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

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***Abstract* - This study explores the optimal integration of renewable energy sources—specifically Solar Photovoltaic (PV) units and Fuel Cells—within a power system, using the Line Stability Index (L-index) as the primary indicator of voltage stability. The analysis is carried out on the IEEE 39-bus test system, beginning with a base case load flow study to pinpoint buses most susceptible to instability. Based on the L-index results, the weakest bus is identified, and a Solar PV system is first connected to it. Subsequent evaluations of voltage profiles, reactive power, and stability demonstrate that PV integration helps reduce L-index values and enhance stability. However, due to the intermittent nature of solar power, maintaining grid reliability remains a challenge. 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. Additionally, the work incorporates a comparative assessment of different optimization algorithms for emission reduction involving 10 generators over a 24-hour period. 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, L-index evaluation, and optimization algorithm benchmarking—offers a comprehensive framework for future advancements in sustainable power systems**

Keywords - Voltage Stability,Line Stability Index (L-index) IEEE 39-Bus System, Solar Photovoltaic (PV), Coati Optimization Algorithm (COA), Fuel Cell; Renewable Energy Integration; Load Flow Analysis; Reactive Power Support; Optimization Algorithms; Emission Reduction; Frilled Lizard Optimization (FLO),Osprey Optimization Algorithm (OOA

I. INTRODUCTION

Load flow analysis, also referred to as power flow analysis, is one of the most important aspects in the planning, operation, and control of modern power systems. It deals with the study of the steady-state behavior of the electrical network, enabling engineers to determine bus voltages, real (active) power, reactive power, and power flows in transmission lines under given operating conditions. As emphasized by C.L. Wadhwa in Electrical Power Systems, the primary objective of load flow studies is to ensure that electrical energy is transmitted and distributed efficiently, economically, and reliably while maintaining system stability. The analysis involves solving a set of nonlinear algebraic equations that represent the electrical network, including generators, transmission lines, transformers, and loads. To solve these equations, iterative numerical techniques are employed, such as the Gauss-Seidel method, Newton-Raphson method, and the Fast Decoupled Load Flow method. Each method has its advantages: Gauss-Seidel being simple but slower, Newton-Raphson being robust and widely used, and Fast Decoupled offering computational efficiency for large-scale systems. Load flow analysis serves several key purposes: System planning: determining whether the system can handle additional load or new generation. Operational optimization: minimizing transmission losses, improving voltage profiles, and reducing generation costs. Reliability assessment: identifying overloaded lines, voltage instability, or potential weak points in the system. In conclusion, load flow analysis is a fundamental tool in power system engineering, indispensable for ensuring stability, efficiency, and economic operation of electrical networks. As highlighted by C.L. Wadhwa, without proper load flow studies, it is nearly impossible to design or operate power systems that meet the required standards of safety, reliability, and economy.

II. STATE OF ART

A. Voltage Stability :IEEE 39-Bus System

The IEEE 39-bus system, a widely used benchmark in power system studies, has been analysed 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 system. Results show that the system, under typical operating conditions, exhibits stable performance with most transmission lines".

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B. Optimization Algorithms

. 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.FLO is inspired by the hunting and retreat behavior of frilled lizards. It balances exploration and exploitation through adaptive position updates, providing fast convergence and effective global search capability. COA mimics the social hunting and predator-avoidance behavior of coatis. It employs cooperative search strategies and social hierarchy to avoid local minima and improve solution quality. OOA is inspired by the hunting strategy of ospreys, incorporating aerial surveillance for global exploration and precision diving for local exploitation. This dynamic balance enhances convergence speed and solution diversity.

C. Power Flow Studies

Load flow analysis is basically a 'checkup point' of the systems performance. Based on the output result of the analysis, the system is dealt with. Whether to modify the system stability or to resume as it is relying on the Load Flow of the system. Power flow studies, also known as load flow studies, are essential tools in electrical power system engineering [13]. These studies involve numerical analyses of the steady-state operation of interconnected power systems to determine the flow of electric power and current through various components of the network. The primary objectives are to calculate the voltage magnitudes and angles at each bus, assess the power flow through transmission lines, and ensure the system operates efficiently and reliably under different load and generation conditions. [14] By modelling the electrical network, power flow studies help identify potential operational issues such as voltage instability, line overloads, or power losses. These analyses are critical for system planning, optimization, and ensuring the safety and reliability of electricity supply. They also serve as a foundation for more advanced studies like fault analysis and stability assessments Power flow analysis employs mathematical techniques like the Gauss-Seidel method, Newton-Raphson method, and Fast Decoupled Load Flow to solve complex network equations. These studies are indispensable for designing new power systems, integrating renewable energy sources, and improving the operational performance of existing grids. Line Stability Index (LSI) acts as a crucial tool of assessment about the system, particularly the line stability under different operational conditions based on the factors affecting it. Line Stability Index is crucial in detecting the voltage stability instability/collapse by analyzing load carrying capability of the transmission lines keeping in consideration factors such as line impedance, load distribution, PQ loads, etc. LSI supports the dynamic operations of the grid, ensuring the grid system remains in safe voltage limits. The necessity of LSI is seen while incorporating distributed generation in the system as it helps in managing the complexity of the voltage fluctuations and power flow changes. There are various forms of Line Stability Indexes based on the type of system and factors that affects it. The effectiveness of each type depends on the ability to mitigate possible voltage collapse and chart out the power flow fluctuations in the system as distributed energy sources are introduced. Renewable energy being a better energy source in supply as well as eco-friendly nature, is being implemented in generation sectors thus implying the need for a better stable and smoothly running system.

In general terms, the steps for deriving the Line Stability Index of a system are as follows:

1. Model the system: The base model to be operated on is to be modelled according to your need of operation. It includes buses, transformers, generators, transmission lines and loads.
2. Perform Load Flow Analysis: After inserting the necessary data, perform Load Flow Analysis on the system and extract the data needed form it.
3. Choose the Stability Index Formula: Select the appropriate Stability Index for the operating system (FVSI, LVSI) by which it is compatible with. The index to be chosen depends on the system configuration of the operating system and the factors around it.
4. Calculate the LSI: Using the stability index formula chosen, perform the analysis. Calculate for each transmission lines and compare them to the threshold value.
5. Observe the output: Based on the output extracted, the system is to delt with and thus the system is prepared for any possible contingencies.
6. The formula for Line Index is referred from [12] and follows to be:

$$Lmn = \frac{4XQr}{[VsSin(\theta - \delta)]^2}$$

D. Optimization Algorithms For Complex Problem-Solving

Introduction to Optimization Algorithms

Optimization algorithms are mathematical techniques used to identify the best solution from a set of feasible options. Widely applied across disciplines like engineering, economics, operations research, and artificial intelligence. These algorithms aim to improve performance, minimize costs, or maximize efficiency. By iteratively adjusting input parameters, they optimize objective functions to ensure optimal outcomes in complex and dynamic systems. For this particular research the following algorithms were considered

- *Frilled Lizard Optimization Algorithm*
- *Osprey Optimization Algorithm*
- *Caoti Optimization Algorithm*

Frilled Lizard Optimization Algorithm (FLO)

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

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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.

Phase-1: Initialization: A population of N lizard is randomly distributed in the search space. Each lizard's position X_i represents a potential solution:

X_i=[x_i1,x_i2,…,x_iD] (I)

D = Problem dimension

Phase-2: Frill Display (Exploration) Whenever a threat (poor solution) is detected, lizards expand their frills to explore new areas The movement is modelled as:

X_i^new=X_i+∝.(X_rand-X_i)+β(X_best-X_i) (II)

where:

X_rand=Random lizard position (encourages exploration)

X_best=Best solution found so far (abstract others)

∝,β=Random coefficient controlling exploration

Applications:

- Engineering Optimization (Aerospace, Mechanical Design)
- Machine Learning (Hyper parameter Tuning, Neural Network Optimization)
- Economics & Finance (Portfolio Optimization)
- Energy Systems (Renewable Energy Placement)

Coati Optimization Algorithm (COA)

The process of updating the position of coatis (candidate solution) in the COA is based on modelling two natural behaviour of coatis. These behaviours include:

- Coati's strategy when attacking iguanas
- Coati's escape strategy from predators

Accordingly, the COA population (dimension size) is updated in two different phases:

Phase-1: Hunting and attacking strategy on iguana (exploration phase)

- Coatis spread out to explore new areas, mimicking the search for food sources. The position update for the *i*th coati is:

$$X_i^{new} = X_i + r_1.(X_{rand} - X_i) + r_2(X_{best} - X_i)$$

where:

X_{rand} = Randomly selected Coati from the population

X_{best} = Best solution found so far

r_2, r_2 = Random numbers in $[0,1]$ controlliing exploration

Phase-2: The process of escaping from predators (exploitation phase)

- Coatis converge toward promising regions using social hierarchy:

α + β = χ. (1) (1)

$$X_i^{new} = X_i + \beta.(X_{leader} - X_i) + \gamma\ (X_{best} - X_i)$$

where:

X_{leader} = Position of dominant Coati(top solution)

$\boldsymbol{\beta, \gamma}$ **= Exploitation weights(tuned adaptively)**

III . OSPREY OPTIMIZATION ALGORITHM (OOA)

After the text edit has been completed, the paper is ready for the template. Duplicate the template file by using the Save As command, and use the naming convention prescribed by your conference for the name of your paper. In this newly created file, highlight all of the contents and import your prepared text file. You are now ready to style your paper; use the scroll down window on the left of the MS Word Formatting toolbar.

A. The Osprey Optimization Algorithm (OOA) draws inspiration from the distinctive hunting pattern of ospreys (fish-

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eating raptors), which exhibit four key biological strategies translated into mathematical optimization principles. First, their aerial surveillance behaviour - soaring at high altitudes to scan vast areas for prey which in turn is modelled as the algorithm's global exploration phase. Second, the precision diving tactic, where ospreys execute rapid vertical dives to capture targeted fish, corresponds to local exploitation in the algorithm. Third, their energy conservation through adaptive flight patterns informs the algorithm's dynamic balance between exploration and exploitation. Finally, territorial competition among ospreys near abundant food sources is mathematically formulated to maintain population diversity and prevent premature convergence. These biologically observed strategies collectively create an optimization framework that mimics the osprey's efficient hunting approach, where broad environmental scanning gradually transitions to focused, energy-efficient exploitation of optimal regions, while competitive interactions preserve solution diversity throughout the search process. The modelling of OOA usually revolves around Initialization phase, Aerial surveillance (Exploration), Precision Diving (Exploitation).

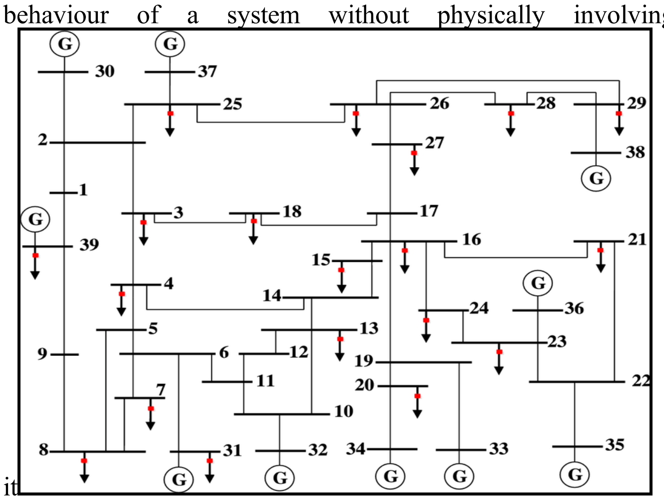
B. Modelling of standard ieee 39-bus test system

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 MATLAB (SIMULINK), etc to chart out the possible characteristics and behaviour of a system without physically involving it



C.Maximum Power Point Tracking (MPPT)

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.

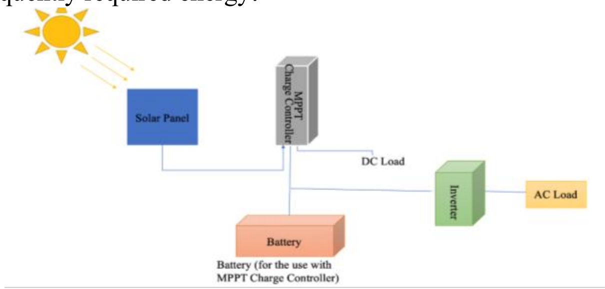


Fig. .1. Block diagram of MPPT algorithm

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

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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

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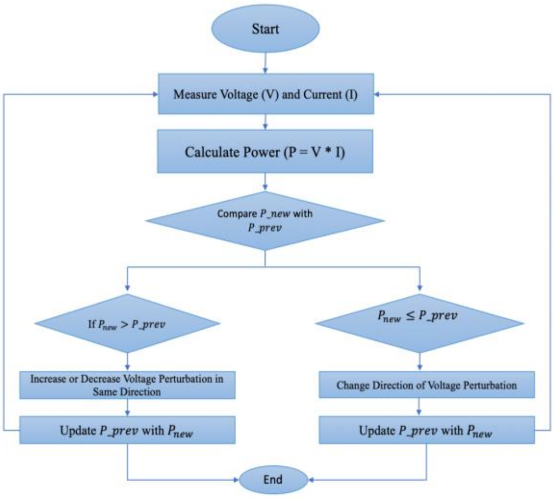
in the same direction; in case the power decreases, the adjustment direction is reversed. This forms an iterative process through which the system converges to the Maximum Power Point (MPP) to provide maximum possible power that the PV system can offer under given environmental conditions



D. 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.[16]

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
21	22	0.0008	0.0140	0.2565
22	23	0.0006	0.0096	0.1846
23	24	0.0022	0.0350	0.3610
25	26	0.0032	0.0323	0.5130
26	27	0.0014	0.0147	0.2396
26	28	0.0043	0.0474	0.7802
26	29	0.0057	0.0625	1.0290
28	29	0.0014	0.0151	0.0249

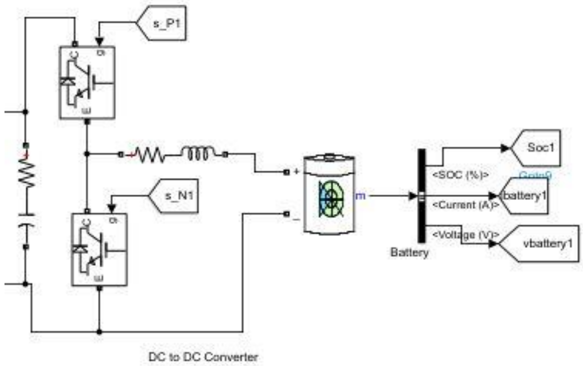


Fig II.. Layout of the battery system implemented
Specifications of IEEE 39 bus system

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

Element name	No of elements
Generators	10
Loads	19
Busbars	39

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	1.760
12	0.075	0.880
15	3.200	1.530
16	3.294	0.323
18	1.580	0.300
20	6.800	1.030
21	2.740	1.150
23	2.475	0.846
24	3.086	-0.922
25	2.240	0.472
26	1.390	0.170
27	2.810	0.755
28	2.060	0.276
29	2.835	0.269
31	0.092	0.046
39	11.04	2.500

Transmission line characteristics of IEEE 39-bus system

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