Integrated Assessment and Enhancement Method for Resiliency Improvement under HILP Events in Distribution Power Networks

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Abstract- Widespread power failures or blackouts may occur because of rare and catastrophic climatic conditions. Recent severe weather disasters have highlighted the need for new approaches and metrics to measure power system resilience in the face of high-impact low-probability (HILP) events. Network reconfiguration has proven to be crucial in preserving power supply continuity to local customers in such situations. This study proposes a quantitative and qualitative framework for assessing and enhancing power system resiliency. In this work, the assessment of power system resiliency is carried out by curve-based and probabilistic-based approaches and the power system resilience enhancement by including distributed generation and tie lines in the distribution system. The optimal location of DG and tie lines and optimal sizing of DG is decided by Differential Evolution based optimization approach considering the reliability cost. The proposed method is implemented in IEEE 33 bus and 69 bus distribution test systems under normal and HILP events in MATLAB/SIMULINK in 2019 version. The proposed probabilistic-based method is implemented on same test system under base case and HILP events in MIPOWER software to measure the enhancement level of resiliency using several resiliency metrics. The proposed model is also developed in OPALRT OP4510 HIL real time simulation platform. The simulation and real time simulation output show promising results in assessing and enhancing system resiliency in distribution grid networks. The outcomes clearly demonstrate how the suggested metrics can assess the resiliency of the power system and pertinent improvement measures.

Keywords Differential Evolution, Distributed Generation, Resilience Assessment, Resilience Enhancement, Resilience Metrics.

1. Introduction

The power grid is subjected to multiple component failures which are frequently caused by abnormalities and natural calamities and hence power systems should withstand any abnormalities including N-1 contingencies. Several natural disasters and artificial attacks are creating disturbances to power grids, resulting in prolonged power outages, which have negative impacts on the economical growth of country. For example, in India every few years, around 4-5 tropical cyclones are expected, and majorly in the eastern coastal regions. In the last three years, there are nearly 19 cyclonic storms with nearly 12 severe, 4 extremely, and 2 super cyclonic storms which has caused 720 deaths and 32 billion dollar damages around the globe. The details of natural disasters which created major power outages in India in recent years are reported in Table 1.

The recent natural attack on the Indian electric grid is due to cyclone Tauktae in the year 2021. Over 2400 villages witnessed power supply failures and 4.6 million people in Maharashtra and Goa are without electricity, and in many parts, the restoration of power took four days. Between 1970 and 2019, the frequency of linked flood events such as landslides, severe rainfall, and thunderstorms increased by 20 times. A flash storm in Uttarkhand wiped down the Tapovan Vishnugad hydropower project, a major change-related disaster in India. As most of the power infrastructure is located above ground, bad weather is the main reason for power disruptions[1-2]. Unpredictable failures and cascade occurrences result in a blackout, which has a significant negative impact on day-to-day life leading to the importance of power system resiliency.

In the recent works, power system control strategies to enhance the power system resiliency are discussed. A. B. Ahmed. et. al [3] proposed state of the art and the requirements of future trends in smart grid. H. Shahinzadeh et al., [4] introduced a nested energy management technique for scheduling microgrids in the day ahead schedule which improves the robustness of weak microgrids by allowing them to establish subgroups in islanded mode. M. H. Amirioun et al., [5] presented a model which combines component fragility curves and windstorms, and the suggested method creates a probabilistic component-based microgrid deterioration framework. The different resilience indices along with resilience curves, are described in [6]. T. Liu et al., [7] proposed a three-stage strategy to enhance the resilience of cyber-physical power systems. The suggested zone division approach and branch active power adjustment method can reduce the risk of cascade failure or system instability due to grid faults in the event of a disaster. The modelling of the state transition of electricity grids integrated with microgrid and proposed different resilience indicators namely expected number of lines on the outage, loss of load probability, and expected demand not supplied for assessing power grid resilience in abnormal conditions and the optimal reliability of a smart grid are described in [8]. A. Oymak et al., [9] presented a study on planning of distribution systems based on available renewable energy sources. The study focused on choosing resilience indicators to better understand resilience evaluation and resilience strategy enhancement.

Yin et al., [10] demonstrated a service restoration strategy, during disaster situations, in which a microgrid picks up emergency loads on the distribution feeder. Also, the decision-making process and the performance of restoration plans are enhanced by remote monitoring and control of power systems. I. Colak et al., [11] proposed an innovative tools are included in to the smart grid technology to monitor and manage the power system in order to identify potential power outages and other risks early on and take the appropriate precautions. An optimization technique for improving MG resilience under various modes is discussed in [12]. Monte Carlo simulations have shown that the suggested strategy can improve emergency loads survivability in a variety of scenarios which also improves load service dependability. F. Ayadi et al., [13] discussed the importance of renewable sources in microgrid. The main contribution of this paper is as follows:

- Comprehensive analysis of curve-based and probabilistic-based metrics suggested for power system resilience assessment.
- Explores the implications of power system resilience metrics evaluation and improvement techniques.
- Evaluation of power system resilience in 33 bus and 69 bus distribution test system using curve-based metric and probabilistic-based metrics is provided as a case study.

The organization of the paper is as follows: Section 2 presents various metrics to assess the power system resiliency under abnormal conditions. The recommended methodology for measuring resilience indicators, as well as the trapezoidal curve resiliency technique, is presented in Section 3. Section 4 presents results and discussion in IEEE 33 and 69 distribution test systems under various system conditions and the conclusion are provided in Section 5.

Table 1. Details of HILP events in India

S. No	Year	Number of cyclones	Names of cyclone	Strongest cyclone	Affected area	Effects
1	2019	7	Pabuk, Fani, Kyarr, Vayu, Hikaa, Bulbul, Pawan, Maha	Kyarr (Super cyclonic storm	The western part of India	50-60 poles damaged. No power supply in many parts of Goa for 8-12 hours.
2	2020	5	Amphan, Gati, Nisarga, Nivar, Burevi	Amphan (Super cyclonic storm)	Eastern area, West Bengal, and Parts of Orissa	Damage to the power grid reached 3.2 billion Indian Rupees.
3	2021	5	Tauktae, Gulab, Yaas, Shaheen, Jawad	Tauktae	The western part of India	In Goa, 1500 poles were bent and 1000 broken. The power outage lasted for 48 hours.

2. Proposed Methodology

A. Proposed Resilience Assessment in Power System

Evaluating the level of resiliency in an electric power system, due to High Impact Low Probability (HILP) events using resilience metrics has attracted many researchers. Many researchers introduced various power system resilience assessments which are categorized as qualitative and quantitative approaches as shown in Figure 1. A resilience assessment can be performed by quantitative metrics namely analytical, probabilistic, curve-based, and reliability-based techniques. In this paper, the assessment of power system resiliency is carried out as a quantitative and probabilistic approach. Many research in the field of resilience has proposed various resilience measures based on specified methods that can be divided into qualitative and quantitative approaches. Qualitative approaches can examine the impact of ancillary infrastructure and services. Quantitative approaches are suitable for comparing two systems under various conditions. Both radial and meshed distribution networks can benefit from the proposed metric in operational contingency and planning scenarios. When the load priority factor is taken into an account, the resistancy metric, recovery metric, and resilience metric are important metrics for the assessment of power system resilience.

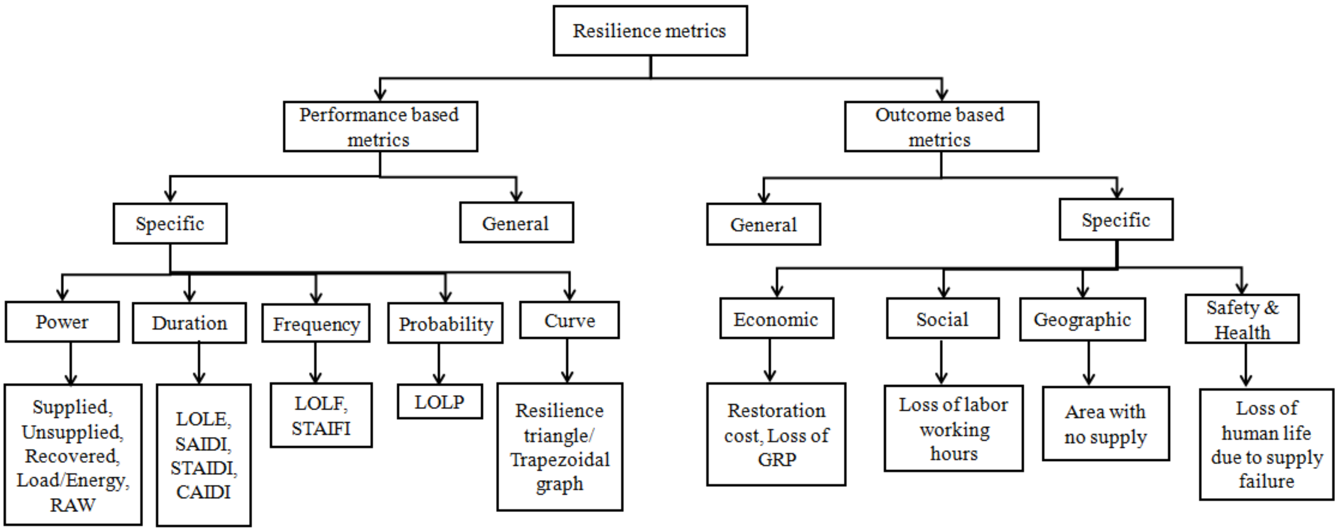

Fig. 1. Assessment Methods of Power System Resiliency

The system performance can be determined by analyzing the system's historical behavior over a period. Performance-based metrics can be computed once the system's performance has been determined. In this paper, the following basic resilience metrics[1] are evaluated based on historical performances as STAIFI, STAIDI, ASAI, ASUI, AENSI. The quantitative resiliency evaluation of a power system requires both the measurement of historical performance and the prediction of future performance. In the proposed framework, the resiliency of the power system is investigated through curve-based and probabilistic based approaches. Based on the proposed framework, a curve-based assessment technique is used to evaluate the Rate of degradation (ϕ metric), Level of degradation (∧ metric), Extensiveness of degradation (E metric), and Rate of recovery (Π metric) respectively. The resilience metrics namely STAIDI, STAIFI, ASAI, ASUI, AENSI are also calculated based on probability-based approaches. This paper proposes a resilience quantification approach based on the resilience trapezoid curve, which captures all the phases including critical infrastructure, in power systems.

i. Curve based metrics

The resilience trapezoidal curve as shown in Fig 2 has three distinct stages [14], namely: Stage I – Disturbance progress ($t_a<t<t_b$) between the start of the event and end of the event, Stage II – Post disturbance degraded state ($t_b<t<t_c$) between the end of the event and before the restoration is initiated, Stage III – Restorative state ($t_c<t<t_d$) time for how promptly the system restore its original position. During Stage I, the resilience level falls from R_{io} to R_{pdo} for operational resilience and R_{ii} to R_{pdi} for infrastructure resilience. It should be noted that depending on the system and the severity of the network incident, R_{pdi} may be smaller or higher than R_{pdo}. During Stage II, the system continues in a degraded operational and infrastructure state for a period until t_c is employed to restore operational and infrastructure performance, respectively. Depending on the resilience solutions, the duration of this period can vary for infrastructure and operational resilience. During Stage III, the resilience level gets improved from R_{pdo} to R_{io} for operational resilience and R_{pdi} to R_{ii} for infrastructure resilience. This stage can be split into two sub-stages namely operational recovery and infrastructure recovery. The operational resilience is measured by the amount of generation capacity (MW) and load demand (MW) during the event. Infrastructure resilience is measured by the number of lines that remain online during the event.

A collection of time-dependent resilience metrics based on the resilience trapezoid is shown in Figure 2 to separate infrastructural and operational resilience. A trapezoidal curve based assessment method based on the proposed framework helps to evaluate the rate of degradation (ϕ metric), Level of degradation (∧ metric), Extensiveness of degradation (E metric), and Rate of recovery (Π metric) respectively. The ϕ metric indicates how quickly the quantity of load connected and the number of lines declines therefore, its value is negative. The Λ metric is to compute how low resilience is receded and hence, this metric value is negative. The E metric measures how long the network remains in a degraded condition following an incident, capturing the post-disturbance response. As the identical response has been assumed for all cases, the value of the E metric is the same. The Π metric assesses how quickly operational and infrastructural recover from a post-disaster state.

The ϕ metric and Λ metrics help to determine the resiliency level in disturbance progress, the E metric is responsible during post-disturbance degradation and the Π metric shows the network in the restorative process. The degradation rate displays the rate at which the quantity of connected load and the number of lines online gets reduced, hence the value of the ϕ metric is negative. This metric has a normalized range for investigating power systems under different operational circumstances. Degradation level is a statistical measure to understand how the resiliency level gets reduced and hence smaller value of degradation level, the system is under resiliency. The extensiveness of degradation (E metric) determines the duration of the system remaining in a degraded state. To have better resiliency, this E metric should have a value as small as possible. The recovery rate (Π metric) evaluates how fast this system has been recovered from the post-disturbance state to its original state.

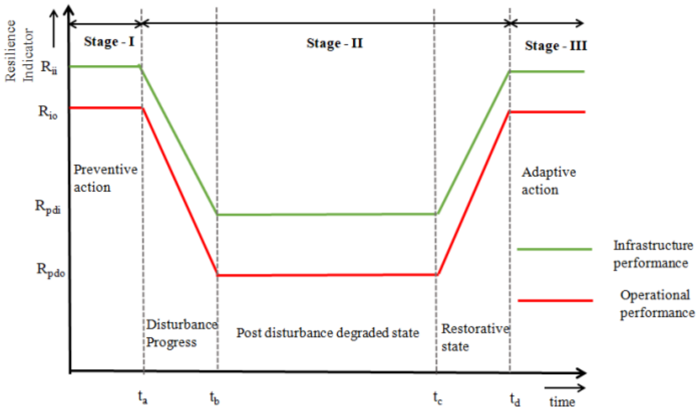

Fig. 2. Resilience Trapezoidal curve

Table 2. Curve-based metrics for Operational and Infrastructure Resiliency

Metric	**Operational Resilience**		**Infrastructure Resilience**	
Φ metric	$\frac{R_{pdo} - R_{io}}{t_b - t_a}$	MW/hours	$\frac{R_{pdi} - R_{ii}}{t_b - t_a}$	Number of lines tripped/hours
Λ metric	$R_{pdo} - R_{io}$	MW	$R_{pdi} - R_{ii}$	Number of lines tripped
E metric	$t_c - t_b$	hours	$t_c - t_b$	hours
Π metric	$\frac{R_{io} - R_{pdo}}{t_d - t_c}$	MW/hours	$\frac{R_{ii} - R_{pdi}}{t_d - t_c}$	Number of lines restored/hours

ii Probabilistic based metrics

Based on the past observations provide an important profile of the current system's dependability. An assessment of system dependability based on existing structures, configuration, operating circumstances, and protective mechanisms. Failure rate, average outage length, and annual availability are the primary indicators related to system load points [15]. The probabilistic based resilience metrics are provided as follows: The Storm Average Interruption Duration Index metric is calculated by dividing the total customer storm interruption hours by the total number of customers served.

$$STAIDI = \Sigma(t_{ri}*N_i)/N_{tot} \text{ in (Hours/Customer year)} \quad (1)$$

The Storm Average Interruption Frequency Index metric represents the number of times that a consumer experiences an interruption throughout the year.

$$STAIFI= \Sigma N_i/N_{tot} \text{ in (Interruptions/Customer year)} \quad (2)$$

The Average Service Availability Index is the ratio of the total number of customer hours available to the total number of customer hours sought over a certain time period.

$$ASAI = 1- \Sigma(t_{ri}*N_i)/(N_{tot}*T) \quad \text{(no unit)} \quad (3)$$

$$ASUI = 1- ASAI \quad \text{(no unit)} \quad (4)$$

The Average Energy Not Supplied Index metric represents the average energy not supplied by the system.

$$AENSI = 1-\Sigma(P_i*U_i)/N_{tot} \text{ in (KWh/Customer year)} \quad (5)$$

Average annual availability

$$U_i = \lambda_i*r_i \quad (6)$$

B. *Proposed Resilience Network Restoration Strategies*

Resilience oriented strategies includes operational strategies such as network reconfiguration, distributed generation, demand side response, islanding, vulnerability analysis and planning strategies includes preventive allocation and optimal sizing. The resiliency level can be enhanced by adopting restoration techniques such as optimal allocation and sizing of DG by taking the reliability cost as an objective function and optimal allocating of tie lines to maintain reliability under various contingencies. In this work, Differential Evolution is used to determine the optimal sizing of DG based on minimizing the energy not supplied (ENS) as reliability index and is formulated as follows [16].

$$F = \sum_{i=1}^{branch} \sum_{j=1}^{bus} L_i \times \lambda_i \times LL_i \times \tau_j \qquad (7)$$

Subjected to constraints

Real power constraint: $P_i^{min} \leq P_i \leq P_i^{max}$

Reactive power constraint: $Q_i^{min} \leq Q_i \leq Q_i^{max}$

Voltage constraint: $V_i^{min} \leq V_i \leq V_i^{max}$

The inadequacy of the system to meet the demand of network customers and the resulting power outage are determined in equation (10), where L_i represents length of the line, λ_i failure rate of the line, LL_i line outage value, τ_j represents fault repair time. The constraint values of control variables are as follows:

Control variable	Min value	Max value
Real Power, Pi	0.6*rated Pi	0.8*rated Pi
Reactive power, Qi	0.5* rated Qi	0.7* rated Qi
Voltage, Vi	0.95pu	1.05pu

To demonstrate the significance of upgrading the existing grid for increased resilience, the test case system is assumed to be equipped with sectionalizing switches, tie lines and DGs. Various enhancement measures, which can be characterized as planning and operational approaches, are being investigated. The planning strategy necessitates significant financial investment whereas the operational approach is both cost effective and time efficient.

The whole process for resilience assessment and numerical case study is depicted in figure 3. Using power flow analysis, the various electrical parameters like voltage, phase angle, real power and reactive power flow in the line can be evaluated. When a disaster occurs, faults break the system into multiple unconnected zones, interrupting power supply. After the end of catastrophic event, the system will return back to the normal state once the restoration process is initiated. During the event, the system is necessary to meet the critical demand by incorporating the tie lines and DG to improve system resiliency level [17].

3. Description of Test Systems

An IEEE 33 bus system is a radial distribution system, and it consists of 33 buses and 32 distribution lines and has a voltage of 12.66 kV. The network is powered by a synchronous generator, while it is loaded with 3.715 MW and 2.3 MVAR coupled to 32 buses. The single line diagram of the IEEE 69 radial distribution system is shown in Fig.5 which consists of 68 lines, 69 buses and has a voltage of 12.66 kV. The bus 1 acts as slack bus while the remaining act as load bus where total loads connected are 3.80 MW and 2.69 MVAR respectively. The first bus is defined as a slack bus, while the subsequent buses are classified as load buses.

The proposed concept is implemented in two IEEE standard test systems namely IEEE 33 and IEEE 69 bus distribution test systems. The resilience of a test system is analyzed using two separate resilience assessment methods namely curve-based and probabilistic-based approaches to

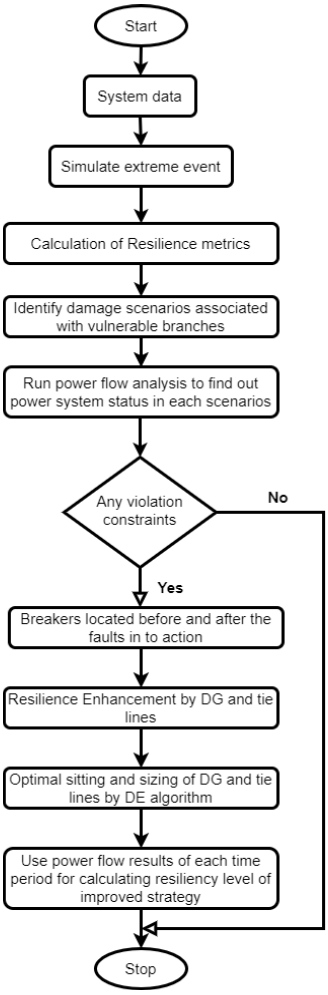

Fig. 3. Flow chart of proposed Resilience Enhancement

provide crucial insights into power system resilience evaluation. The resilience of a test system is analyzed using two separate resilience assessment methods namely curve-based and probabilistic-based approaches to provide crucial insights into power system resilience evaluation. The simulation models are carried out using MATLAB 2019 version and MIPOWER version 6.0 simulation platforms to evaluate power system resilience metrics and investigated under various case studies. To calculate the failure probability of a distribution line against a hurricane, a wind fragility model as developed

Monte Carlo simulation is utilized to produce random failures of distribution lines. In order to achieve more reliability, the DG and tie lines location are placed optimally [18]. The optimal sizing of DG is obtained using Differential Evolution Optimization method. The control parameters are voltage magnitude, real power setting of the generator bus in base case, contingency case, real and reactive power demand of the buses where load shed is going to perform. The following case studies are analyzed under network restoration under base case and 125% overloading conditions.

Case I: The system has no tie lines and no DG
Case II: The system has tie lines
Case III: The system has DG
Case IV: The system has both DG and tie lines

4. Simulation Results

A. Determination of Trapezoidal based resilience metrics in IEEE 33 bus distribution system

i. IEEE 33 bus distribution system

The single line diagram of the modified IEEE 33 radial distribution system along with fault locations, optimal location of DG and tie lines is shown in Figure 4. The arrows represent the fault taken into consideration due to the occurrence of catastrophic events. Random failures are considered in the following distribution lines L4-5, L8-9, L26-27, L19-20. The DE based optimal algorithm is developed by considering reliability as objective function and the optimal sizing of DG's during the HILP restoration process is obtained. In order to strengthen the restoration process two DG's (Solar PV) are optimally placed at bus 6 and bus 30 whose sizing are of 0.68 MW and 2.56 MW respectively. Three tie lines are connected for the enhancement of the resiliency level of the test system between 22-12, 25-29 and 18-33.

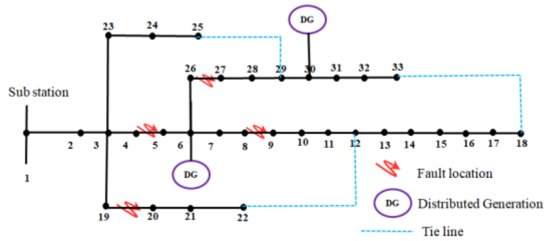

Fig. 4. IEEE 33 bus Distribution test system

Table 3. Resilience Enhancement with DG's and Tie lines for IEEE 33 bus distribution system

Case-I Without tie-lines and DG

Number of lines online	P_D (MW)		Q_D (MVAR)	
	Base case	*125% overloading*	*Base case*	*125% overloading*
7	1.33	1.66	0.67	0.84
12	1.91	2.39	0.94	1.18
15	2.18	2.73	1.06	1.33
22	3.04	3.80	1.99	2.49
32	3.72	4.64	2.30	2.87

Case-II Three tie-lines and DG

Number of lines online	P_D (MW)		Q_D (MVAR)	
	Base case	*125% overloading*	*Base case*	*125% overloading*
18	2.77	3.46	1.87	2.34
22	3.04	3.80	1.99	2.49
32	3.72	4.64	2.30	2.87

Case-III No tie-lines and Two DG

Number of lines online	P_D (MW)		Q_D (MVAR)	
	Base case	*125% overloading*	*Base case*	*125% overloading*
25	3.14	3.92	2.02	2.53
26	3.34	4.17	2.13	2.66
31	3.70	4.61	2.30	2.87
32	3.72	4.64	2.30	2.87

Case-IV Three tie-lines and two DG

Number of lines online	P_D (MW)		Q_D (MVAR)	
	Base case	*125% overloading*	*Base case*	*125% overloading*
28	3.46	4.32	1.68	2.10
30	3.54	4.54	2.01	2.21
32	3.72	4.64	2.30	2.87

To obtain the resilience trapezoidal graph for this test system, it is considered to have faults due to natural disasters occurring in the 11th hour and lasts until the 27th hour, resulting in degradation in the electrical network and commencement of repair work on the damaged infrastructure after the 15th hour. The average repair time for the distribution line is estimated as 6 hours, in which the travel time of the repair crew being ignored. This curve-based approach is a most powerful method for assessing resilience metrics in both operational and infrastructure performance. The power flow analysis using the forward/backward sweep algorithm is carried in 33 and 69 distribution test systems under various cases in two different loading conditions (base case and 125% overloading) and the system is investigated in four case studies as provided in Table 3 considering the restoration operations of DG power injection and tie line power flow and comparing the case studies in terms of enhancement in distribution system resiliency.

From the tabulated values, the trapezoidal graphs are plotted both for operational and infrastructure restoration operations as shown in figure [5], [6], & [7] for calculating resilience metrices. The curve-based resilience metrics as discussed in section IV is obtained under all test cases in both base case and 125% loading conditions and is tabulated in Table 5. In all four cases, the values of four resilience measures as shown in Table 5, are determined to assess both operational and infrastructural resilience. The Φ-metric indicates how quickly the total number of connected load and the number of online lines decline, and so its values are negative. The Λ-metric is an indicator of how much resilience is decreased, hence its values are negative. The E-metric indicates how longer the network remains in a degraded state following an incident. Finally, the Π-metric evaluates how quickly operations and infrastructure recover from a post-disaster state. After taking the corrective actions, these metric values get decreased which explains the system is quickly restored.

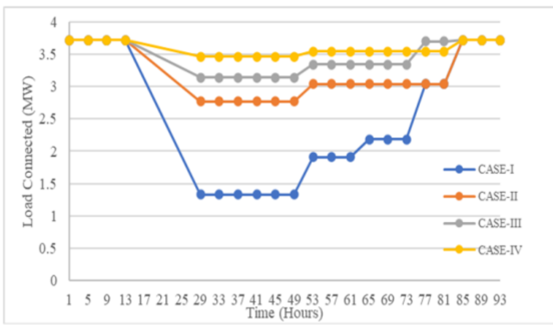

Fig. 5. Operational trapezoids for IEEE 33 bus distribution system under base case

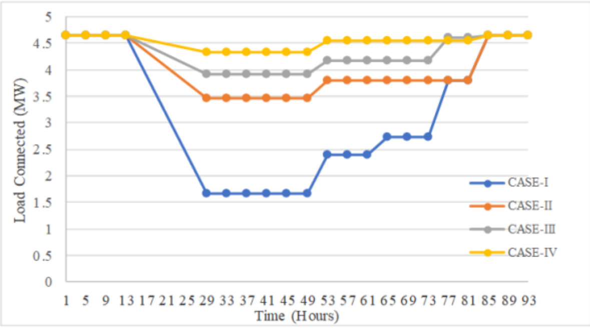

Fig. 6. Operational trapezoids for IEEE 33 bus distribution system under 125% overloading conditions

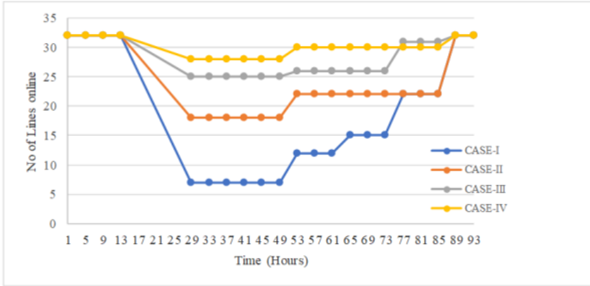

Fig. 7. Infrastructure trapezoids for IEEE 33 bus distribution system under base case and 125% overloading conditions

Table 4. Improvement of Trapezoidal based Resilience metrics in 33 bus distribution test system

	Case study	Resilience Metrics							
		Φ-metric (MW/h)		*Λ-metric (MW)*		*E-metric (h)*		*Π-metric (MW/h)*	
		Base case	*125% overloading*	*Base case*	*125% overloading*	*Base case*	*125% overloading*	*Base case*	*125% overloading*
Operational Trapezoids	I	-0.1494	-0.1863	-2.39	-2.98	20	20	0.06639	0.08278
	II	-0.0594	-0.0738	-0.95	-1.18	20	20	0.02639	0.03278
	III	-0.03625	-0.0450	-0.58	-0.72	20	20	0.01611	0.02000
	IV	-0.01625	-0.0200	-0.26	-0.32	20	20	0.00722	0.00889
Infrastructure Trapezoids	I	-1.5625	-1.5625	-25	-25	20	20	0.6944	0.6944
	II	-0.875	-0.875	-14	-14	20	20	0.3889	0.3889
	III	-0.4375	-0.4375	-7	-7	20	20	0.1944	0.1944
	IV	-0.2500	-0.2500	-4	-4	20	20	0.1111	0.1111

ii. IEEE 69 bus distribution system

The single line diagram of the modified IEEE 69 radial distribution system is shown in Figure 8. Monte Carlo simulation is used to generate random failures of IEEE 69 bus distribution test system [3] and it is marked in Fig. 4 (L6-7, L11-66, L28-29, L33-34, L42-43, L56-57, L22-23). In order to achieve the enhancement of power system resiliency, the network reconfiguration has been done by optimally placing DG's and tie lines. Three DG's (Solar PV) are connected at Bus 11, 18 and 61 whose sizing are 0.560 MW, 0.427 MW and 2.15 MW and five tie lines are connected between 13-21, 11-43, 15-46, 27-65, and 50-59 respectively[16]. An IEEE 69 bus distribution system load flow analysis was determined using a forward/ backward sweep algorithm under various cases including the corrective actions. The measured parameters include real power generation and demand, reactive power generation and demand, and the number of lines online. Based on the parameters measured the resiliency trapezoidal curve for IEEE 69 bus system is obtained as shown in Figure [9], [10] & [11] for both operational and infrastructure performance. The various resilience metrics are calculated based on the operational and infrastructure trapezoids.

Table 5. Resilience Enhancement with DG's and Tie lines for IEEE 69 bus distribution system

Case-I Without tie-lines and DG

Number of lines online	P_D (MW)		Q_D (MVAR)	
	Base case	*125% overloading*	*Base case*	*125% overloading*
17	0.98	1.22	0.70	0.87
50	1.99	2.49	1.40	1.75
59	3.65	4.57	2.59	3.24
68	3.80	4.75	2.69	3.37

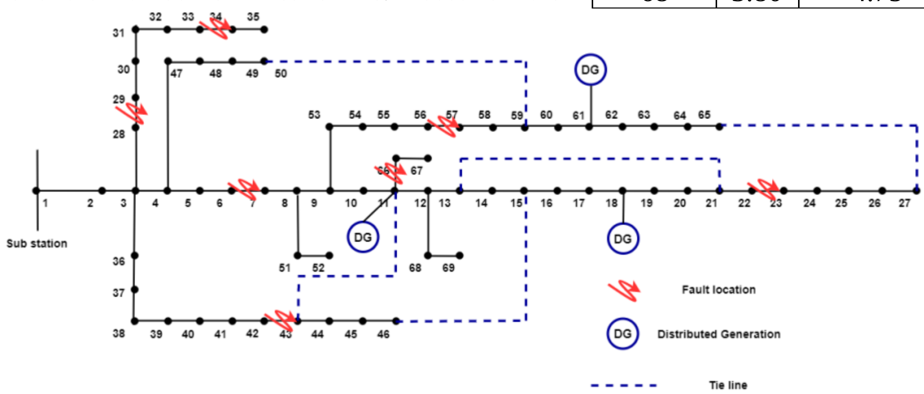

Fig. 8. IEEE 69 bus Distribution test system

Case-II Five tie-lines and no DG

Number of lines online	P_D (MW)		Q_D (MVAR)	
	Base case	*125% overloading*	*Base case*	*125% overloading*
28	2.70	3.37	1.93	2.41
61	3.74	4.67	2.65	3.31
66	3.78	4.72	2.68	3.35
68	3.80	4.75	2.69	3.37

Case-III No tie-lines and three DGs

Number of lines online	P_D (MW)		Q_D (MVAR)	
	Base case	*125% overloading*	*Base case*	*125% overloading*
47	3.56	4.45	2.53	3.16
55	3.63	4.53	2.57	3.21
65	3.77	4.71	2.67	3.34
68	3.8	4.75	2.69	3.37

Case-IV Five tie-lines and three DGs

Number of lines online	P_D (MW)		Q_D (MVAR)	
	Base case	*125% overloading*	*Base case*	*125% overloading*
55	3.70	4.63	2.62	3.28
64	3.74	4.68	2.65	3.31
66	3.77	4.71	2.67	3.34
68	3.80	4.75	2.69	3.37

From the tabulated values, the trapezoidal graphs are plotted both for operational and infrastructure restoration operations as shown in figure [11], [12], & [13] for calculating resilience metrices. The curve-based resilience metrics as discussed in section IV is obtained under all test cases in both base case and 125% loading conditions and are tabulated in Table 6. The value of the Φ-metric is less in case-IV than other cases as the slopes of degradation get less

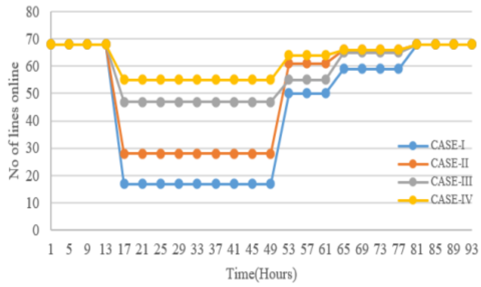

Fig. 11. Infrastructure trapezoids for IEEE 69 bus distribution system under base case and 125% overloading conditions

steep from case-I to case-IV and hence the value for this metric is negative. Like, Φ-metric, Λ-metric also decreases from case-I to case-IV because these metric measures how lower the resiliency gets decreased. The E-metric indicates how long the network remains in a degraded state following an incident. Finally, the Π-metric evaluates how quickly operations and infrastructure recover from a post-disaster state. Finally, both operational and infrastructure resilience can be assessed using curve-based indicators.

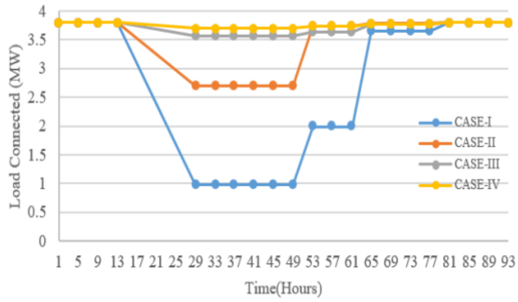

Fig. 9. Operational trapezoids for IEEE 69 bus distribution system under base case

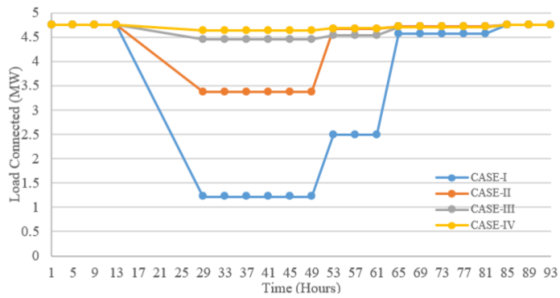

Fig. 10. Operational trapezoids for IEEE 69 bus distribution system under 125% overloading conditions

Table 6. Improvement of Trapezoidal based Resilience metrics in 69 bus distribution test system

	Case study	Resilience Metrics							
		Φ-metric (MW/h)		*Λ-metric (MW)*		*E-metric (h)*		*Π-metric (MW/h)*	
		Base case	*125% overloading*	*Base case*	*125% overloading*	*Base case*	*125% overloading*	*Base case*	*125% overloading*
Operational Trapezoids	I	-0.17625	-0.2206	-2.82	-3.53	20	20	0.07833	0.09806
	II	-0.06875	-0.0863	-1.10	-1.38	20	20	0.03055	0.03833
	III	-0.01500	-0.0186	-0.24	-0.30	20	20	0.00667	0.00833
	IV	-0.0625	-0.0750	-0.10	-0.12	20	20	0.00278	0.00333
Infrastructure	I	-3.1875	-3.1875	-51	-51	20	20	0.6944	0.6944

Trapezoids	II	-2.5	-2.5	-40	-40	20	20	0.3889	0.3889
	III	-1.3125	-1.3125	-21	-21	20	20	0.1944	0.1944
	IV	-0.8125	-0.8125	-13	-13	20	20	0.1111	0.1111

A. Evaluation of Probability based resilience metrics under different cases

The enhanced resiliency indices are primarily used to calculate the system's level of resilience during major outages caused by HILP occurrences, namely Storm Average Interruption Frequency Index (STAIFI), Storm Average Interruption Duration Index (STAIDI), Average Service Availability Index (ASAI), Average Service Unavailability Index (ASUI) and Average Energy Not Supplied Index (AENSI). As a result, for major failures, the system level is reduced, necessitating the need for restorative steps to improve resiliency in various instances. Table [7] and [8] represents the load point indices for the base case, effect of manual sectionalizing, effect of transferring load and main circuit breaker trip in IEEE 33 bus distribution test system under normal and 125% overloading conditions. The metrics are validated in all the four case studies considering different combinations in MIPOWER software of DG and tie lines.

Table 7. Comparative analysis for Probabilistic based Resilience metrics for 33 bus systems in the base case and 125% overloading

Resilience Metrics	**Case Case Study**	**Base case**		**Effect of manual sectionalizing**		**Effect of transferring load**		**Only main circuit breaker trip**	
		Normal loading	**125% overloading**	**Normal loading**	**125% overloading**	**Normal loading**	**125% overloading**	**Normal loading**	**125% overloading**
STAIFI	I	2.11	3.20	3.09	3.20	3.22	3.43	3.60	4.10
	II	1.26	1.30	3.24	3.50	3.28	3.57	3.60	4.10
	III	2.23	2.10	3.61	3.20	3.63	3.90	4.00	4.42
	IV	2.12	2.10	3.68	3.20	3.62	3.82	5.00	5.24
STAIDI	I	7.61	13.2	4.36	4.39	2.13	3.63	13.20	12.80
	II	3.64	5.20	4.06	5.91	2.72	3.78	12.60	14.00
	III	8.41	8.40	6.13	3.40	2.56	2.93	14.8	12.80
	IV	5.85	8.40	5.62	3.40	2.04	2.93	13.72	12.81
ASAI	I	0.99913	0.99849	0.99950	0.99950	0.99976	0.99959	0.99849	0.99854
	II	0.99958	0.99941	0.99954	0.99933	0.99969	0.99957	0.99856	0.99840
	III	0.99904	0.99904	0.99930	0.99961	0.99971	0.99967	0.99831	0.99854
	IV	0.99933	0.99967	0.99936	0.99961	0.99977	0.99966	0.99843	0.99854
ASUI	I	0.00087	0.00151	0.00050	0.00050	0.00024	0.00041	0.00151	0.00146
	II	0.00042	0.00059	0.00046	0.00067	0.00031	0.00043	0.00144	0.00160
	III	0.00096	0.00096	0.00070	0.00039	0.00029	0.00033	0.00169	0.00146
	IV	0.00067	0.00033	0.00064	0.00039	0.00023	0.00034	0.00157	0.00146
AENSI	I	8.84	19.16	4.77	6.02	2.44	5.27	15.32	18.58
	II	3.80	7.55	4.41	9.24	3.03	5.49	14.63	20.32
	III	9.70	12.19	7.56	4.90	2.83	4.25	17.18	18.58
	IV	6.91	4.25	7.00	4.90	2.42	4.24	15.93	18.58

Table [9] and [10] represents the load point indices for the base case, effect of manual sectionalizing, effect of transferring load and only main circuit breaker trip in IEEE 69 bus distribution test system under normal and 125% overloading conditions. This system has 68 distribution lines, and the overall load demand is 3.80 MW. However, after the incidence of faults, 26% (0.98 MW) load is served, and 25 % (17 lines) lines are operable. 11 more lines are restoring with the help of tie lines, bringing the total number of operable 41% (28 lines) and 71% (2.70 MW) load is served. 86% (3.27 MW) of the load can be restored by using DGs, allowing for the energization of 68% of lines (46 lines). 78% lines (53 lines) may be recovered using DG and tie lines which allows 97% (3.70 MW) of the load to be satisfied.

Table 9. Comparative analysis for Probabilistic based Resilience metrics for 69 bus systems in the base case and 125% overloading

Resilience Metrics	**Case Study**	**Base case**		**Effect of manual sectionalizing**		**Effect of transferring load**		**Only main circuit breaker trip**	
		Normal loading	**125% overloading**	**Normal loading**	**125% overloading**	**Normal loading**	**125% overloading**	**Normal loading**	**125% overloading**
STAIFI	I	13.99	29.79	29.38	32.34	29.27	34.35	31.4	41.54
	II	19.79	29.91	30.14	35.38	29.97	30.15	31.9	40.35
	III	13.99	23.99	29.38	39.38	29.27	39.27	31.4	41.04
	IV	19.79	30.91	30.14	40.10	29.84	35.77	31.9	35.93
STAIDI	I	50.35	71.96	31.46	31.46	14.75	28.95	117.82	117.87

	II	71.96	72.46	46.89	47.33	14.97	46.33	117.87	117.82
	III	50.35	50.35	31.46	31.46	14.75	28.95	117.82	117.82
	IV	68.96	72.46	45.02	47.33	14.91	14.97	106.34	117.87
ASAI	I	0.99425	0.99179	0.99641	0.99461	0.99832	0.99829	0.98655	0.98655
	II	0.99179	0.99173	0.99465	0.99640	0.99829	0.99470	0.98654	0.98655
	III	0.99425	0.99425	0.99641	0.99641	0.99832	0.99670	0.98655	0.98655
	IV	0.99213	0.99173	0.99846	0.99640	0.99830	0.99829	0.98786	0.98654
ASUI	I	0.00575	0.00575	0.00359	0.00359	0.00168	0.00168	0.01345	0.01345
	II	0.00821	0.00827	0.00535	0.00540	0.00171	0.00530	0.01346	0.01346
	III	0.00575	0.00575	0.00359	0.00359	0.00168	0.00168	0.01345	0.01345
	IV	0.00787	0.00827	0.00514	0.00540	0.00170	0.00171	0.01214	0.01346
AENSI	I	79.67	99.83	51.66	64.80	23.14	28.99	186.65	233.89
	II	115.73	146.04	87.88	110.65	23.52	29.47	186.73	233.99
	III	79.67	99.83	51.66	64.80	23.14	28.99	186.65	233.89
	IV	110.95	146.04	85.22	110.65	23.48	29.47	168.46	233.99

Table 10. Comparative analysis for trapezoidal based Resilience metrics for 69 bus systems with the reference article

	Case study	**Resilience Metrics**							
		Φ-metric (MW/h)		***Λ-metric (MW)***		***E-metric (h)***		***Π-metric (MW/h)***	
		Ref [3]	***Proposed method***	***Ref [3]***	***Proposed method***	***Ref [3]***	***Proposed method***	***Ref [3]***	***Proposed method***
Operational Trapezoids	I	-0.176	-0.17625	-2.820	-2.82	20	20	0.076	0.07833
	II	-0.069	-0.06875	-1.1	-1.10	20	20	0.03	0.03055
	III	-0.033	-0.01500	-0.53	-0.24	20	20	0.014	0.00667
	IV	-0.006	-0.0625	-0.1	-0.10	20	20	0.003	0.00278
Infrastructure Trapezoids	I	-3.188	-3.1875	-51	-51	20	20	1.378	0.6944
	II	-2.5	-2.5	-40	-40	20	20	1.081	0.3889
	III	-1.375	-1.3125	-22	-21	20	20	0.595	0.1944
	IV	-0.938	-0.8125	-15	-13	20	20	0.405	0.1111

5. OPAL-RT HIL Simulation

In this work, the IEEE 33 bus distribution test system is modelled in MATLAB and the real time simulation is carried out in OPAL-RT HIL environment. The OPAL-RT package, RT-LAB, allows users to create models appropriate for real time simulation. MATLAB/Simulink models are fully integrated with RT-LAB models. OPAL-RT and a PC with RT-LAB installed are needed to set up an electric power system. The power simulation model can be loaded into the OPAL-RT, once the simulation model has been successfully compiled in RTLAB. RT simulator runs the REDHAT as an operating system and communicates with the host through Telnet.

The OPAL-RT OP4510 simulator is used to build and run the Simulink model in real time with the OPAL-RT environment. Voltage, current, active power and reactive power have all been observed on the CRO. Figure 12 shows an experimental setup of the OPAL-RT OP4510 SIMULATOR, the outport connector, and the entire hardware arrangement. Signals such as voltage and active power are extracted from the OPAL-RT simulator using the outport device. Figure 13 shows the base case results under normal conditions for IEEE 33 bus distribution test system. The values are generated from the load flow analysis in MATLAB, and in OPAL RT the values are scaled to the range is [-16,16]. However, with the occurrence of faults, 21.875% lines (7 lines) are operable and 35.76% of demand (2.77 MW), enabling the energization of 56.25% of distribution lines (18 lines). With the aid of tie lines, 7 more lines are being restored, bringing the overall number of operable lines to 78.125% (25 lines), and 84.41% of demand (3.14 MW). By incorporating both DG and tie lines the load supplied is increased to 93.1% (3.46 MW) and the number of active distribution lines is increased to 87.5 % (28 lines).

The channel 1 indicates the real power flow from line 2-3 has the magnitude of 3.12 MW, the channel 2 indicates the real power flow between line 3-4 has the magnitude of 2.05 MW, the channel 3 represents the real power flow between line 1-2 as the magnitude of 3.59 MW and the channel 4 represents the one of the phase voltage in bus 1. To study the resiliency concept in IEEE 33 bus system, four faults were created between the lines line 4-5, line 8-9, line 19-20 and line 26-27. Figure 14 represents the power flow for various lines under fault conditions. The four channel indicates the real power flow between line 5-6, line 6-7, line 30-31 and line 31-32.

By incorporating tie lines between various locations which was decided by optimally to improve the reliability of the power system, the real power flow between the buses is measured and recorded. Figure 15 shows the waveform for the test system after taking one of the corrective actions as adding interconnector between the buses. The first four channels represent the real power flow between bus 11-12 has the magnitude of 0.65 MW, the power flow between the bus 17-18 has the magnitude of 0.11 MW, the power flow between the bus 29-30 has the magnitude of 0.78 MW and the input voltage at bus 1 whose magnitude is 1 p.u.

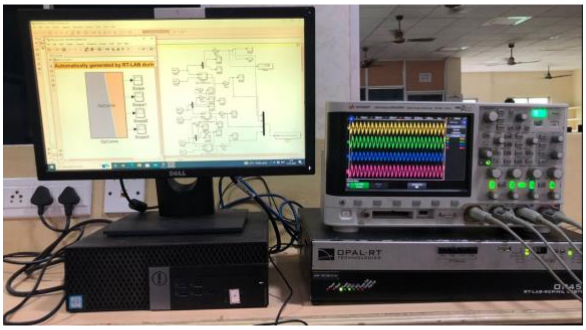

Fig. 12 Hardware set up OPAL-RT OP4510

After adding DG in the desirable location to improve the reliability of the system, the voltage at various buses is measured and recorded. The four channels represent one of the phase voltages at buses 6, 7, 30 and 31. Even though these lines were under fault, the addition of DG at bus 6 and 30 energies the above lines. Hence, the above-mentioned buses still in active even though under fault conditions.

After adding both DG and tie lines, the results proved that the system resiliency level has improved. Figure 17 shows the improvement level in the power system. The four channels indicate real power flow between line 2-3 which has the magnitude of 3 MW, real power flow between line 3-4 has the magnitude of 1.92 MW, real power flow between line 1-2 has the magnitude of 3.26 MW and the voltage level at bus 1 whose magnitude is 1 p.u.

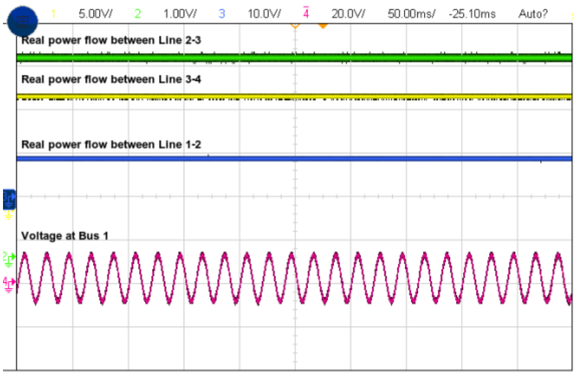

Fig. 13. Base case results

6. Conclusion

Unprecedented difficulties have been placed on the electrical grids by global climate change which leads to HILP events. To fortify the electric power grid against HILP incidents, resilience concept is highly important. This paper is focused on to measure the resiliency level using various metrics under HILP events in power distribution system and proposed a novel formulation technique based on an analytical and probabilistic approach to assessing resilience metrics under three important stages namely before the event occurs, during the event and after the event (restoration process). This research also focuses on how the resiliency level can be enhanced by optimal selection of Distributed Generations and Tie-lines in the distribution system. The optimal sizing of DG is determined using Differential Evolution based optimal algorithm employ reliability as an objective function. The planning and operational measures to

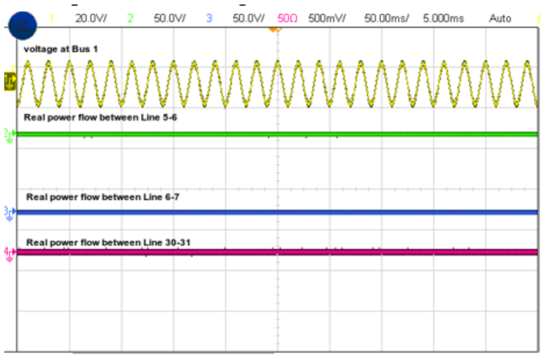

Fig. 14. Power flow under fault conditions

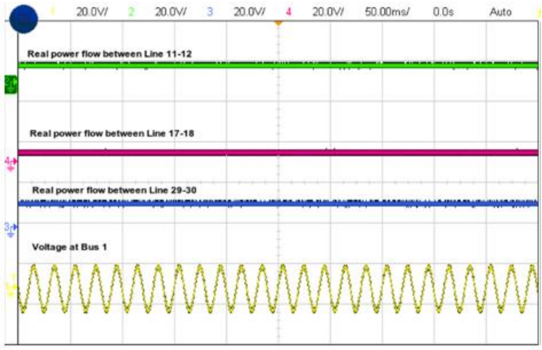

Fig. 15. Results showing after adding tie lines

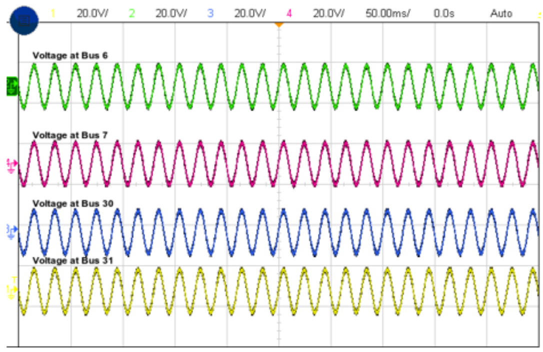

Fig. 16. Results showing after adding DGs

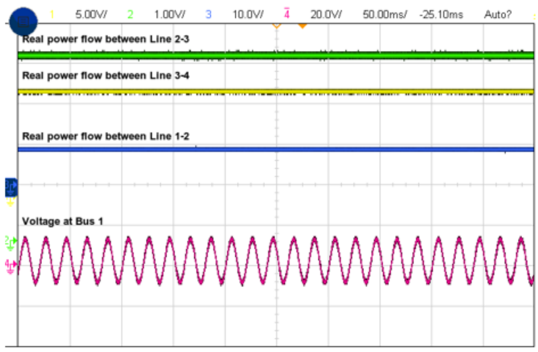

Fig. 17. Results showing after adding DG and Tielines

improve the electrical grid's resilience are summarized. The assessment of a 33 and 69 bus distribution system's resilience against a HILP event using existing resilience indicators illustrates resilience evaluation and the effectiveness of distributed generation and tie lines under normal loading and 125% overloading conditions. Simulation results are tabulated under various cases in IEEE

33 and 69 bus distribution systems using MATLAB and MIPOWER software and its resilience metrics are also highlighted. To improve resilience, a reliable network reconfiguration strategy is proposed, and its effectiveness is verified using various resiliency metrics. The proposed method is also validated in OPAL-RT based real time simulation by which resilience assessment and enhancement is investigated in distribution test systems. Challenges such as the requirement for data collecting to comprehend, evaluate, and improve system resilience is constantly growing. Incorporating machine learning tools, which are useful for modeling damages, forecasting outages, evaluating the resilience of power system and taken intelligent decision in advance. Future research also includes to increase the system's transient stability index when HILP events that could cause a cascade failure of the system.

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