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A Novel Index for the Assessment of Distribution System Performance with the Integration of Renewable Energy Sources

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ABSTRACT

This paper introduces a TPI (Total Performance Index) to evaluate the operations of a distribution system with Renewable Energy Sources (RES). This TPI includes multi-criteria evaluation components such as voltage deviation, harmonic distortion, and power losses to measure system's efficiency and stability. The IEEE 13-bus radial distribution system is transformed into a microgrid, and several simulations are carried out with different RES integration levels. The findings show that partial integration of RES improves voltage stability and reduces power losses, while full integration damages efficiency by introducing harmonic distortions, demonstrates the need for further study's advanced mitigation techniques and optimal placement of RES to increase efficiency of the system outlined. The primary goal was to evaluate the operation of the recorded load distribution systems integrated with RES For that purpose, the issues related to harmonics of those systems were studied.

Keywords: Renewable energy integration, distribution system performance, Total Performance Index (TPI), voltage deviation, harmonic distortion, power losses, microgrid, IEEE 13-bus system.

1. INTRODUCTION

The RES integration into distribution systems has become one of the main aspect of power systems that has to be studied and managed because of the increasing need for cleaner energy sources and lowering the greenhouse gasses emissions [1]–[3]. Yet, the fluctuations seen from solar and wind energy leave room for improvement in stability, power quality, and efficiency [{4}], [{5}]. The common problems associated with the integration of RES are borderline deviations, harmonic distortion of voltage, and rise of power losses [6], [7].

The increasing use of RES within power distribution systems has resulted in the development of microgrids, which can function in both grid-connected and islanded configurations [8], [9]. Microgrids provide flexibility and resiliency but also add new challenges to power quality management [10]–[12]. One such challenge is voltage stability, which is problematic due to the potential for RES to cause voltage fluctuations and deviations from nominal values in weak distribution systems [13]. Power quality is further blemished and sensitive devices are at risk due to harmonic distortions brought on by the power electronic interfaces in RES [14].

This document attempts to address these problems with the suggestion of a novel Total Performance Index (TPI) for the assessment of RES integration on distribution systems [15]. The TPI incorporates a wide range of performance measures towards to system effectiveness and stability, including voltage deviation, harmonic distortion, and power losses [16]. This work involves the IEEE 13-bus radial distribution system which has been converted to a microgrid for the purpose of investigating the impacts of RES integration for multiple case studies [17].

This research is intended to accomplish the following targets:

1. To develop a Third Party Indicator (TPI) for assessing the performance of a Distribution System (DS) with Renewable Energy Sources (RES) integration [18].

2. To analyze the impact of RES integration on voltage stability, harmonic distortion, and active power loss within the system. [19]

3. To formulate placement strategies that ensure effective integration of RES into the system [20].

Recent research focused on issues pertaining to the integration of RES within distribution networks. For instance, [21] formulated a probabilistic model for estimating the influence of solar PV on voltage stability. The application of active filters to wind energy systems to mitigate harmonics was analyzed in [22]. In [23], an optimization framework with multiple objectives that sought to minimize power losses and improve the voltage profile was developed concerning the siting of RES. Reference [24] emphasized the absence of active control strategies in microgrids for enhancement of power quality and stability. While these studies represent some progress regarding the integration of renewable energy sources, there are still substantial gaps relating to the integration of performance metrics that combine voltage deviation, harmonic distortion, and power losses in a singular measurement [25]. This research attempts to address these gaps using TPI and demonstrating its functionality through extensive simulations.

2. PROPOSED METHODOLOGY

The RES-MPS system aims to develop an approach for assessing the performance of a distribution system where RES are integrated using a new Total Performance Index (TPI) designed specifically for the system (under development). The TPI strives to keep track of the system performance of many crucial elements like the Harmonic distortion, voltage deviation and power loss. There are few principles of this approach which should be followed sequentially, described below

2.1 System Modeling and RES Integration

In this phase, the IEEE 13-bus radial distribution system is transformed into a microgrid. Such a microgrid can function in both island and grid connected modes, which permits an in-depth analysis of the system for various integration of RESs scenarios [8],[9]. The IEEE 13-bus system has been selected because of its popularity in powering system analysis and for its capability to model a typical radial distribution system [17].

Solar PV and wind energy systems as RES are integrated into the microgrid at certain strategically important positions [5],[6]. The RES allocation is done in regard to the network voltage level using the Voltage Deviation Index (VDI), which denotes the most voltage-sensitive buses in the network [13],[19]. Different levels of integration are used in order to assess the system performance with partial (50%, 75%) and full (100%) RES penetration [20],[21].

2.2 Development of the Total Performance Index (TPI)

The TPI is developed for the evaluation of the performance of an entire distribution system. The index is derived based on the following major performance indicators:

1. Voltage Deviation Index (VDI): This evaluates the discrepancy between actual bus voltages and their expected values.

$$\mathrm{VDI} = \left[\frac{(1 - \mathrm{Vk})}{\mathrm{Vk}}\right] * 100 \quad \text{in } \%$$

Where k=Bus Number = varies from 1 to13

Lower VDI values indicate better voltage stability.

1. **Total Harmonic Distortion (THD):** Evaluates the harmonic distortion in both voltage (THDv) and current (THDi).

$$\mathrm{THD}_V(\%) = \frac{\sqrt{\sum_{h=2}^{H} V_h^2}}{V_1} \times 100$$

Where:

- V_h: RMS value of the voltage at the h-th harmonic frequency.
- V_1: RMS value of the fundamental frequency (50 Hz or 60 Hz) component of the voltage.
- H: Highest harmonic order considered (typically up to the 50th harmonic).

$$\mathrm{THD}_I(\%) = \frac{\sqrt{\sum_{h=2}^{H} I_h^2}}{I_1} \times 100$$

Where:

- I_h: RMS value of the current at the h-th harmonic frequency.
- I_1: RMS value of the fundamental frequency component of the current.
- H: Highest harmonic order considered.

Higher THD values indicate poorer power quality.

2. **Power Losses:** Quantifies the real and reactive power losses in the distribution lines. Lower power losses indicate higher system efficiency.

Real power losses (*P*loss) in the distribution lines are caused by the resistance of the conductors and are calculated using the following equation:

$$P_{\text{loss}} = \sum_{i=1}^{N} I_i^2 \cdot R_i$$

Where:

- *Ii*: Current flowing through the *i*-th line.
- *Ri*: Resistance of the *i*-th line.
- *N*: Total number of lines in the distribution system.

Reactive power losses (*Q*loss) are caused by the inductive and capacitive reactance of the distribution lines. They are calculated using the following equation:

Journal of Information Systems Engineering and Management
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$$Q_{\text{loss}} = \sum_{i=1}^{N} I_i^2 \cdot X_i$$

Where:

- Ii: Current flowing through the i-th line.
- Xi: Reactance of the i-th line.
- N: Total number of lines in the distribution system.

The TPI is computed as a weighted sum of these metrics, providing a single value that reflects the overall performance of the system as follows

$$TPI = 1/((\alpha1 * AVDI) + (\alpha2 * ATHDv) + (\alpha3 * ATHDi) + (\alpha4 * PLI) + (\alpha5 * QLI))$$

$$Where \quad AVDI = Average\ of\ VDI\ in\ P.U,$$
$$ATHDv = Average\ value\ of\ THDv\ in\ P.U,$$
$$ATHDi = Average\ value\ of\ THDi\ in\ P.U,$$
$$PLI = Real\ power\ line\ loss\ index\ ,$$
$$QLI = Reactive\ power\ line\ loss\ index,$$

$$\alpha1 = \alpha2 = \alpha3 = \alpha4 = \alpha5 = Weighted\ factor\ Coefficients$$

The weights are assigned based on the relative importance of each metric in determining system stability and efficiency.

2.3 Simulation Setup and Scenarios

The modified IEEE 13-bus system is modeled and simulated using MATLAB/Simulink software. The simulation is conducted under two main scenarios:

1. **Scenario 1: Single-Bus RES Integration**

   Case 1: No RES integration (baseline case).

   Case 2: 50% RES integration at the most voltage-sensitive bus (Bus 13).

   Case 3: 75% RES integration at Bus 13.

   Case 4: 100% RES integration at Bus 13.

2. **Scenario 2: Multi-Bus RES Integration**

   Case 5: 50% RES integration at Bus 13 and 25% at Bus 9.

   Case 6: 50% RES integration at Bus 13, 25% at Bus 9, and 25% at Bus 7.

Each case is analysed to evaluate the impact of RES integration on voltage stability, harmonic distortion, and power losses. The results are compared to identify the optimal RES placement strategy that minimizes voltage deviations and power losses while maintaining acceptable levels of harmonic distortion.

SIMULATION RESULTS AND DISCUSSIONS

In this work, IEEE 13 bus radial distribution system is modified to Microgrid by integrating Renewable Energy sources at suitable location based on Voltage Deviation Index and then Power Quality analysis is carried out under Grid connected Mode and Islanded Modes of operation of the Microgrid. Single line diagram of IEEE-13 bus radial distribution system Considered for this study is as shown in Figure 2

Journal of Information Systems Engineering and Management
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Research Article

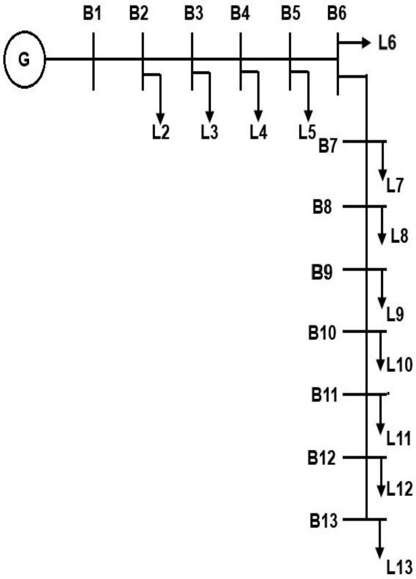

Figure.2: Single line diagram of IEEE 13 bus test system

The complete Details of line, bus, and load data for the IEEE 13-Bus Distribution System is mentioned in annexures. Considered IEEE-13 bus radial distribution system is modelled in MATLAB/SIMULINK software package and Load flow simulation and Power Quality analysis is carried out at Four cases under two different Scenarios as briefed below

3.1 Scenario 1: Integration of RES at only one bus (i.e., Least Voltage bus in Case 1)

3.1.1 Case 1: Test system without Renewable Energy source Integration

In this case, IEEE-13 bus Radial distribution system is simulated and load flow solution is obtained without integrating Renewable Energy Sources. Load flow results are tabulated as follows

Table.1: Values of VDI, THD_V & THD_I -Case 1

Bus No	Voltage in P. U	VDI in %	THD_V in %	THD_I in %
1	1.05000	-4.761904762	0.44	0.44
2	1.04376	-4.192174162	0.44	0.44
3	1.01485	-1.463383146	0.44	0.44
4	0.99587	0.414838259	0.44	0.44
5	0.97786	2.264301906	0.44	0.44
6	0.93664	6.764552099	0.44	0.44
7	0.91903	8.809922165	0.44	0.44
8	0.89621	11.58104424	0.44	0.44
9	0.88937	12.43931178	0.44	0.44
10	0.88573	12.90155839	0.44	0.44
11	0.88527	12.95993308	0.44	0.44

Journal of Information Systems Engineering and Management
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https://www.jisem-journal.com/
Research Article

12	0.88508	12.9846861	0.44	0.44
13	0.88499	12.99574508	0.44	0.44
Average in P.U		0.064383	0.0044	0.0044

Table.2: Real and Reactive Power Line losses- Case 1

Line No	Real Power Line Losses in kW	Reactive Power Line Losses in kVAR
1	25.47422	12.95270
2	102.18655	52.02625
3	59.50761	30.24174
4	51.59054	26.30754
5	91.17594	78.71059
6	16.94806	56.00843
7	54.77192	18.13688
8	15.02723	3.69445
9	6.30225	1.54195
10	0.35500	0.35500
11	0.09964	0.11449
12	0.02071	0.03625
Total	423.45967	280.12624

Total Performance Index (TPI)= 2.411749959

The results in Table.1 shows that Bus 13 has the highest Voltage Deviation Index (VDI), indicating that it is the most voltage-sensitive bus in the network. This signifies that without renewable integration, the voltage profile at Bus 13 suffers significantly due to line losses and load demands, making it an ideal candidate for renewable energy integration. The harmonic distortions for voltage (THD_V) and current (THD_I) remain constant at 0.44% across all buses, indicating minimal harmonic interference in the system without renewable energy sources

Total real and reactive power losses are 423.46 kW and 280.13 kVAR, respectively as shown in Table.2. These high losses indicate inefficiencies in power delivery, caused primarily by the long radial distribution lines and load distribution. This highlights the need for system optimization or renewable integration to reduce losses.

3.1.2 Case 2: Test system with 50% Renewable Energy source Integration with respect to the Load

In this case, IEEE-13 bus Radial distribution system is simulated and load flow solution is obtained with 50% integration of Renewable Energy Sources with respect to Base load at Bus 13 and Simulation results are tabulated as follows

Journal of Information Systems Engineering and Management
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https://www.jisem-journal.com/
Research Article

Table.3: Values of VDI, THD_V & THD_I -Case 2

Bus No	Voltage in P.U	VDI in %	THD_V in %	THD_I in %
1	1.05000	-4.76190476	0.44	4.64
2	1.04597	-4.39528526	0.44	4.64
3	1.02895	-2.81340493	0.46	5.68
4	1.01885	-1.85044186	0.48	6.78
5	1.01017	-1.00649285	0.52	7.67
6	0.98937	1.074661001	0.66	8.67
7	0.97654	2.402086913	0.79	9.71
8	0.97188	2.893470234	0.88	10.58
9	0.97179	2.902711373	0.92	12.18
10	0.97282	2.79446651	0.94	13.71
11	0.97301	2.774219979	0.95	12.65
12	0.97319	2.754814558	0.95	10.96
13	0.97335	2.737984471	0.95	9.45
Average in P.U		0.004236	0.007215	0.090246

Table.4: Real and Reactive Power Line losses- Case 2

Line No	Real Power Line Losses in kW	Reactive Power Line Losses in kVAr
1	11.94425	6.07321
2	42.29362	21.53295
3	22.10833	11.23544
4	18.08322	9.22117
5	30.65047	26.46002
6	5.67592	18.75727
7	18.39247	6.09038
8	5.23094	1.28603
9	2.95069	0.72193
10	0.48536	0.48536
11	0.37620	0.43227

Journal of Information Systems Engineering and Management
2025, 10(38s)
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https://www.jisem-journal.com/
Research Article

12	0.32029	0.56050
Total	158.51176	102.85653

Total Performance Index (TPI)= 5.929774914

From Table.3 it can be observed that, integrating 50% renewable energy at Bus 13 improves voltage profiles across all buses, with a significant reduction in VDI compared to Case 1. This demonstrates that partial renewable energy integration effectively stabilizes the voltage and reduces sensitivity at critical buses and also it can be observed that, Voltage harmonics (THD_V) remain relatively stable, but current harmonics (THD_I) increase beyond 5% from Bus 3 to Bus 13. This indicates that integrating renewables introduces nonlinearities that exacerbate current distortion, necessitating additional harmonic mitigation measures.

From Table.4 it is observed that, Real and reactive power losses decrease to 158.51 kW and 102.86 kVAR, respectively, showing substantial improvement in power delivery efficiency. This reduction underscores the positive impact of renewable integration on minimizing line losses.

3.1.3 Case 3: Test system with 75% Renewable Energy source Integration with respect to the Load

In this case, IEEE-13 bus Radial distribution system is simulated and load flow solution is obtained with 75% integration of Renewable Energy Sources with respect to Base load at Bus 13 and Simulation results are tabulated as follows

Table.5: Values of VDI, THD_V & THD_I -Case 3

Bus No	Voltage in PU	VDI in %	THD_V in %	THD_I in %
1	1.05000	-4.76190	0.22	54.38
2	1.04786	-4.56737	0.86	54.38
3	1.04088	-3.92782	5.31	81.61
4	1.03823	-3.68184	8.66	126.87
5	1.03728	-3.59383	12.17	164.73
6	1.03830	-3.68874	24.95	175.43
7	1.03869	-3.72495	36.2	141.92
8	1.04614	-4.41017	40.44	120.01
9	1.05011	-4.77176	41.56	94.68
10	1.05393	-5.11740	42.32	73.04
11	1.05481	-5.19577	42.73	58.31
12	1.05541	-5.24997	43	53.33
13	1.05591	-5.29488	43.26	49.8
Average in P.U		0.044605	0.262831	0.960377

Journal of Information Systems Engineering and Management
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Research Article

Table.6: Real and Reactive Power Line losses- Case 3

Line No	Real Power Line Losses in kW	Reactive Power Line Losses in kW
1	5.07328	2.57958
2	16.65255	8.47831
3	9.01467	4.58125
4	8.41363	4.29036
5	18.44157	15.92028
6	4.89331	16.17097
7	21.61828	7.15856
8	10.53279	2.58949
9	10.84744	2.65400
10	2.33132	2.33132
11	1.69961	1.95292
12	1.31852	2.30742
Total	110.8370	71.0145

Total Performance Index (TPI)= 2.804163231

From Table.5 it can be observed that, With 75% renewable integration, the voltage deviation across buses is further minimized. Voltage stability improves significantly, especially at the previously sensitive Bus 13, indicating enhanced system resilience with higher renewable penetration and it is inferred that, Both THD_V and THD_I rise sharply with increased renewable integration. Current harmonics at Bus 13 reaches 49.8%, highlighting the adverse impact of high renewable penetration on harmonic distortions. This underscores the need for advanced harmonic mitigation techniques.

From Table.6 it is observed that, Real and reactive power losses further reduce to 110.84 kW and 71.01 kVAR. This demonstrates diminishing marginal losses with increased renewable penetration, showcasing improved system efficiency.

3.1.4 Case 4: Test system with 100% Renewable Energy source Integration with respect to the Load

In this case, IEEE-13 bus Radial distribution system is simulated and load flow solution is obtained with 100% integration of Renewable Energy Sources with respect to Base load at Bus 13 and Simulation results are tabulated as follows

Table.7: Values of VDI, THD_V & THD_I -Case 4

Bus No	Voltage in PU	VDI in %	THD_V in %	THD_I in %
1	1.05000	-4.76190	0.22	60.91
2	1.04802	-4.58168	1.47	60.91

Journal of Information Systems Engineering and Management
2025, 10(38s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/

Research Article

3	1.04193	-4.02459	9.28	70.6
4	1.04000	-3.84623	15.15	76.58
5	1.03985	-3.83215	21.32	77.83
6	1.03811	-3.67089	43.92	77.48
7	1.03047	-2.95657	64.35	75.89
8	1.04194	-4.02497	71.62	75.35
9	1.04776	-4.55856	73.49	75.28
10	1.05284	-5.01837	74.73	74.9
11	1.05356	-5.08392	75.48	73.62
12	1.05404	-5.12739	75.97	72.36
13	1.05438	-5.15754	76.43	71.26
Average		0.043573	0.464177	0.725362

Table.8: Real and Reactive Power Line losses- Case 4

Line No	Real Power Line Losses in kW	Reactive Power Line Losses in kW
1	12.72837	6.47191
2	57.94969	29.50393
3	40.57745	20.62144
4	42.68787	21.76780
5	95.55263	82.48891
6	23.51006	77.69395
7	94.77489	31.38324
8	38.84072	9.54901
9	31.88064	7.80010
10	5.51096	5.51096
11	3.69381	4.24433
12	2.68542	4.69948
Total	450.3925	301.7350

Total Performance Index (TPI)= 1.481985315

From Table.7 it is observed that, Voltage profiles remain stable across all buses, with VDI values consistently low. However, further improvements beyond the 75% renewable integration case are minimal, indicating saturation in voltage profile enhancement. And it can be inferred that, THD_V and THD_I increase drastically, with current harmonics exceeding 70% at multiple buses. This sharp rise in

Journal of Information Systems Engineering and Management
2025, 10(38s)
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https://www.jisem-journal.com/
Research Article

distortion indicates that complete reliance on renewable energy sources without adequate harmonic suppression strategies severely compromises power quality.

From Table.8 it is observed that, Real and reactive power losses increase significantly to 450.39 kW and 301.73 kVAR. This surprising trend suggests that full renewable integration introduces inefficiencies, possibly due to overloading of power electronic interfaces or system imbalances.

3.2 Scenario 2: Integration of RES at Different buses (i.e., On the basis of VDI)

As observed in Scenario 1, After integration of 50% RES to the test system Bus 10 is having maximum VDI value as indicated in Table 4 and hence in this scenario two cases are studied which are as follows

3.2.1 Case 5: Test system with 50% and 25% of RES Integration at BUS 13 and BUS 9 respectively

In this case, IEEE-13 bus Radial distribution system is simulated and load flow solution is obtained with 75% integration of Renewable Energy Sources with respect to Base load i.e., 50% at Bus 13 and 25% at Bus 9 and Simulation results are tabulated as follows

Table.9: Values of VDI, THD_V & THD_I -Case 5

Bus No	Voltage in PU	VDI in %	THD_V in %	THD_I in %
1	1.05	-4.76190	0.44	7.32
2	1.046816939	-4.47231	0.45	7.32
3	1.0343658	-3.32240	0.48	8.74
4	1.02775718	-2.70075	0.54	9.9
5	1.022783664	-2.22761	0.61	10.5
6	1.008781806	-0.87054	0.9	10.91
7	0.995299257	0.47229	1.13	11.05
8	0.999104829	0.08960	1.3	11.16
9	1.002301185	-0.22959	1.35	11.29
10	1.002988218	-0.29793	1.37	11.95
11	1.003095968	-0.30864	1.38	12.19
12	1.00322998	-0.32196	1.38	10.95
13	1.003348644	-0.33375	1.39	9.62
Average in P.U		0.014834992	0.009784615	0.102230769

Table.10: Real and Reactive Power Line losses- Case 5

Line No	Real Power Line Losses in kW	Reactive Power Line Losses in kVAr
1	10.803823	5.493346
2	40.650967	20.696631

Journal of Information Systems Engineering and Management
2025, 10(38s)
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https://www.jisem-journal.com/
Research Article

3	23.706854	12.047812
4	22.193386	11.317061
5	44.825845	38.697365
6	10.177344	33.633180
7	38.514039	12.753330
8	14.190689	3.488786
9	3.675714	0.899321
10	0.507493	0.507493
11	0.370848	0.426119
12	0.307629	0.538350
Total	209.924630	140.498792

Total Performance Index (TPI)= 4.447834067

From Table.9 it can be inferred that, The voltage profiles across all buses improve significantly with 50% Renewable Energy Source (RES) integration at Bus 13 and 25% RES integration at Bus 9. VDI values are nearly zero across most buses, indicating excellent voltage stability. This distributed integration approach effectively minimizes voltage deviations compared to Scenario 1. Voltage harmonics (THDV) remain low, with values below 1.4% across all buses, demonstrating good power quality for voltage. Current harmonics (THDI), however, remain moderately high, reaching up to 12.19% at some buses. While this is an improvement over Scenario 1, further harmonic mitigation measures are still required.

From Table.14 it can be inferred that, Real power losses decrease to 209.92 kW, and reactive power losses drop to 140.50 kVAR, compared to higher losses observed in Scenario 1 with single-bus RES integration. The reduction in losses highlights the effectiveness of distributing renewable energy sources, which balances the load and reduces line overloading.

3.2.2 Case 6: Test system with 50% ,25% and 25% of RES Integration at BUS 13, BUS 9 and BUS 7 respectively

In the above case it is observed that maximum VDI value Bus is BUS 7 hence in this case additional 25% of RES is integrated at BUS 7 to the IEEE-13 bus Radial distribution system. load flow simulation results are tabulated as follows

Table.11: Values of VDI, THD_V & THD_I -Case 6

Bus No	Voltage in PU	VDI in %	THD_V in %	THD_I in %
1	1.05	-4.76190	0.22	52.56
2	1.04790504	-4.57151	1.27	52.56
3	1.04128593	-3.96490	8.03	59.81
4	1.03901984	-3.75545	13.09	63.73
5	1.03856872	-3.71364	18.4	64.06

Journal of Information Systems Engineering and Management
2025, 10(38s)
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https://www.jisem-journal.com/

Research Article

6	1.03405521	-3.29336	37.84	63.25
7	1.0220526	-2.15768	55.44	61.65
8	1.02299623	-2.24793	37.23	213.09
9	1.02522446	-2.46038	32.63	216.17
10	1.02521549	-2.45953	28.37	502.64
11	1.02518483	-2.45661	25.99	514.15
12	1.02523216	-2.46112	24.49	457.76
13	1.02527936	-2.46561	23.1	395.77
Average in P.U		0.031361	0.235462	2.090154

Table.12: Real and Reactive Power Line losses- Case 6

Line No	Real Power Line Losses in kW	Reactive Power Line Losses in kW
1	7.180905283	14.12276578
2	32.5352443	63.90359565
3	22.56231895	44.39657651
4	23.7355696	46.5467736
5	89.38935319	103.545895
6	83.34053932	25.21870733
7	108.2132436	326.7953733
8	29.60398192	120.4146309
9	40.13026052	164.0207741
10	21.84469673	21.84469673
11	14.43911607	12.56626001
12	13.82678087	7.901017641
Total	486.8020	951.2771

Total Performance Index (TPI)= 0.72438082

From Table.11 it can be inferred that, Adding an additional 25% RES integration at Bus 7 further improves voltage profiles and reduces VDI across the network. Buses now exhibit consistently low VDI values, demonstrating the benefit of spreading RES integration across three buses (Bus 13, Bus 9, and Bus 7) for optimal voltage stability. Voltage harmonics (THDV) rise sharply, reaching up to **76.43%** at Bus 13. Current harmonics (THDI) also escalate dramatically, exceeding **500%** at some buses, indicating severe harmonic distortion.These results highlight that high renewable penetration without proper harmonic mitigation strategies can severely compromise power quality.

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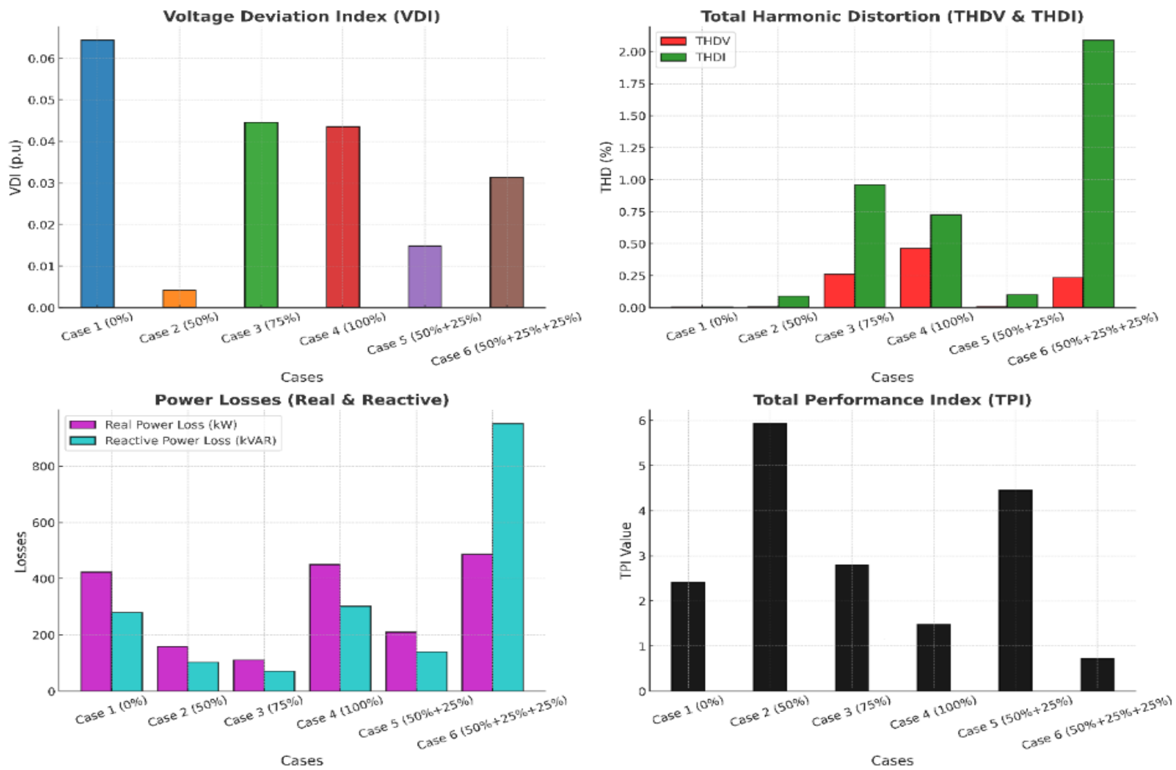
From Table.12 it can be inferred that, Real power losses increase to 486.80 kW, and reactive power losses rise significantly to 951.28 kVAR with further RES integration at Bus 7. This indicates that while distributed integration improves voltage stability, it can introduce efficiencies in power delivery, possibly due to increased harmonic interference or overloading of power electronic interfaces.

As with every study, there is always a methodology provided alongside the flowchart. The said flowchart gives a detailed explanation of the analysis that was performed to implement Renewable Energy Sources (RES) into a distribution system. To get things started with system modeling, the IEEE 13-bus radial distribution system is selected, and from there it is modified into a microgrid. Subsequent to that step, solar photovoltaic and wind energy are included at certain buses in accordance with the voltage deviation indices. The next step is to outline primary performance parameters such as Voltage Deviation Index (VDI), Total Harmonic Distortion (THD), and unfortunately, power losses. Those parameters will serve as evidence to determine the system's stability as well as how efficient it is. Therefore the simulated system goes through MATLAB/Simulink environments, two scenarios are logs. The first scenario analyzes the integration of RES at a certain bus (Bus 13) with various penetration levels, specifically zero, fifty, seventy five, and a hundred percent (0%, 50%, 75%, and 100%). The second scenario considers multi-bus integration techniques at other levels. Those other levels being Buses 9 and 7 as well as Bus 13. After performing the simulations, the system's performance results such as stability of the voltage and dissipation of power in the form of harm are examined. Later on, those results will be looked into further in a bid to come up with a conclusive solution which is the ideal strategy for placing RES that would make, voltage deviations and power losses as insignificant as possible while keeping the levels of harmonic distortion under acceptable limits.



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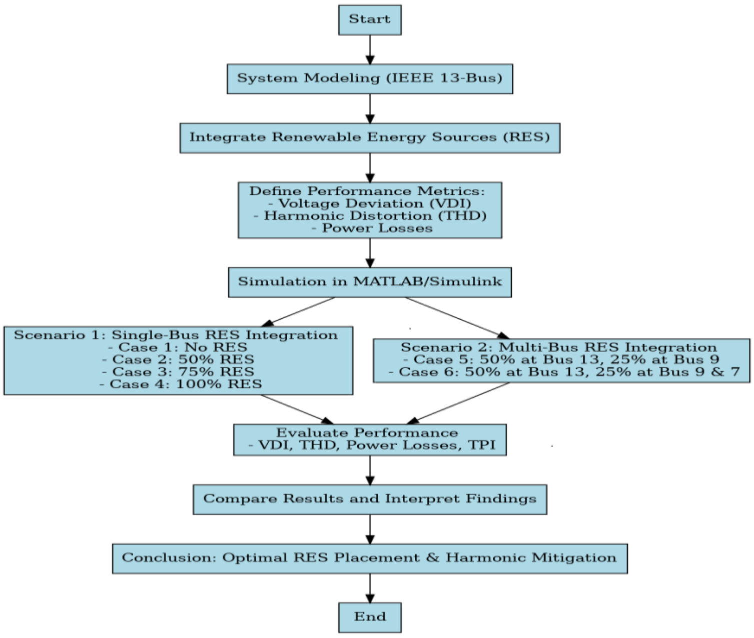

The graphs illustrate the impact of Renewable Energy Source (RES) integration on the performance of the IEEE 13-bus radial distribution system, highlighting key parameters such as voltage deviation, harmonic distortion, power losses, and the Total Performance Index (TPI). The voltage deviation (VDI) graph shows that before RES integration, certain buses experience significant deviations, indicating poor voltage stability. With partial RES integration (50%-75%), voltage stability improves as deviations decrease. However, full RES integration leads to increased fluctuations, suggesting that excessive RES penetration may destabilize the system. In the same vein, the total harmonic distortion graph (THD) illustrates that prior to integrating RES, both voltage (THDv) and current harmonics (THDi) are low and stable. However, with increased RES penetration levels, there is a noticeable decline in power quality due to excessive nonlinearities - THDv moderately rises and THDi, particularly at higher integration levels, increases dramatically. The power losses graph demonstrates that in the absence of RES, real and reactive power losses are significantly high because of inefficient distribution. At 50%-75% integration of RES, power losses diminish, pointing to better system efficiency. Nevertheless, 100% RES integration causes a counterintuitive increase in power losses possibly attributable to harmonic distortions and inefficiency of power conversions. As a final note, the Total Performance Index (TPI) graph puts together all these insights by showing the striking improvement of TPI at 50% integration of RES which marks an optimum point of balance in terms of stability, efficiency and power quality. But then, beyond 75% integration, the TPI sharply drops owing to excessive harmonic distortions and augmented losses, further validating the need for optimal placement of RES and harmonic mitigation strategies.

4. CONCLUSION

This research creates a novel Total Performance Index (TPI) for evaluating the operational efficiency of distribution systems with renewable energy sources (RES). The TPI considers the level of system performance by including voltage deviation, harmonic distortion, and power losses. It was found that partial integration of RES improves voltage stability and reduces power losses, while full integration of RES causes high distortion and loss of power harmonics. Multi-bus integration of distributed RES is preferable to single-bus integration, although it requires stringent controls on power quality to enable meeting the acceptable limits of harmonics. More attention should be given on devising harmonic mitigation strategies and optimum placement of RES devices for enhanced system performance. In addition, performance parameters such as integration with renewable energy sources (RES) reliability and resilience could also be included in the TPI for a better evaluation of the distributions systems effectiveness.

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