Volume 11, Issue 2, February – 2026 International Journal of Innovative Science and Research Technology
ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/26feb749

Genetic Algorithm-Based Probabilistic Load Flow Evaluation in Radial Distribution System

W. Ikonwa[1]; E. C. Obuah[2]

[1,2]Electrical Engineering, Rivers State University, Port Harcourt, Nigeria

Publication Date: 2026/02/21

Abstract: The growing adoption of photovoltaic (PV) distributed generation (DG) in Nigerian distribution networks introduces operational uncertainty arising from variable solar irradiance and fluctuating load demand. This work develops a probabilistic assessment framework that combines the Three-Point Estimation Method (3-PEM) with a Genetic Algorithm (GA) to evaluate and optimize PV integration in a radial distribution network. Load and PV uncertainties are incorporated into probabilistic load flow analysis to estimate expected voltage profiles and voltage violation probabilities. The GA is employed to identify optimal PV locations and capacities that enhance voltage stability and reduce network stress. The proposed approach was implemented on the Nigerian 11 kV Ayepe-34 bus radial feeder using MATLAB R2022a. Three PV-DG of size 300kW each was used in the simulation. Gaussian normal distribution was used for the stochastic load variation. The results show that Fixed PV locations were buses 14, 24 and 30. The optimal PV buses using GA were buses 17, 18 and 34. Results indicate that GA-optimized PV placement significantly improves voltage performance and lowers the probability of voltage violations compared to fixed and no-PV scenarios. The framework provides an efficient and practical planning tool for renewable energy deployment in Nigerian distribution systems.

Keywords: *Genetic Algorithm, Three-Point Estimation Method, Distributed Generation, Load Variation.*

How to Cite: W. Ikonwa; E. C. Obuah (2026) Genetic Algorithm-Based Probabilistic Load Flow Evaluation in Radial Distribution System. *International Journal of Innovative Science and Research Technology*, 11(2), 1141-1146. https://doi.org/10.38124/ijisrt/26feb749

I. INTRODUCTION

The integration of photovoltaic (PV) generation into radial distribution networks presents significant challenges due to the stochastic nature of solar irradiance and load demand, which conventional deterministic load flow analysis cannot adequately capture (probabilistic load flow methods have therefore gained prominence). Probabilistic Load Flow (PLF) provides a framework to quantify the uncertainty in system variables such as bus voltages, line flows, and losses by modeling random inputs and computing statistical characteristics of outputs [1].

Among PLF techniques, the Point Estimation Method (PEM) especially Three-Point Estimation Method (3PEM) is recognized for its ability to approximate the probability distributions of output quantities using a minimal number of representative points, thereby reducing the computational intensity associated with Monte Carlo Simulation while maintaining reasonable accuracy [2]. In distribution networks with high PV penetration, 3PEM effectively captures first- and higher-order statistical moments of network responses, enabling planners to assess performance under uncertainty without prohibitive computational costs.

Simultaneously, optimal placement and sizing of PV distributed generation in radial distribution systems is fundamental for improving voltage profiles, reducing real power losses, and enhancing overall system efficiency. Genetic Algorithms (GAs), a class of evolutionary metaheuristic optimization techniques have demonstrated strong capabilities in solving non-linear, multi-objective problems like DG placement due to their robust global search behavior and flexibility in handling complex constraints [4]. Numerous studies apply GA for DG allocation to optimize voltage regulation and loss minimization in radial systems, showing substantial improvements compared with traditional deterministic approaches as shown in ([8], [9]) where SVC, capacitor banks and transformers of higher ratings were used.

The combination of probabilistic load flow using 3PEM with GA-based PV placement is particularly advantageous. This integrated methodology acknowledges the uncertainty in PV output and load demand while simultaneously optimizing PV siting and capacity to achieve overall network performance objectives. By incorporating stochastic modeling into the optimization process, the approach ensures that PV placement decisions remain robust across a range of probable operating conditions, rather than being tuned to a single deterministic scenario a critical consideration as renewable penetration rises in modern distribution networks ([1], [2]).

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/26feb749

Probabilistic Load Flow (PLF) analysis has become increasingly important in modern power systems planning due to the stochastic nature of renewable energy sources like photovoltaic (PV) generation and load demand variability. Traditional deterministic load flow techniques fail to account for uncertainties associated with PV output and demand patterns, which can lead to inaccurate assessments of voltage profiles, line loadings, and power losses in radial distribution networks [1]. PLF methods provide statistical descriptions of system states by modeling random input variables and calculating probabilistic distributions of outputs, thus offering more realistic planning outcomes under uncertainty ([1], [6]).

Among PLF approaches, point estimation methods (PEMs) especially three-point estimation have been widely studied because they significantly reduce computational effort compared to Monte Carlo simulations while still producing accurate estimates of output statistics [4]. PEMs approximate the impact of input uncertainties on network performance by using a small set of representative points that capture the first and higher-order moments of random variables. This method has been applied to probabilistic DG planning and PV hosting capacity studies, demonstrating its utility in capturing uncertainty effects on distribution system states ([1], [4]).

Optimal placement and sizing of PV units are critical for minimizing system losses and improving voltage profiles. Metaheuristic optimization algorithms such as Genetic Algorithms (GAs), Particle Swarm Optimization (PSO), and hybrid methods are frequently used to solve the highly nonlinear and multi-objective allocation problem in radial distribution systems ([3], [5]). These methods systematically search for optimal bus locations and PV capacities that balance loss reduction with voltage regulation constraints, often yielding improved performance over random or heuristic placements ([3], [5]).

Despite advances, many PLF studies focus on test systems or generic network models, with limited work contextualized within actual Nigerian distribution infrastructures, which are characterized by long radial feeders, high R/X ratios, and frequent voltage variability [7]. Although optimization studies exist for Nigerian distribution networks using PSO and GA for DG placement, they rarely integrate probabilistic load flow analysis accounting for uncertainties in PV generation and load demand**.** Most Nigerian studies have focused on deterministic placement or size optimization without incorporating stochastic methods that reflect real-world variability ([5], [7]).

Another emerging trend is the use of correlation modeling in PLF to capture dependency between load and PV generation profiles, which can significantly impact distribution system performance metrics. This has been explored in recent 2025 research, but not specifically applied to Nigerian radial networks with seasonal and diurnal variability patterns [6].

While global literature has applied three-point estimation methods and genetic algorithms to PV placement under uncertainty, there is a distinct lack of studies that integrate a 3-point estimation based probabilistic load flow with GA-optimized PV placement specifically for Nigerian radial distribution networks**.** In particular**,** research that models Nigeria-specific load uncertainty, solar variability, and network topology constraints within a unified probabilistic optimization framework is sparse**,** limiting the practical deployment of PV-DG solutions optimized for Nigeria's operational conditions. This study therefore focuses on probabilistic load flow analysis using 3-point estimation method combined with genetic algorithm optimized photo voltaic placement in Ayepe-34 bus Nigerian radial distribution network.

II. MATERIALS AND METHOD

This study adopts a probabilistic optimization-based methodology to evaluate the impact of photovoltaic (PV) integration in a radial distribution network under uncertainty. The proposed framework integrates Probabilistic Load Flow (PLF) using the Three-Point Estimation Method (3-PEM) with a Genetic Algorithm (GA) for optimal PV placement and sizing. The methodology captures uncertainties in load demand and PV generation while ensuring optimal network performance in terms of voltage profile improvement and power loss minimization. The overall process consists of network modeling, uncertainty modeling, probabilistic load flow formulation, GA-based optimization, and performance evaluation.

➢ *Modeling of the Radial Distribution Network*

The distribution network is modeled as a balanced radial system comprising buses and branches characterized by resistance Rij and reactance Xij. The backward–forward sweep load flow method is adopted due to its suitability for radial networks.

- *The Complex Power Injection at Bus I is Given by:*

$$S_i = P_i + jQ_i$$

Where:

P_i and Q_i represent the net active and reactive power injections at bus I, respectively.

- *Bus Voltages are Updated Iteratively Using:*

$$V_j = V_i - I_{ij}(R_{ij} + jX_{ij})$$

Where I_{ij} is the branch current between buses I and j

➢ *Uncertainty Modeling of Load and PV Generation*

Load demand at each bus is modeled as a random variable following a normal distribution:

$$P_L \sim \mathrm{N}(\mu_L, \sigma_L^2)$$

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/26feb749

$$Q_L = P_L \tan(\cos^{-1}(pf))$$

Where:

μ_L and σ_L are the mean and standard deviation of the load demand, and pf is the power factor.

➢ *PV Generation Uncertainty*

PV output power modeled as a stochastic variable dependent on solar irradiance, commonly approximated using a beta distribution:

$$P_{PV} = P_{PV}^{max} \times \frac{G}{G_{STC}}$$

Where:

P_{PV}^{max} is the rated PV capacity

G is the solar irradiance

G_{STC} is irradiance at standard test condition

➢ *Probabilistic Load Flow Using Three-Point Estimation Method*

The Three-Point Estimation Method approximates the probabilistic behaviour of output variables using three representative points for each uncertain input variable. For a random variable X with mean μX and standard deviation σ_X, the three estimation points are:

$$X_1 = \mu_X$$

$$X_2 = \mu_X + \sqrt{3}\sigma_X$$

$$X_3 = \mu_X - \sqrt{3}\sigma_X$$

- *The Corresponding Weights are:*

$$w_1 = \frac{2}{3}, w_2 = \frac{1}{6}, w_3 = \frac{1}{6}$$

For any output variable Y (e.g., bus voltage or power loss), the expected value and variance are computed as:

$$E[Y] = \sum_{k=1}^{3} w_k Y(X_k)$$

$$Var[Y] = \sum_{k=1}^{3} w_k (Y(X_k) - E[Y])^2$$

➢ *Genetic Algorithm for Optimal PV Placement and Sizing*

- *Objective Function*

The optimization objective is to minimize real power losses and voltage deviation under probabilistic conditions:

$$minF = \alpha \sum_{l=1}^{N_b} P_{loss,l} + \beta \sum_{i=1}^{N} |V_i - V_{ref}|$$

Where:

α and β are weighting factors,

$P_{loss,l}$ is the real power loss in branch l, and

V_{ref} is the reference voltage (1.0 p.u).

- *Constraints*

Voltage constraint:

$$V_{min} \leq V_i \leq V_{max}$$

- *PV Capacity Constraint*:

$$0 \leq P_{PV,i} \leq P_{PV,i}^{max}$$

- *Power Balance Constraint:*

$$P_{G,i} + P_{PV,i} - P_{L,i} = P_{loss,i}$$

➢ *Integration of GA with Probabilistic Load Flow*

Each GA chromosome encodes PV location and size. For each chromosome, PLF is executed using 3-PEM to evaluate the expected system performance. The fitness value is computed using the expected objective function:

$$F_{exp} = E[F]$$

The GA iteratively evolves the population through selection, crossover, and mutation until convergence to the optimal solution.

➢ *Performance Evaluation Indices*

The effectiveness of the proposed method is evaluated using:

- Expected bus voltage magnitude (p.u.) compared with the base case
- Expected voltage instability probability

III. RESULT AND DISCUSSION

The results obtained from probabilistic load flow analysis using the three-point estimation method (3-PEM) for the Ayepe -34 bus radial distribution system are shown below. The impact of photovoltaic distributed generation (PV-DG) on mean bus voltage profile and voltage violation probability were investigated. Three scenarios were considered: no PV integration, fixed PV placement at buses 14, 24, and 30, and GA-optimized PV placement. The minimum voltage limit considered in this study is 0.9p.u. Three PVs of 300kW rating each, were used in this simulation. The GA population size is 60 and the maximum generations is 80. In this study, the active power uncertainty (SigmaP) which represents the standard deviation of the real

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/26feb749

power, is 25, the reactive power uncertainty (SigmaQ) is 5 and the PV uncertainty (SigmaPV) is 40. The GA-based optimization aims to improve the voltage profile and minimize voltage violation probability. The results are presented in terms of bus-wise voltage profiles and voltage violation probabilities, with clear identification of the optimal PV placement.

➢ *Optimal PV Placement*

The genetic algorithm (GA) identified the optimal PV locations as follows:

Table 1 Optimal PV Locations Identified by GA

Scenario	**PV Locations (Bus Numbers)**
GA-Optimized PV	17, 18, 34
Fixed PV	14, 24, 30
No PV	_-

The GA-selected buses correspond to locations with high load demand and low voltage profiles, ensuring maximum impact on voltage stability and loss reduction. The GA optimization effectively redistributes generation closer to critical load points, reducing feeder currents and voltage drops.

➢ *Voltage Profiles*

The mean voltage profile across all buses for the three scenarios is shown in Fig. 1.

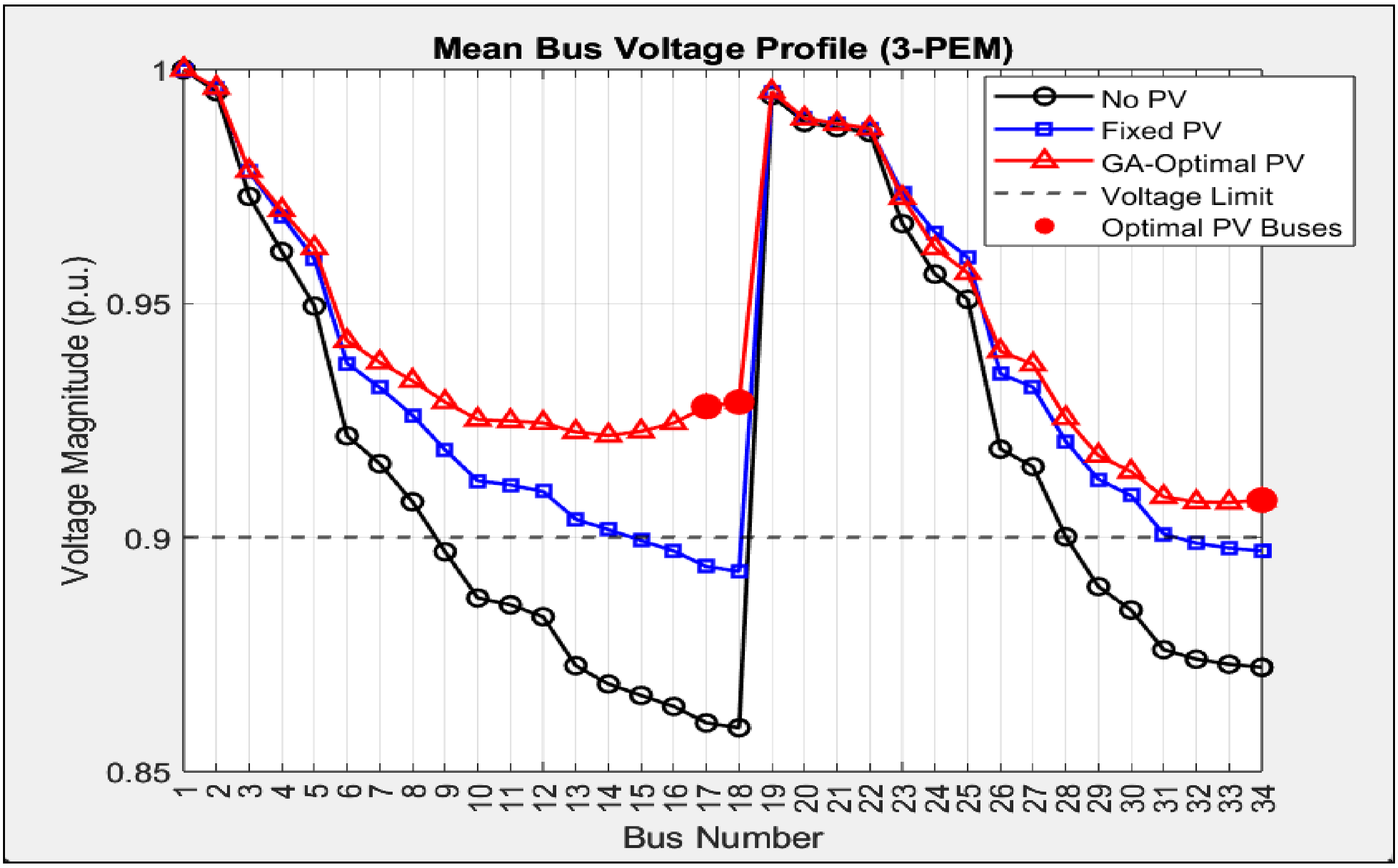

Fig 1 Mean Bus Voltage Profile (3-PEM)

The plot demonstrates that the GA-optimized PV placement maintains bus voltages above the minimum limit of 0.90 p.u., whereas buses 9 – 18 & 29 - 34 experienced under-voltage conditions in the no PV and buses 16 – 18 & 32 – 34 experienced under-voltage conditions in the fixed PV scenarios. All the buses were above the minimum bus voltage limit of 0.9p.u in the GA-optimized PV case. GA-Optimized PV buses; 17, 18 and 34, are highlighted with red markers, clearly showing their contribution to voltage improvement. Without PV integration, buses 17-18 & 34 exhibited the lowest voltages, approaching the 0.90 p.u. limit. Fixed PV placement improves the voltage profile but leaves some buses; 16 – 18 & 32 – 34 still below the limit. GA-optimized PV placement results in a uniformly improved voltage profile across all buses.

➢ *Voltage Violation Probability*

Figure 2 illustrates the bus-wise voltage violation probability calculated using the 3-PEM method for no-PV case, fixed PV case and GA-optimized PV case.

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/26feb749

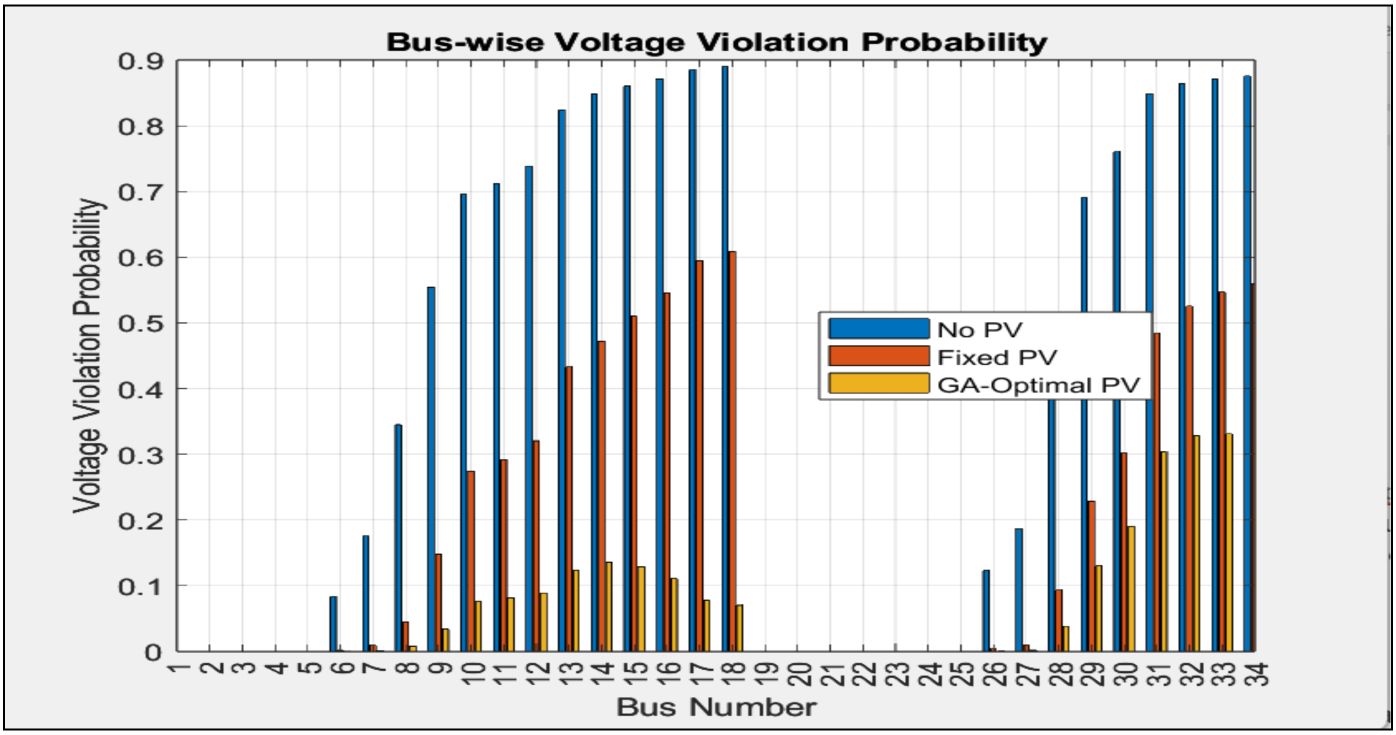

Fig 2 Bus-Wise Voltage Violation Probability

The voltage violation probability quantifies the likelihood that bus voltages fall below 0.90 p.u. under uncertainty in load and PV generation. GA-optimized PV placement significantly reduces the probability of voltage violations across all buses with buses 6 – 9 & 26 – 28 having voltage violation probability less than 0.05 compared to no PV or fixed PV scenarios. Without PV, several buses have violation probabilities exceeding 0.05. Fixed PV placement lowers violation probabilities at buses with PV, but other critical buses still show significant risk. GA-optimized PV placement minimizes voltage violations system-wide, achieving the dual goal of reliability and stability. The GA successfully identifies PV locations that maximize voltage improvement, outperforming fixed PV placements and no-PV case.

IV. CONCLUSION

This study has presented a probabilistic framework that integrates the Three-Point Estimation Method with Genetic Algorithm-based photovoltaic placement for radial distribution networks under uncertainty. Application to the Nigerian 11 kV Ayepe-34 bus feeder demonstrates that optimally placed PV units significantly improve voltage profiles and reduce voltage violation probabilities compared to fixed and no-PV configurations. By explicitly accounting for stochastic variations in load demand and solar generation, the proposed method offers a more realistic assessment of network performance than deterministic approaches. The results confirm that GA-optimized PV placement enhances voltage stability and operational reliability, making the approach suitable for planning and operation of Nigerian distribution networks with increasing renewable energy penetration.

REFERENCES

[1]. A. Abbasi, M. Fotuhi-Firuzabad, and M. Moeini-Aghtaie, "Probabilistic load flow analysis of active distribution networks considering renewable energy sources," Electric Power Systems Research, vol. 223, pp. 109–121, 2023.

[2]. J. Wang, Y. Liu, X. Zhang, and H. Chen, "Probabilistic power flow analysis using point estimation methods for renewable-rich distribution networks," Frontiers in Computer Science, vol. 5, no. 4, pp. 1–12, 2023.

[3]. G.A, Adepoju, A.S.O., Ogunjuyigbe, & T.O. Akinbulire. Optimal placement and sizing of photovoltaic distributed generation in radial distribution networks using metaheuristic optimization techniques, International Journal of Electrical Power & Energy Systems, 147, 108863, 2023.

[4]. S. Hossain, M. A. Mahmud, A. M. T. Oo, and M. J. Hossain, "Genetic algorithm-based optimal placement and sizing of distributed generation in radial distribution systems," Energies, vol. 14, no. 23, pp. 1–20, 2021.

[5]. Y.M., Bulus. Optimization-based allocation of distributed generation for loss minimization and voltage profile improvement in Nigerian distribution networks. Journal of Electrical Systems and Information Technology, 12(1), 1–15, 2025.

[6]. M. Wohlfart, T. Müller, & P. Schneider. Probabilistic load flow analysis of distribution networks under uncertainty. IEEE Transactions on Power Systems, 40(2), 1234–1245, 2025.

[7]. O.C., Eberechi, E. N., Okafor, & C. I., Nwankwo. Probabilistic load flow assessment of Nigerian radial distribution feeders under load and renewable

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/26feb749

generation uncertainties. Electric Power Systems Research, 230, 109904, 2025.

[8]. W. Ikonwa, U. Okogbule, B. Dike, and E. Wodi, “Power flow studies of 132/33/11kV distribution network using Static Var Compensator for Voltage Improvement, International Research Journal of Innovations in Engineering and Technology, Vol. 12, Issue 3, pp. 51-58, 2023

[9]. W. Ikonwa, H. N. Amadi, and U. Okogbule, “Performance evaluation of 11/0.415kV power distribution network, International Research Journal of Innovations in Engineering and Technology, Vol. 7, Issue 4, pp. 25-36, 2023.