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A Systematic Review of Optimal Power Flow Studies with Renewable Energy Sources Penetration

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ABSTRACT

The increasing penetration Renewable Energy Source (RES) in electrical power grid, the power system must minimize costs and comply with operational and safety requirements. Optimal power flow (OPF) contributes to this objective by determining the optimal control settings, satisfying system and safety constraints, and enhancing operational efficiency. A systematic review was conducted to assess how OPF studies have been evaluated in the literature. The review analyzed 64 journal articles to identify specific OPF studies from three perspectives: type of RES penetration, objective function, and method of OPF. The results indicate that (a) wind turbines are the most commonly used RES model in OPF studies, (b) cost function is the primary objective that the majority of research has considered, and (c) novel meta-heuristics have often been used in OPF methods under uncertain RES penetration. This systematic review identifies research gaps and topics for further research to study OPF with RES penetration. The findings are expected to benefit researchers in deciding the best OPF method under uncertain RES.

KEYWORDS: *Optimal Power Flow (OPF), Renewable energy, Power grid.*

1.0 INTRODUCTION

The electrical power is facing the challenge of meeting the growing demand for electricity while reducing carbon emissions. To achieve this, renewable energy sources (RES) must be integrated into the power grid. However, RES has uncertain and variable characteristics that influence the power system dynamics. Therefore, protection measures must be revised to ensure secure operation under uncertainty. The primary objective of a power system is to minimize costs while complying with operational and safety requirements. Optimal power flow (OPF) contributes to this objective by determining the optimal control settings, satisfying system and safety constraints, and enhancing operational efficiency. The OPF problem is non-convex and nonlinear and seeks to minimize fuel costs and power losses in power systems by considering various equality and inequality constraints. However, conventional OPF only considers thermal power plants, which are not environmentally friendly or sustainable for energy generation [1], [2].

Various OPF approaches have been proposed and implemented to optimize the power flow operation in electric power systems in the last two decades. Each approach has a distinct mathematical property and computational demand. The incorporation of RES such as wind energy and solar photovoltaic sources into the system has added to the complexity of OPF and posed a difficult problem for scholars. To achieve a dependable and efficient integration of RES into the electric power grid, the stochastic nature of solar PV and wind energy sources has to be considered [3]. To deal with uncertainty, three key aspects are needed [4]: predictions of unpredictable factors such as the amount of energy from solar and wind sources, or the demand for electricity; strategies for adjusting to errors in predictions; and analysis of how uncertainties affect the system over time and space.

The methods for addressing the Optimal Power Flow (OPF) problem with uncertainty can be grouped into: analytical, approximate, numerical, and meta-heuristic [5]. Meta-heuristic methods, in particular, are optimization techniques that draw inspiration from natural processes or phenomena. Examples of these include genetic algorithms and particle swarm optimization. These methods provide different strategies to address the optimal power flow problem and have demonstrated potential in resolving large-scale, non-linear optimization problems. In recent times, there has been a growing interest in utilizing meta-heuristic methods to address

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the optimal power flow problem.

Meta-heuristic algorithms are such as the Bacteria Foraging Algorithm [6], which draws inspiration from the evolutionary principle of E. coli bacteria residing in the human intestines, and the Flower Pollination Algorithm (FPA), a novel meta-heuristic algorithm inspired by the natural process of flower pollination [7]. In addition, various other meta-heuristic algorithms such as the Grey Wolves Optimizer [8], Particles Swarm Optimization [9], Gravitational Search Algorithm [10], Moth-Flame Optimization [11], a novel Sine-Cosine algorithm [12] and Barnacles Mating Optimizer [13] have also been employed to tackle the optimal power flow problem in various research studies [14] These studies have aimed at optimizing different objective functions, including minimizing the cost of power generation, reducing power loss, and minimizing both cost and emission of power generation. The utilization of meta-heuristic algorithms in addressing the optimal power flow problem has yielded promising outcomes.

This study is designed to conduct a systematic review of Optimal Power Flow (OPF) studies that incorporate renewable energy penetration. The review is structured around the following research questions (RQs): (1) What kind of renewable energy penetration have been implemented in OPF studies?; (2) Which objective functions have been utilized in OPF studies that incorporate renewable energy penetration ? ; (3) Which studies have concentrated on varying objective functions within the context of renewable energy source penetration in OPF studies?

2.0 METHOD

This review employed a systematic and structured approach to literature review, focusing on the topic of optimal power flow with renewable energy penetration. The process was carried out in the following stages:

1. Identification of the topic and search for pertinent studies across comprehensive digital databases.
2. Screened documents to relevant essential studies.
3. Examination of the eligibility of the studies based on predefined criteria.
4. Inclusion of eligible studies for further analysis, synthesis, and description.

This method ensured a thorough and comprehensive exploration of the existing literature on the subject.

The article material was conducted across various databases from scientific journals, specifically articles indexed by SCOPUS, ELSEVIER, DOAJ, and Google Scholar, to identify potentially relevant research. Articles can be selected using the keywords "optimal power flow" and "renewable energy" or "photovoltaic", or "wind turbine" from 2013 to 2023. During the search for articles, filtering was performed in accordance of the criteria specified in the OPF with penetration of renewable energy, which led to the identification of 88 articles. However, after a thorough review of the abstracts and full texts, only 71 articles met the specified criteria, as depicted in Figure 1.

The final step involved carrying out an extraction. This process, which was based on the extraction stages from the original 88 articles, resulted in 64 research studies on OPF with renewable energy source penetration. During the review process, the chosen articles were examined using specific recorded keywords:

(a) authors and publication year
(b) title
(c) OPF method
(d) test system
(e) renewable energy sources
(f) result.

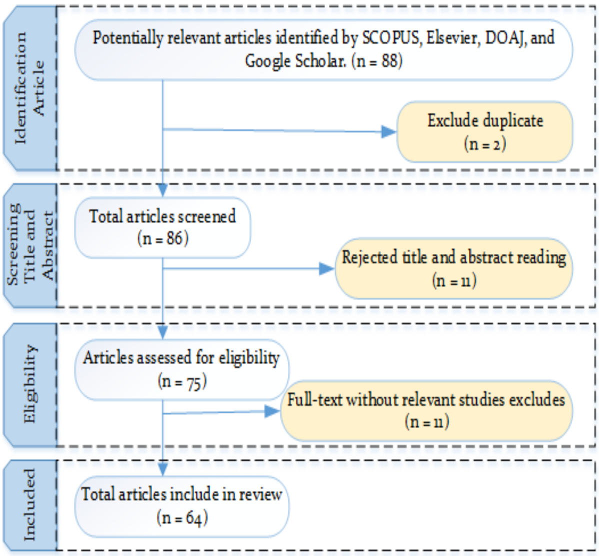

Figure 1: Steps of the systematic review

3.0 RESULT AND DISCUSSION

3.1 Renewable energy source model used for OPF studies

Few studies optimal power flow has been conducting renewable energy penetration to grid. The total model renewable energy as present in Table 1, wind turbines were the most used for 84.38% of the studies. Solar panels and small hydro were also frequently used in the OPF studies, at 79.69% and 15.63% respectively. On the other hand, energy storage and biomass were less common, with their usage in the reviewed studies for renewable energy penetration at 6.25% and 3.13% respectively. Most studies used more than one RES model penetration to grid on OPF studies to find better result of objective function under complexity and uncertain on power system.

Table 1: Renewable Energy model of reviewed studies OPF

RES model	Reference	Number	Percent
Wind Turbine	[2], [3], [5]–[7], [9]–[11], [14]–[59]	54	84.38%
Solar Panel	[2], [3], [5], [7]–[9], [13]–[15], [17]–[34], [36], [40], [42]–[49], [51]–[56], [60]–[67]	51	79.69%
Small Hydro	[2], [6], [7], [23], [24], [29], [32], [34], [40], [45]	10	15.63%
Energy Storage	[16], [23], [60], [61]	4	6.25%
Biomass	[24], [29]	2	3.13%

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3.2 Objective function used for OPF studies

The goal of Optimal Power Flow (OPF) under uncertainty is to find a solution that takes into account the given objective function. Different studies have different objective functions, as presented in Table 2. The cost of a thermal power generation unit can be represented as a quadratic function in relation to the output power of the generator.

$$min\, cost(x,y) = \sum_{i=1}^{NG}(\alpha_i + b_i P_G i + c_i P_{Gi}^2) \quad (1)$$

Where P_{Gi} is active power output of *i* thermal power plant and a,b, and c are the cost coefficient that correlate to the power plant. The following aim function has to be met in order to achieve minimizing the overall active power loss (P_{loss}) in the system, as shown by following expression:

$$min\, P_{Loss}(x,y) = \sum_{i=1}^{NTL}\sum_{\substack{j=1\\ j\neq i}}^{NTL} G_{ij}V_i^2 + B_{ij}V_j^2 - 2V_iV_j cos\delta_{ij}) \quad (2)$$

Service and safety quality might to measure by looking bus voltage. The objective her to reduce of voltage deviation (VD) on load bus, as shown by following expression:

$$Min\, VD(x,y) = \sum_{i=1}^{NL}|V_i - V_i^{ref}| \quad (3)$$

Where V_i is the voltage standard of bus *i*, which is typically 1. p.u and indicates the level of voltage present on bus-*i*. Power plant has runs which fossil fuels are accomplished by the combustion of those fuels. Some objective power flow is to reduce emission prediction of both Nitrogen Oxide (NOx) and Sulfur Oxides (Sox) [20], as shown by following expression;

$$Min\, Emision\,(x,y) = \sum_{i=1}^{NG}(\alpha_i + \beta_i P_{Gi} + \gamma_i P_{Gi}^2 + \xi_i exp\,(\theta_i P_{Gi}) \quad (4)$$

Where α_i (ton/h), β_i (ton/h MW), γ_i (ton/h MW2),ξ_i (ton/h) and θ_i are emission coefficients of *i* power plant. *Min* the field of Optimal Power Flow (OPF) studies, it has been observed that the cost function is the primary objective in a significant majority of the research. Specifically, the main objective of 84.38% of the 64 articles that were reviewed is the consideration of the cost function. Furthermore, the reduction of active power loss and voltage deviation is also frequently examined objectives, with 81.25% and 59.38% of the articles focusing on these aspects respectively. Upon examination of the calculation methods utilized in these studies pertaining to Optimal Power Flow (OPF), it becomes evident that a predominant use of the single-objective approach is observed. This preference is likely due to the increased complexity associated with multi-objective calculations. However, it is imperative to note that despite their complexity, multi-objective calculations are not as widely utilized, even though they generally offer superior efficiency compared to single-objective calculations.

Table 2. Objective function of reviewed studies OPF

Ref	Objective function				
	Total Cost	Total emission	Voltage deviation	Min Active power loss	Min Reactive power loss
[15]	✓	✓	✓	✓	✓
[2]	✓	✓	✓	✓	-
[3]	✓	✓	✓	✓	-
[16]	✓	-	-	✓	-
[17]	✓	✓	✓	✓	✓
[18]	-	-	✓	✓	✓
[19]	✓	✓	✓	✓	✓
[7]	✓	-	✓	✓	✓
[20]	✓	✓	✓	✓	-
[60]	✓	-	-	✓	-
[21]	-	-	✓	✓	✓
[22]	✓	✓	-	-	-
[61]	-	-	✓	-	-
[23]	✓	✓	✓	✓	-
[24]	✓	✓	✓	✓	-
[25]	-	-	✓	✓	✓
[62]	✓	-	-	✓	-
[26]	✓	✓	✓	✓	✓
[27]	✓	-	✓	✓	✓
[28]	✓	-	-	✓	-
[29]	✓	✓	✓	✓	-
[63]	-	-	✓	✓	-
[30]	✓	✓	-	✓	-
[31]	✓	-	✓	✓	✓
[32]	✓	✓	-	✓	-
[64]	✓	✓	✓	✓	✓
[33]	✓	✓	✓	✓	-
[34]	✓	✓	✓	✓	✓
[9]	✓	-	✓	✓	✓
[35]	✓	✓	✓	✓	-
[36]	✓	✓	-	✓	✓
[37]	-	-	✓	✓	✓
[38]	✓	-	-	-	-
[39]	-	-	✓	✓	-
[40]	✓	-	-	✓	-
[41]	✓	-	✓	✓	✓
[11]	✓	-	-	✓	-
[42]	✓	✓	-	-	-
[65]	-	-	✓	✓	-
[43]	✓	✓	✓	✓	-
[44]	✓	✓	✓	✓	
[6]	✓	-	✓	✓	-
[45]	✓	✓	✓	✓	-
[46]	✓	-	-	-	-
[47]	✓	-	✓	✓	✓
[48]	✓	-	-	✓	-
[49]	✓	-	-	✓	-
[5]	✓	-	-	✓	-
[10]	✓	✓	✓	✓	-
[50]	✓	-	✓	✓	-
[51]	✓	-	-	-	-
[66]	✓	✓	-	-	-
[52]	✓	✓	-	✓	-
[13]	✓	✓	✓	✓	-
[14]	✓	✓	-	-	-

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Ref	Objective function				
	Total Cost	Total emission	Voltage deviation	Min Active power loss	Min Reactive power loss
[53]	✓	-	-	-	-
[54]	✓	-	-	✓	-
[8]	✓	✓	-	-	-
[55]	✓	-	✓	✓	-
[67]	✓	-	✓	✓	-
[56]	✓	-	✓	✓	-
[57]	-	-	✓	✓	-
[58]	✓	-	-	✓	-
[59]	✓	-	-	-	-

3.3 Method of OPF Studies on Varying Objective Functions

The Optimal Power Flow (OPF) problem typically presents a challenge due to its non-convex, non-smooth, and non-differentiable objective functions. This necessitates the development of innovative methods to attain the optimal global solution. A significant portion of OPF research involving Renewable Energy Sources (RES) penetration employs meta-heuristic approaches to discover the most effective solution for the objective function.

New meta-heuristic approaches to OPF are often evaluated against methods utilized in prior research for each discovered objective function. Some studies focus on a single objective function, while others explore multiple objective functions of OPF, as detailed in Table 3. This comparative analysis aids in the continuous improvement and refinement of methodologies in this field.

Table 3. Meta-heuristic approach for solving OPF with RES

ref	Purpose studies	Test System	Obj	
			S	M
[15]	Multi Objective thermal exchange optimization (MOTEO)	modified IEEE 30-Bus system	✓	✓
[47]	Fitnes distance balance-based teaching-learning-based artificial bee colony (FDB-TLABC)	modified IEEE 30-Bus system with FACTs	✓	
[3]	hybrid particle swarm gray wolf optimizer (HPS-GWO)	modified IEEE 30-Bus system	✓	
[17]	white shark optimizer (WSO)	modified IEEE 30-Bus system	✓	
[18]	Adaptive lightning attachment procedure optimization (ALAPO)	modified IEEE 57-Bus system	✓	
[19]	Success history based adaptive differential evolution - Superiority of feasible solutions (SHADE -SF)	modified IEEE 30-Bus system	✓	
[7]	flower pollination algorithm (FPA)	modified IEEE 30-Bus system	✓	
[20]	modified turbulent water flow-based optimization (MTFWO)	modified IEEE 30-Bus system	✓	
[60]	novel Differential evolution (NDE) algorithm	Modified IEEE 30 bus system	✓	
[21]	a radial-basis neural network (RBFNN),	Wood and Woollenberg 6-bus system IEEE 14-bus IEEE 118-bus 33-bus Distribution 574-node	✓	
[22]	hybrid modified imperialist competitive algorithm and sequential quadratic programming (HMICA-SQP)	IEEE 30, IEEE 57 and IEEE 118	✓	
[23]	novel manta ray foraging optimization approach based non-dominated sorting strategy (NSMRFO)	modified IEEE 30-Bus system	✓	✓
[24]	Modified JAYA (MJAYA) algorithm: the member with the best fitness value of the objective function is used only to update the values of the remaining members.	IEEE 30-bus system and IEEE 118-bus system.	✓	
[26]	the Fitness–Distance Balance the adaptive guided differential evolution (FDBAGDE) algoritm	modified IEEE 30-Bus system	✓	
[27]	a novel Enhanced Coati Optimization Algorithm (ECOA)	IEEE 57-bus; IEEE 118-bus	✓	
[28]	Artificial Gorilla Troops Optimization (GTO)	IEEE 30-Bus Test System 118-Bus Test System	✓	
[29]	Modified Rao-2	IEEE 30-Bus Test System 118-Bus Test System	✓	
[30]	hybrid imperialist competitive and grey wolf algorithm (HIC-GWA)	IEEE 30-Bus Test System 118-Bus Test System	✓	✓
[32]	multi-objective particle swarm optimization-fuzzy membership function (MOPSO -FMF)	modified IEEE 30-Bus system	✓	✓
[64]	Non-Linear Time-Varying Multi-Objective Particle Swarm Optimization (NLTV-MOPSO)	Modified 33-bus test System	✓	✓
[33]	Point Estimate Method (PEM)	Modified 33-bus test System	✓	✓
[34]	Levy Flight Interior search algorithm (LISA) strategy-II Levy Flight Interior search algorithm (LISA) strategy-I	IEEE 30-bus system, IEEE 118-bus system and real-time electrical network 62-bus Indian system	✓	
[9]	Particle swarm optimization (PSO)	modified IEEE 30-Bus system	✓	
[35]	Mayfly algorithm.	modified IEEE 30-Bus system	✓	✓
[36]	evolutionary algorithm GWO	modified IEEE 30, IEEE 57	✓	✓
[40]	Flow direction algorithm	IEEE 30-Bus Test System,	✓	✓

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ref	Purpose studies	Test System	Obj S	Obj M
[11]	hybrid GBO-MFO	IEEE 57-Bus Test System, IEEE 118-Bus Test System modified IEEE 30-Bus system with FACTs	✓	✓
[42]	a parallel epsilon-variable multi-objective genetic algorithm (Pεv-MOGA)	IEEE 30-Bus Test System, IEEE 57-Bus Test System, IEEE 118-Bus Test System	✓	✓
[43]	Golden Ratio Optimization Method (GROM)	modified IEEE 30-Bus system	✓	✓
[44]	Equilibrium optimizer algorithm (EO)	modified IEEE 30-Bus system	✓	
[6]	Modified Bacteria foraging algorithm (MBFA)	modified IEEE 30-Bus system	✓	✓
[45]	Moth Flame Optimisation (MFO) dan Multi-Objective Moth Flame Optimisation (MOMFO)	modified IEEE 30-Bus system	✓	✓
[47]	hybrid algorithm by combining the exploration capability of differential evolution and exploitation capability of symbiotic organisms search (HSOS)	modified IEEE 30-Bus system	✓	
[48]	Heap optimization algorithm (HOA)	IEEE 30-Bus Test System, IEEE 57-Bus Test System, IEEE 118-Bus Test System	✓	
[49]	harrishawks optimization (HHO)	IEEE 57-Bus Test System, IEEE 118-Bus Test System	✓	
[5]	circle search algorithm (CSA)	IEEE 57-Bus Test System, IEEE 118-Bus Test System	✓	
[10]	hybrid approach MSA–GSA	IEEE 30-Bus Test System, IEEE 57-Bus Test System, IEEE 118-Bus Test System	✓	
[50]	Hybrid Dragonfly Algorithm - Aging Particle Swarm Optimization (DA-APSO)	modified IEEE 30-Bus system	✓	
[66]	Improved Salp Swarm Algorithm (iSSA)	modified IEEE 30-Bus system	✓	
[52]	to assess the performance of these selected metaheuristic algorithms on OPF	modified IEEE 30-Bus system	✓	
[13]	barnacles mating optimizer (BMO)	modified IEEE 30-Bus system	✓	
[14]	Teaching–Learning-Based Optimization (TLBO)	modified IEEE 30-Bus system	✓	
[8]	Grey Wolves Optimizer (GWO)	modified IEEE 30-Bus system	✓	
[55]	The hybrid PPSOGSA algorithm is a combination of phasor particle swarm optimization (PPSO) and gravitational search algorithm (GSA).	modified IEEE 30-Bus system	✓	
[67]	CUCKOO search optimization algorithm	IEEE 123 nodes test	✓	

*Objective function: Single (S), Multi (M)

In addressing the Optimal Power Flow (OPF) problem with Renewable Energy Sources (RES) penetration, several studies have employed not only metaheuristic approaches but also analytical and numerical methods based on deterministic mathematical models, as shown on table 4. These models consider input variables, such as power demand and power injection from renewable generation units, as deterministic variables. However, in real network scenarios, variables like voltages, currents, power flow, and power losses are subject to uncertainties [25]. These uncertainties can arise from various factors, including: 1) Errors in forecasting demand and power generation; 2) Calculation and measurement errors of electrical parameters; 3) Unplanned interruptions; 4) Imbalances in phase loading; 5) Volatility in fuel prices for thermoelectric generators.; 6) Uncertainty in weather conditions affecting hydroelectric generators; 7) Uncertainty in power injection from renewable energy sources.; 8) Fluctuations in electricity prices. These factors highlight the complexity of the OPF problem and the need for robust and adaptable solutions.

Tabel 4. Analytics and numbering approach for solving OPF with RES

Ref	Purpose studies	Test System
[16]	Chance-constrained a second-order cone problem (CC-SOCP)	IEEE 5 bus IEEE 39 bus IEEE 57 bus
[61]	Convex reformulation is developed by resorting to suitable linear approximations of the AC power-flow equations as well as convex approximations of the chance constraints	IEEE 37-node test
[25]	Fast-specialized point estimate method	IEEE 69-bus ; real 202-bus EDS.
[62]	A multi period stochastic optimization method	IEEE 37 nodes distribution circuit
[63]	Semi-definite programming	a radial 15 bus
[31]	A three-stage framework for parallel processing real-time optimal power flow	IEEE 14-bus, 57-bus, 118-bus, and 300-bus
[37]	Distributed and parallel OPF and compared with centralize OPF	26-bus test system
[38]	A distributionally-robust chance constrained optimal power flow	2209 buses and 176 controllable generator
[39]	The evidence theory (ET) and affine arithmetic (AA)	modified IEEE 30-Bus system; real 183 buses with 308 branches, and 30 conventional generation units.
[41]	A framework for real-time optimal power flow (RT-OPF) is used to compute optimal operation strategies for distribution networks (DNs) under wind energy penetration	A 41-bus medium-voltage
[65]	An OPF algorithm is implemented using the predictor-corrector primal-	IEEE 34-bus and EPRI Circuit-5

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Ref	Purpose studies	Test System
	dual interior point method (PCPDIPM)	2998 bus systems
[46]	Mean adjustment cost is calculated considering day-ahead schedule and various probabilistic real-time operating scenarios.	modified IEEE 30-Bus system
[51]	A novel Alternating direction method of multipliers (ADMM)-based Distributed model predictive control (DMPC) algorithm	Three subsystems in a simplified IEEE-123 test feeder.
[54]	A novel hybrid machine learning algorithm: P-ELM to forecast wind and solar powers,	Andhra Pradesh—14-bus system and a 124-bus Indian utility real time system (IND-124).
[56]	Interval optimal power flow (IOPF) is a model that computes optimal operation strategies for distribution networks (DNs) under wind energy penetration.	PEGASE 13,659-bus system
[57]	A probabilistic optimal power flow (POPF) technique based on the quasi-Monte Carlo simulation (QMCS) considering the correlation of wind speeds using copula functions.	modified IEEE 118-Bus system
[58]	The constraints in the traditional OPF formulation are modified with robust constraints, which are deduced from probabilistic power flow (P-PF) formulation and Taguchi's Orthogonal Array Testing (TOAT).	IEEE 14-Bus System; IEEE 118-Bus System; 2736-BUS SYSTEM
[59]	A single-period chance constrained optimal power flow (CC-OPF) with uncertain reserves from loads using distributionally robust (DR) optimization and two different ambiguity sets	IEEE 9-bus, 39-bus, and 118-bus systems
[53]	The evaluation of 'best-fit' participation factors by taking into account the minute-to-minute variability of solar, wind and load demand for Real Time-OPF (RT-OPF0, and every 15 min variability for Day-Ahead-OPF(DA-OPF), over a scheduling period.	modified IEEE 30-Bus system

This systematic review aims to evaluate the Optimal Power Flow (OPF) approach within the context of power systems that have a high penetration of Renewable Energy Sources (RES). The goal is to identify the methods that researchers have discussed and to pinpoint the gaps in current research. Despite the limited number of studies reviewed, this paper enhances our understanding of OPF in the context of renewable energy integration under real power system conditions. The results indicate that the majority of OPF studies focus on the integration of wind turbines and solar panels. Numerous topics within the reviewed literature remain open and continue to pique the interest of researchers, while many others point towards potential future avenues of study. The authors provide their perspective on how the operations research community can optimally contribute to the advancement of OPF applications with RES penetration. They highlight several promising results from various studies, which include:

- The development and enhancement of meta-heuristic algorithms.
- The introduction of a new model for RES.
- The effective modeling of uncertainty within diverse OPF contexts.
- The integration of power system management and security.

These elements collectively represent the authors' belief in the potential for significant contributions to this field. This statement is unambiguous and provides a clear overview of the systematic review's aims, findings, and implications for future research.

4.0 CONCLUSION

This systematic review evaluated studies on Optimal Power Flow (OPF) with Renewable Energy Sources (RES) penetration. It identified existing research gaps and suggested areas for further investigation, particularly in relation to novel OPF studies that offer more efficient and faster calculations. The majority of Optimal Power Flow (OPF) studies, within the context of uncertain Renewable Energy Sources (RES), primarily focus on heuristic approaches. In summary, OPF studies were used for single or multi-objective optimization and can apply to all RES models. The cost function is the primary objective that the majority of research has considered, especially for wind turbines and solar panels.

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