and timing

| Line No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 0 |
| 2 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 1 |
| 3 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 1 |
| 4 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 0 | 0 | 1 | 1 | 0 | 1 | 0 | 1 | 0 | 0 | 1 | 0 | 1 | 1 | 0 | 0 | 0 |
| 5 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 1 |
| 6 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 1 | 0 |
| 7 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| 8 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 1 | 1 | 0 | 1 |
| 11 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 1 | 1 | 1 | 0 | 0 |
| 12 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 0 | 0 | 1 | 0 | 1 | 0 |
| 19 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 1 | 0 | 1 | 1 | 1 | 0 | 1 | 0 | 0 | 1 | 1 | 0 | 1 | 1 |
| 37 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 0 | 1 | 1 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 1 | 1 | 0 | 0 |
| 113 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 1 | 0 | 1 |
| 115 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 1 | 1 | 0 | 1 | 0 | 0 | 1 | 0 |
| 121 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 0 |
| 126 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 0 | 0 |
| 141 | 0 | 0 | 1 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 1 |
| 149 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 1 |


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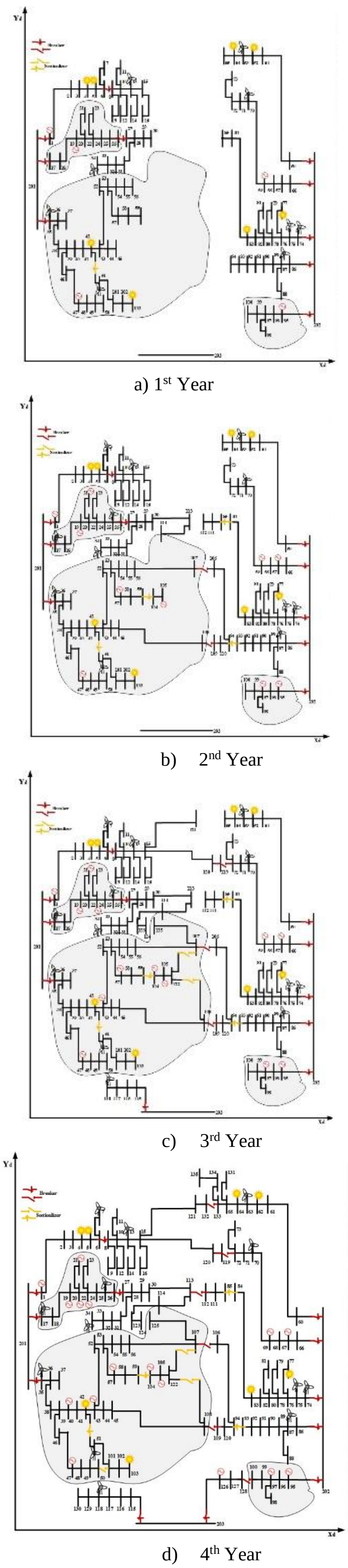


**Fig. 6.** Annual configuration of the optimal DN

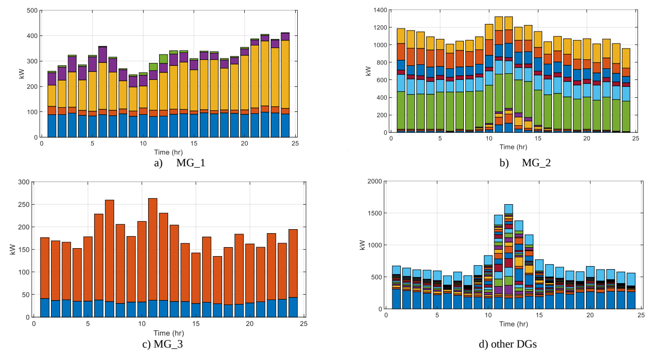


**Fig. 7.** DG generation at $4^{th}$ year

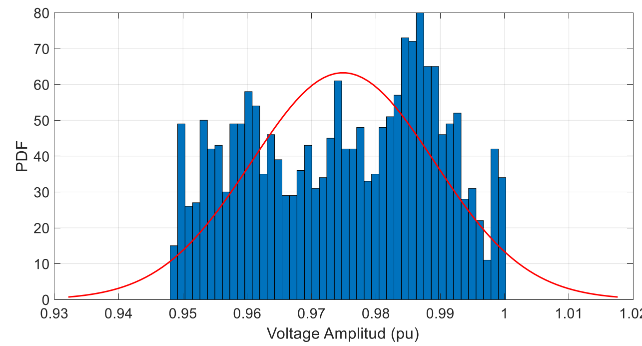


**Fig. 8.** Voltage Amplitude

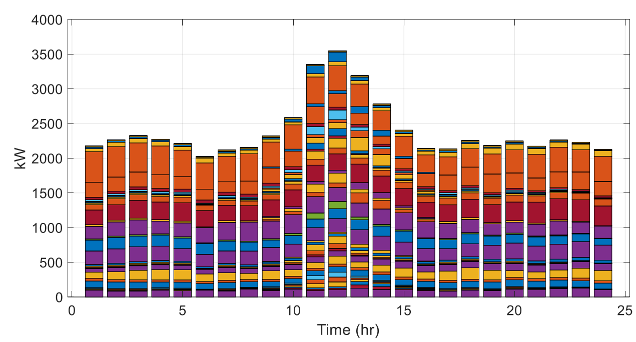


**Fig. 9.** Hourly power Generation of all DGs at rainy day

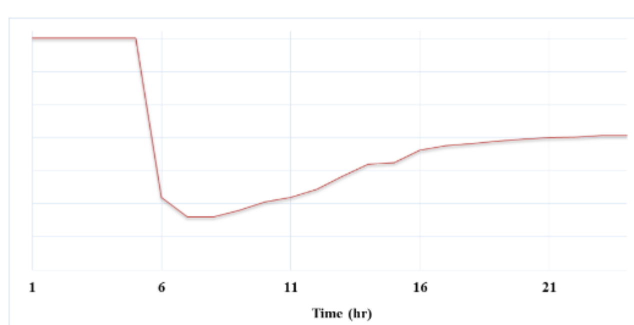


**Fig. 10.** The responsibility of distribution network curve