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Optimal Placement of Renewable Energy Sources and Fuel Cell in Power System using Line Stability Index

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***Abstract* - The increasing penetration of renewable energy sources (RES) in modern power systems has raised concerns regarding voltage stability and system reliability. Proper placement and sizing of renewable energy sources and fuel cells are essential to enhance system performance while maintaining stability limits. This paper presents an optimal placement strategy for renewable energy sources and a fuel cell in a power system using the Line Stability Index (LSI) as a voltage stability indicator. Initially, load flow analysis is performed to identify weak transmission lines based on their LSI values. Buses associated with high LSI values are considered as candidate locations for the integration of RES and fuel cell units. An optimization problem is formulated with the objective of minimizing the maximum LSI, improving voltage profile, and reducing real power losses, subject to system operational constraints. A suitable optimization technique is employed to determine the optimal locations and capacities of the RES and fuel cell. Simulation studies conducted on a standard IEEE test system demonstrate that the proposed approach significantly enhances voltage stability, reduces power losses, and improves overall system performance. The results confirm the effectiveness of the Line Stability Index as a reliable tool for optimal resource placement in power systems with high renewable penetration. To overcome this limitation, a Fuel Cell—capable of continuously supplying both active and reactive power—is also installed at the same weak bus. A re-analysis shows that Fuel Cells provide greater improvements in voltage stability and L-index reduction compared to PV systems, particularly under varying load scenarios. To further assess system performance, a cost function evaluation is conducted to examine the economic implications of the integration. The algorithms tested include the Frilled Lizard Optimization (FLO), Osprey Optimization Algorithm (OOA), and Coati Optimization Algorithm (COA). Results indicate that FLO and OOA exhibit strong convergence and efficient search capabilities, making them highly effective for emission minimization in power system optimization. In conclusion, the research highlights the critical role of carefully planned renewable energy placement in improving grid stability while reducing environmental impacts. The combined methodology—spanning load flow analysis, Lindex evaluation, and optimization**

algorithm benchmarking - offers a comprehensive framework for future advantage.

Keywords - Renewable Energy Sources, Fuel Cell, Optimal Placement, Line Stability Index, Voltage Stability, Power System Planning, Distributed Generation, Load Flow Analysis, Power Loss Minimization, Optimization Techniques. Flow Analysis; Reactive Power Support; Optimization Algorithms; Emission Reduction.

I. INTRODUCTION

The rapid growth in electricity demand and increasing environmental concerns have accelerated the integration of renewable energy sources (RES) into modern power systems. Renewable sources such as solar photovoltaic and wind energy offer clean and sustainable alternatives to conventional fossil-fuel-based generation. However, the intermittent nature of these resources and their improper placement within the power network can lead to operational challenges, including voltage instability, increased power losses, and line congestion.

Voltage stability has become a critical issue in power system planning and operation, particularly with the rising penetration of distributed generation. Weak transmission lines and heavily loaded buses are more susceptible to voltage collapse, which can compromise system reliability. Therefore, identifying vulnerable locations and reinforcing them with suitable energy sources is essential to maintain stable and secure operation.

Fuel cells have emerged as a promising complementary energy source due to their high efficiency, fast dynamic response, and ability to supply both active and reactive power. When strategically integrated alongside renewable energy sources, fuel cells can mitigate the adverse effects of renewable intermittency and enhance voltage support in critical areas of the network.

This paper proposes an optimal placement methodology for renewable energy sources and a fuel cell using the Line Stability Index as the primary stability assessment tool. Load flow analysis is initially performed to determine the base-case operating condition and identify weak lines. An optimization framework is then applied to determine the optimal locations and capacities of the RES and fuel cell with the objectives of improving voltage stability, enhancing voltage profiles, and reducing system power losses. The effectiveness of the

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proposed approach is validated through simulation studies on a standard IEEE test system.

II.LINE STABILITY INDEX

A. *IEEE 39-bus system)*

The Line Stability Index (L-index) is employed to assess voltage stability by evaluating the power transfer capability of transmission lines. It is derived from the power flow equations of a two-bus system and depends on parameters such as line reactance, reactive power demand, sending-end voltage magnitude, and power angle. The IEEE 39-bus system, a widely used benchmark in power system studies, has been analyzed using load flow analysis to evaluate the steady-state operational conditions of electrical grids. Through the usage of this analysis, it helps to determine voltage magnitudes, power flows, and stability across the network. Recent studies, including voltage stability analysis, have also highlighted the application of line stability indices to assess the system's robustness under varying load conditions. Specifically, the Line Stability Index (Lmn) has been utilized to monitor the stability of transmission lines within the IEEE 39-bus systems L-index value close to zero indicates a stable operating condition, while a value approaching unity signifies proximity to voltage collapse. In this study, L-index values are calculated for all transmission lines in the IEEE 39-bus system. The bus associated with the maximum L-index value is identified as the weakest bus and selected for renewable energy integration.

B. *System Modeling*

(IEEE 39-Bus Test System)

The IEEE 39-bus (New England) test system is used to validate the proposed methodology. The system consists of 39 buses, 10 generators, 19 load buses, and multiple transmission lines and transformers. It is widely accepted as a standard benchmark for voltage stability and optimization studies. Results show that the system, under typical operating conditions, exhibits stable performance with most transmission lines classified as stable, indicating that the power network can withstand minor disturbances without significant risk of instability. The integration of these stability indices enhances the understanding of the system's resilience, confirming its adequacy in both normal and stressed operational scenarios. In addition to that, Optimization algorithms have also been introduced to the system and the outcome of each algorithm has been compared to highlight their problem solving capability.

Solar PV Modeling

The Solar PV system is modeled as a distributed generation unit connected to the identified weak bus. The PV unit injects active power into the system and provides limited reactive power support through inverter control. While PV integration improves voltage profile, its output varies with solar irradiance, affecting system reliability

Fuel Cell Modeling

The Fuel Cell system is modeled to supply continuous active and reactive power. Unlike Solar PV, the Fuel Cell provides stable output regardless of environmental conditions, making it suitable for enhancing voltage stability under varying load scenarios

III.OPTIMIZATION ALGORITHMS

Frilled Lizard Optimization (FLO)

FLO is inspired by the hunting and defensive behavior of frilled lizards. It effectively balances exploration and exploitation by dynamically updating candidate solutions, resulting in fast convergence and improved global search capability. The Frilled Lizard Optimization (FLO) algorithm is a bio-inspired metaheuristic method modelled after the natural behaviours of the frilled lizard, particularly its sit-and-wait hunting strategy and its tendency to retreat to treetops after feeding. The algorithm emulates these behaviours by incorporating an exploration phase, which mimics the lizard's sudden attack on prey, leading to significant positional changes in the population to enhance global search capabilities. Conversely, the exploitation phase replicates the lizard's retreat to a treetop, focusing on refining solutions in promising regions to improve convergence toward optimal solutions. Key parameters governing FLO's performance include population size, maximum number of iterations, exploration rate, and exploitation rate, which collectively balance the algorithm's search dynamics between broad exploration and localized refinement. This biologically inspired approach ensures an adaptive and efficient optimization process suitable for complex problem-solving. The mathematical model of FLO is as follows.

Osprey Optimization Algorithm (OOA)

OOA is based on the hunting strategy of ospreys, combining wide-area exploration through aerial surveillance and precise local exploitation through targeted dives. This dual behavior enhances convergence speed and solution accuracy. The Coati Optimization Algorithm (COA) is a bio-inspired metaheuristic technique that emulates the behaviour of coatis, social mammals closely related to raccoons. This algorithm replicates the collective hunting tactics and movement dynamics of coatis as they explore their environment for food, transforming these natural processes into an effective optimization method. COA operates through two key stages: an exploration phase, where simulated coatis disperse widely to discover potential food locations (analogous to global search), and an exploitation phase, where they focus on rich areas to maximize resource utilization (similar to local search). In the exploration stage, individual agents (representing coatis) navigate randomly or follow probabilistic cues to ensure comprehensive search space coverage. During exploitation, information sharing within the group drives coordinated movements toward high-quality solutions, enhancing precision.

Coati Optimization Algorithm (COA)

COA mimics the cooperative hunting behavior of coatis. It utilizes social interaction and group coordination to explore the search space and avoid local minima

C . Cost Function and Emission Modeling

The economic performance of the system is evaluated using a cost function that considers generation cost and operational constraints. Emission modeling is carried out for a system comprising ten generators over a 24-hour operating period. The objective is to minimize total emissions while satisfying power balance and generator constraint.

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D.Units

- V – Volt
- kV – Kilovolt
- A – Ampere
- MW – Megawatt (Active Power)
- MVAr – Megavolt–Ampere Reactive
- Ω – Ohm
- Hz – Hertz
- p.u. – Per Unit System

E.Equations

Power Flow Equations

The active and reactive power at bus *i* are expressed as

$$P_i=\sum_{j=1}^{N} V_i V_j \left(G_{ij}\cos\theta_{ij}+B_{ij}\sin\theta_{ij}\right)$$

$$Q_i=\sum_{j=1}^{N} V_i V_j \left(G_{ij}\sin\theta_{ij}-B_{ij}\cos\theta_{ij}\right)$$

where
V_j, V_j are bus voltages,
G_{ij}, B_{ij} are elements of the bus admittance matrix,
θ_{ij} is the voltage angle difference.

Line Stability Index (L-index)
he L-index for a transmission line connecting sending bus *s* and receiving bus *r* is given by:

$$L = 4XQ_r / V_s^2 \sin^2(\delta)$$

Where
X is the line reactance.
Q_r is the reactive power at the receiving end.
V_s is the sending-end voltage magnitude.
δ is the power angle difference.
Cost Function
The total generation cost is expressed as:

$$C=\sum_{i=1}^{N_g}\left(a_iP_i^2+b_iP_i+c_i\right)$$

Where

a_i, b_i, c_i are cost coefficients of generator *i*

P_i is the active power output,

N_g is the number of generators

Fuel Cell Power Output

$$P_{FC}=V_{FC}\times I_{FC}$$

Where

V_{FC} is fuel cell voltage

I_{FC} is fuel cell current.

Solar PV Output Power

$$P_{PV}=Hag$$

$$P_{PV}=\eta AG$$

Where,

η is PV efficiency,

A is panel area

G is solar irradiance

IV. MODELLING OF STANDARD IEEE 39-BUS TEST SYSTEM

A typical bus system in power systems serves as a node in a power grid allowing for power distribution between elements in the system. Buses are commonly divided into three types:

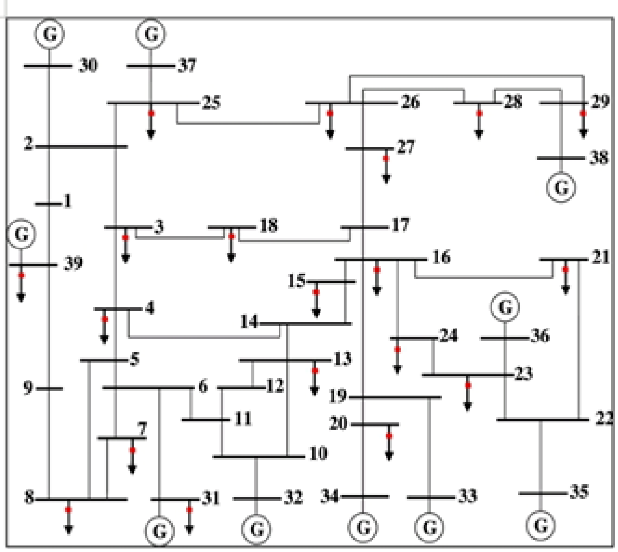
1. PQ Bus: Also known as load bus. This type of bus has both real and reactive power specified and based on these power values, the voltage is determined.

2. PV Bus: Both active power and voltage is mentioned in this type of bus. The reactive power is adjusted to maintain the voltage. Hence it also known as Generator bus.

3. Swing Bus: This bus type is usually used as a reference point for the system where both voltage and real power are adjusted to balance out the system.

39-Bus system

The IEEE 39-bus system is a power network in the New England area of the V.S. It consists of 10 generators, 39 busbars, 12 transformers, loads, capacitors banks and transmission lines. IEEE bus systems are used by researchers to implement new ideas and concept. These bus systems consist of load, capacitor banks, transmission lines and generators. With the help of these bus systems, certain theoretical analysis can be performed on software such as Authors and Affiliations. MATLAB (SIMULINK), etc to chart out the possible characteristics and behaviour of a system without physically involving



IV.Maximum Power Point Tracking (MPPT)

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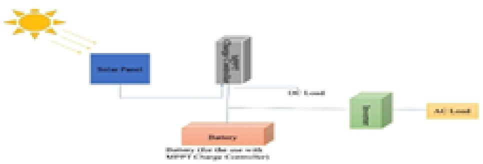
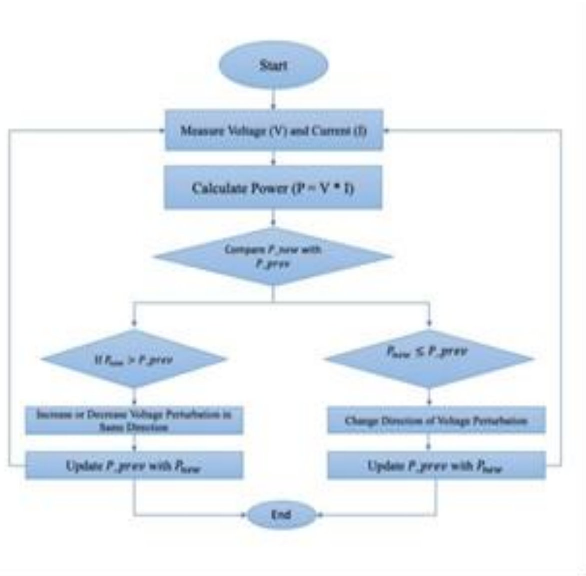


MPPT technology is aimed at the maximum optimization of energy generation from the solar panel by continuously adjusting the parameters of the process so that it lies on the variable MPP. This is more critical since, when the PV system does not lie on the MPP, the environmental conditions, in the course of a day, change and lead to losses in power. Operating points that are conventionally set will not tend to these changes resulting in suboptimal energy capture. In solar power systems, MPPT can help eradicate the need for extra panels or storages to be installed to compensate for the frequently required energy.

Block diagram of MPPT algorithm

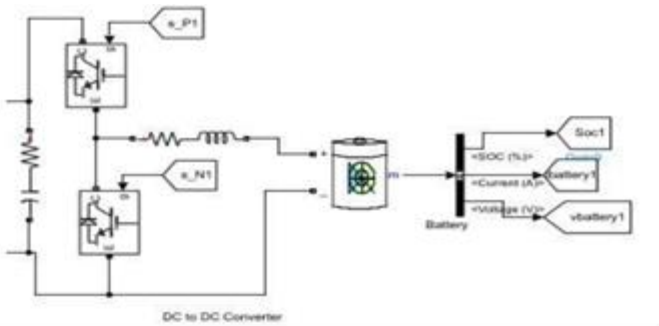
The energy produced by the MPPT controller can now be fed directly into DC loads or stored in a battery for later use. The stored DC energy can be used to feed the loads that work on AC, after converting it via an inverter, thus making this setup work in accordance with standard electrical appliances. Therefore, different load types can have energy converted and stored efficiently The energy produced by the MPPT controller can now be fed directly into DC loads or stored in battery for later use. The stored DC energy can be used to feed the loads that work on AC, after converting it via an inverter, thus making this setup work in accordance with standard electrical appliances. Therefore, different load types can have energy converted and stored efficiently.The perturb and observe algorithm is one of the popular techniques for MPPT in PV systems, working by periodically perturbing the PV system operating voltage and observing the result of the perturbation on the power output. In case the power output increases after a perturbation, the system adjusts in the same direction; in case the power decreases, the adjustment direction is reversed. This forms an iterative process through which the system converges to the Maximum Power Point (MPP) to provide maximum possible power that the PV system can offer under given environmental conditions.



FLOW CHART MPPT IN PV

V.BATTERY STORAGE SYSTEM

A battery storage system has also been implemented for an optimal usage of the PV array energy source. The PV array model supplies the input energy through the transmission lines and a DC-DC converter has been implemented in the system to convert the receiving energy suitable for the battery to store. Given below isa small glimpse of the Battery system implemented



the battery system implemented Specifications of IEEE 39 bus system The standard IEEE 39 bus system adopted in this work consists of 10 generators where 19 buses are considered as PQ load buses where loads are connected. The general specifications of IEEE 39 bus system are given below [19].Types of element and their quantity

E. Specifications of IEEE 39 bus system

The standard IEEE 39 bus system adopted in this work consists of 10 generators where 19 buses are considered as PQ load buses where loads are connected. The general specifications of IEEE 39 bus system are given below

. *Types of elements and their quantity*

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TABLE I. TABLE STYLES

ELEMENTS NAME	NO. OF ELEMENTS
GENETORTS	10
LOAD	19
BUSBARS	39

TAB LE-1I Load data of IEEE 39-bus system

BUS	*P(pu)*	*Q(pu)*
3	*3.220*	*0.024*
4	*5.000*	*1.840*
7	*2.338*	*0.840*
8	*5.220*	*0.840*

a.

Bus	P(pu)	Q(pu)
12	5.220	0.880
15	0.075	1.530
16	3.200	0.323
18	3.294	0.300
20	1.580	1.030
21	6.800	1.150
23	2.740	0.846
24	2.475	-0.922
25	3.086	0.472
26	2.240	0.170
27	1.390	0.755
28	2.810	0.276
29	2.060	0.269
30	2.835	0.046
31	0.092	0.086
39	11.04	2.500

Table III. Transmission line characteristics of IEEE 39-bus system

From Bus	To Bus	R (pu/m)	X (pu/m)	B (pu/m)
1	2	0.0035	0.0411	0.6987
1	39	0.0010	0.0250	0.7500
2	3	0.0013	0.0151	0.2572
2	25	0.0070	0.0086	0.1460
3	4	0.0013	0.0213	0.2214
3	18	0.0011	0.0133	0.2138
4	5	0.0008	0.0128	0.1342
4	14	0.0008	0.0129	0.1382
5	6	0.0002	0.0026	0.0434
5	8	0.0008	0.0112	0.1476
6	7	0.0006	0.0092	0.1130
6	11	0.0007	0.0082	0.1389
7	8	0.0004	0.0046	0.0780
8	9	0.0023	0.0363	0.3804
9	39	0.0010	0.0250	1.2000
10	11	0.0004	0.0043	0.0729
10	13	0.0004	0.0043	0.0729
13	14	0.0009	0.0101	0.1723
14	15	0.0018	0.0217	0.3660
15	16	0.0009	0.0094	0.1710
16	17	0.0007	0.0089	0.1342
16	19	0.0016	0.0195	0.3040
16	21	0.0008	0.0135	0.2548
16	24	0.0003	0.0059	0.0680
17	18	0.0007	0.0082	0.1319
17	27	0.0013	0.0173	0.3216
22	23	0.0006	0.0096	0.1846

VI. SIMULATION AND RESULTS

The IEEE 39-bus system, also known as the New England power system, is a well-established benchmark for power system analysis. It represents a simplified model derived from a section of the New England electric grid and is designed to

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study power flow, stability, and dynamic performance under various operating scenarios. This system comprises 39 buses, 10 generators, 46 transmission lines, 19 loads, and 12 transformers, offering a practical yet simplified representation of a real-world power network, making it highly valuable for both academic research and industrial applications [20].

System is the inclusion of an infinite bus at Bus 39, which serves as a strong and stable voltage source. This system's interconnection with a larger grid. The system's is distributed across various buses, mirroring real-world consumption patterns. Transmission lines and transformers are modelled parameters, such as resistance (R), reactance (X), and susceptance (B), making the system suitable for a wide range of analyses, including power flow studies, fault simulations, and dynamic stability tests.

This is widely used for stability studies, encompassing both small-signal and transient stability analyses. It enables researchers to investigate network behaviour under disturbances such as generator outages, line faults, or sudden load variations. Additionally, it serves as a standard test case for optimization problems like economic dispatch, unit commitment, and optimal power flow (OPF).

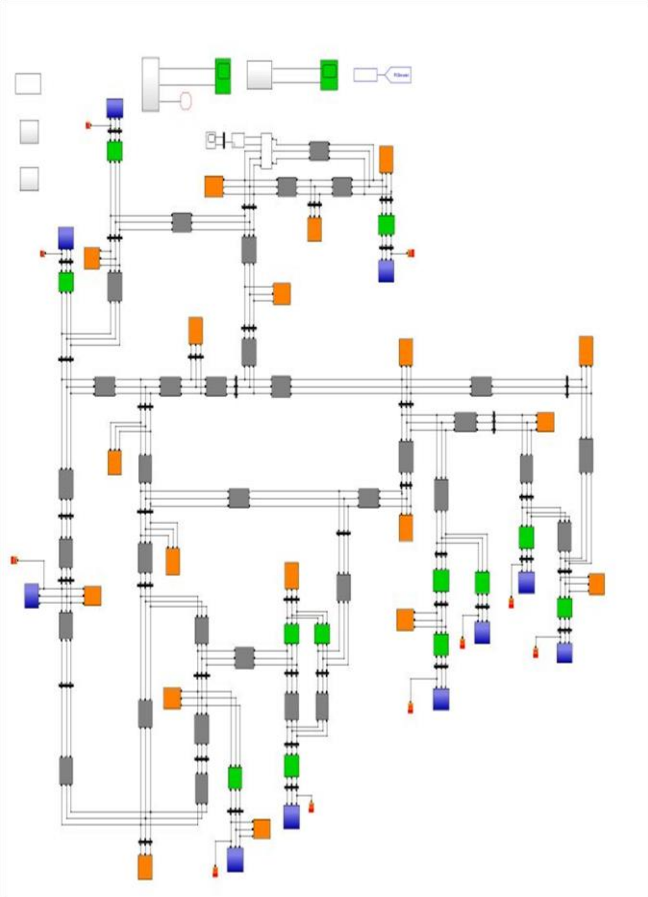
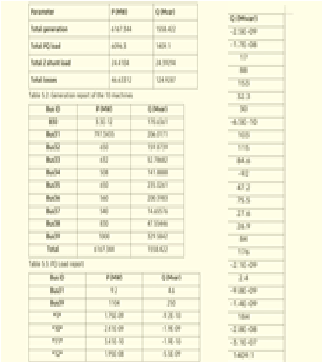


Diagram for base system of 39-bus

F. Load Flow Results

The first stage of the test was done with the completion of acquiring the Load Flow Analysis data (Table 4). The data collected works as a reference point from which the later analysis operations are done. Given below are the data taken from the Load Flow analysis done performed through MATLAB Simulink.

Table IV Active and Reactive power values of IEEE 39 bus system without PV integration



Parameter	P (MW)	Q (Mvar)
Total generation	6167.344	1558.422
Total PQ load	6094.3	1409.1
Total Z shunt load	24.4104	24.9929
Total losses	46.6331	124.9287

Table 5.1 Generation report of the 10 machines

Bus ID	P (MW)	Q (Mvar)
B30	[illegible]	[illegible]
Bus31	[illegible]	[illegible]
Bus32	650	[illegible]
Bus33	632	[illegible]
Bus34	508	[illegible]
Bus35	650	[illegible]
Bus36	560	[illegible]
Bus37	540	[illegible]
Bus38	830	[illegible]
Bus39	1000	[illegible]
Total	[illegible]	1558.422

Table 5.1 PQ load report

Bus ID	P (MW)	Q (Mvar)
Bus31	9.2	4.6
Bus39	1104	250
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]

Q (Mvar)
[illegible]
[illegible]
[illegible]
88
[illegible]
32.3
30
[illegible]
[illegible]
115
84.6
-92
47.2
75.5
27.6
26.9
[illegible]
176
[illegible]
2.4
[illegible]
[illegible]
184
[illegible]
[illegible]
[illegible]

After load flow analysis, this data will be take for reference

Line Stability Index calculation

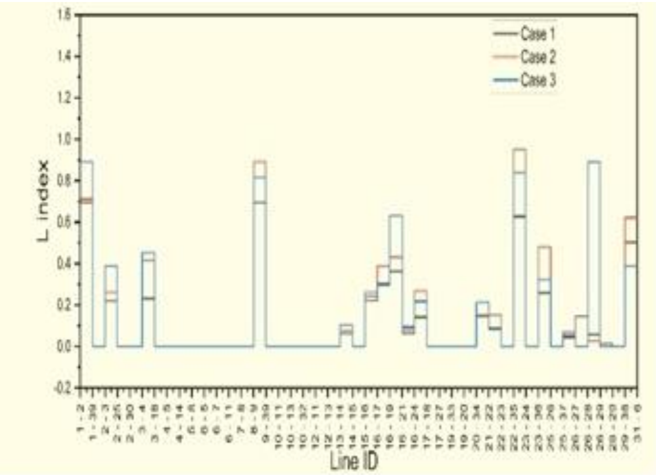
The Line Stability Index (LSI) is a critical parameter for evaluating the stability and security of power transmission lines. LSI calculation becomes important when integrating

From bus	To bus	Line index Case 1	Line index Case 2	Line index Case 3
1	2	9.71E-08	1.78E-07	1.81E-07
1	39	0.612	0.71	0.891
2	3	3.652E-08	6.62E-08	4.66E-08
2	25	0.220	0.26	0.389
2	30	0	0	0
3	4	1.212E-07	2.36E-07	1.29E-07
3	18	0.2306	0.415	0.454
4	5	1.759E-06	3.10E-06	2.26E-06
4	14	1.693E-06	2.37E-06	2.22E-06
5	8	3.243E-07	4.33E-07	6.23E-07
6	5	7.160E-09	9.89E-09	1.29E-08
6	7	3.330E-07	3.54E-07	4.64E-07
6	11	2.503E-08	3.29E-08	3.45E-08
7	8	1.862E-07	2.43E-07	3.72E-07
8	9	6.154E-09	9.00E-09	1.03E-08
9	39	0.6956	0.597	0.575
10	11	4.449E-08	6.24E-08	7.48E-08
10	13	5.154E-07	5.92E-07	8.27E-07

0
6.11E-08
[illegible]
1.75E-07
[illegible]
[illegible]
0.243
0.296
0.632
0.0929
0.217
7.58E-05
0
1.47E-04
0
0.212
0.0876
0
0.84
0
0.3219
0
0.0702
1.81E-07
0.890
4.66E-06
0

The line stability index for the IEEE 39 bus system was primarily carried out on standard system without adding any renewable energy sources with the help of load flow studies in MATLAB Simulink software. The L index values show that with the introduction of renewable energy sources, the stability of the system, although not

drastically but improvements are visible



. L index values for the lines connected in IEEE 39 bus system with different cases

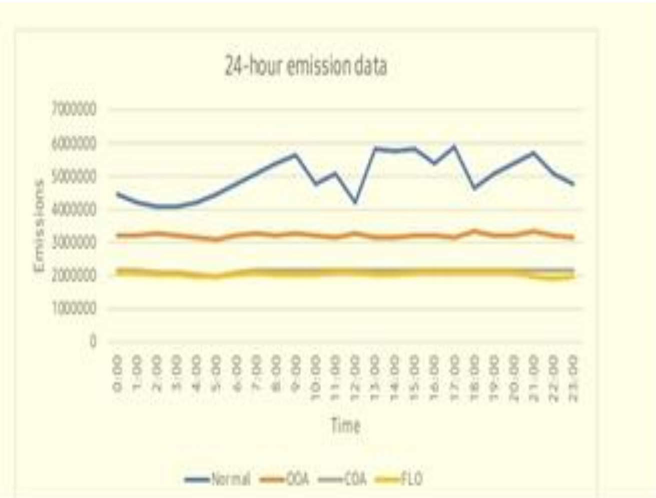
Cost Function Analysis for the system

Table V Cost Function comparisons for the algorithms

Algorithms	Cost Function	% decrease
Normal	₹6699510.6	
COA	₹4740185.38	29.25
OOA	₹4510876.87	32.67
FLO	₹4212275.01	39.3

COA, OOA, and FLO, relative to the baseline system without optimization. The findings revealed substantial cost savings: COA reduced expenses by 29.25%, OOA by 32.67%, and FLO outperformed both with a 39.3% reduction. FLO's exceptional results suggest its superior capability in lowering generation costs, attributed to its balanced approach between global search and local refinement

The emission study monitored output from 10 generators across a full day, comparing standard operations against COA, OOA, and FLO implementations. While all three optimization methods successfully curbed pollution levels, FLO emerged as the most effective, consistently producing the cleanest results



CONCLUSION AND FUTURE WORK

Conclusion

This research examined the incorporation of solar photovoltaic arrays and fuel cell technology within the IEEE 39-bus electrical network to improve operational stability and performance. Through comprehensive power flow studies and stability index evaluations, critical system vulnerabilities were pinpointed, enabling strategic deployment of renewable energy resources. While solar installations enhanced voltage regulation, their variable output necessitated supplemental solutions, with fuel cells proving more effective by delivering reliable power and substantially improving stability metrics.

An assessment of nature-inspired optimization methods - including Frilled Lizard, Osprey, and Coati algorithms - revealed significant potential for economic and environmental optimization. The Frilled Lizard approach showed particular promise, delivering nearly 40% cost savings and superior emission control capabilities in daily operations. These results emphasize the value of integrating computational optimization with traditional power system analysis.

The study recommends adopting combined renewable energy configurations with energy storage to address generation variability. Potential extensions of this work include adaptive control strategies, AI-driven power quality management, and expanded renewable integration scenarios. These findings contribute meaningful guidance for energy sector stakeholders pursuing sustainable infrastructure development

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