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Applications of Flower Pollination Algorithm in Electrical Power Systems: A Review

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ABSTRACT The use of metaheuristic, nature inspired algorithms for solving complex optimization problems with non-linearity and multimodality, has become a popular tool in the field of science and engineering. Presently, there has been much development of such tools, with academics creating new nature-inspired algorithms that could potentially be more efficient and effective. One such algorithm is the Flower Pollination Algorithm (FPA) developed by Xin-She Yang in 2012. This metaheuristic algorithm is modelled after the evolutionary process of flowering plants and has been useful in many fields of science and engineering, particularly in electrical power systems. With the rapid expansion of industries and population growth, engineers are faced with the arduous task of satisfying the growing electrical demand. To improve electrical power systems and reduce running costs, FPA and its variants have been implemented to determine optimal solutions to complex combinatorial optimization problems, with little computational effort, and has proven to be more effective than other popular metaheuristic algorithms, such as Particle Swarm Optimization (PSO) and Genetic Algorithm (GA). Owing to its balanced global and local search capabilities, and better convergence characteristics, numerous studies have been conducted to utilize FPA and its variants in real-world optimization problems. Thus, this paper aims to provide a comprehensive review of FPA and its variants to successfully determine optimal results to non-deterministic polynomial-time hard problems in electrical power systems and other fields of science. To accomplish this, an in-depth description of FPA and its parameters that influence its performance are discussed, including the various modifications and hybridizations of the algorithm. In addition, an in-depth review of applications using FPA and its variants in electrical power systems and other fields of science, is provided.

INDEX TERMS Optimization, algorithms, flower pollination algorithm, genetic algorithms, metaheuristic algorithm, particle swarm optimization, non-deterministic polynomial-time.

ABBREVIATIONS

ABC	Artificial Bee Colony
APP	Antennae Positioning Problem
BCFA	Binary Control Flow Analysis
BCFPA	Binary Clonal Flower Pollination Algorithm
BFA	Bacteria Forging Algorithm
BFPA	Binary Flower Pollination Algorithm
BeFPA	Bee Flower Pollination Algorithm
BPSO	Binary Particle Swarm Optimization
BMCFPA	Binary Modified Chaos Flower Pollination Algorithm
CHAOS-MFPA	Chaos Modified Flower Pollination Algorithm
CM	Congestion Management
CE	Cross Entropy
CSA	Clonal Selection Algorithm
DE	Differential Evolution
DG	Distribution Generation
DNR	Distribution Network Reconfiguration
DynDE	Dynamic Differential Evolution
EDP	Economic Dispatch Problem
EEG	Electroencephalogram
EOFPA	Elite Opposition-Based Flower Pollination Algorithm
FF	Feedforward
FACTS	Flexible AC Transmission System
FPA	Flower Pollination Algorithm
FOPID	Fractional Order Proportional Integral Derivative
FVSI	Fast Voltage Stability Index

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GM	Gradient Method
GWO	Grey Wolf Optimizer
GA	Genetic Algorithm
GMPP	Global Maximum Power Point
GMPT	Global Maximum Power Point Tracking
HAS	Harmony Search Algorithm
HFPGA	Hybrid Flower Pollination and Genetic
HFPGA	Hybrid Flower Pollination and Genetic Algorithm
IC	Incremental Conductance
ICT	Information and Communication Technologies
ISO	Independent System Operator
LBI	Load Balancing Index
IFPA	Improved Flower Pollination Algorithm
MFPA	Modified Flower Pollination Algorithm
MO-FPA	Multi-Objective Flower Pollination Algorithm
MPPT	Maximum Power Point Tracking
MSR	Multi-Scale Retinex
NFL	No Free Lunch
NRTL	Non-Random Two-Liquid
OPF	Optimal Power Flow
PDF	Probability Density Function
PI	Proportional, Integral
PID	Proportional, Integrate and Derivative
PSNR	Peak to Signal-to-Noise Ratio
PSO	Particle Swarm Optimization
P & O	Perturb and Observe
QAP	Quality Assurance Plan
RMSE	Root Mean Square Error
RSM	Response Surface Methodology
SA	Simulated Annealing
SD	Standard Deviation
SSR	Single Scale Retinex
SNP	Single nucleotide polymorphism
SVC	Static Var Compensator
SVM	Support Vector Machine
TCSC	Thyristor Controlled Series Capacitor
UNIQUAC	Universal Quasi-chemical
WEC	Wave Energy Converter
WEDM	Wire-Cut Electrical Discharge Machining

I. INTRODUCTION

In many engineering and industrial design applications, there is a great need to find optimal solutions to complex problems under difficult constraints. These constrained optimization problems are often highly non-linear and so, finding optimal solutions is a difficult challenge as conventional optimization techniques are inefficient in solving problems with non-linearity and multi-modality [1]–[4]. As such, meta-heuristic algorithms are chosen to solve these types of problems. These algorithms are modelled after successful processes in nature, which have been solving difficult problems for billions of years to achieve certain evolutionary goals. The efficacy of meta-heuristic algorithms depends on their use of explorative and exploitative ranges across a search space [5], [6]. The explorative phase of these algorithms involves either a local or global search mechanism and forms the basis for convergence to an optimal solution, with the exploitation process focused on using the information obtained from past iterations to guide the search towards the optimal solution [5], [6]. Xin-She Yang [1] proposed a new population-based meta-heuristic algorithm, known as the Flower Pollination Algorithm (FPA). This algorithm imitates the process of flower pollination to solve optimization problems and is proven to perform better than other more popular algorithms such as Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) [1], [7], [8]. The unique benefit of FPA is its ability to employ both long-distance pollinators and flower consistency (both global and local search) to achieve a balance between exploitative and explorative ranges modality [1], [2]. The interaction of these ranges, as well as its commendable convergence characteristics, contributes to the efficiency of the algorithm. The unique local/global search traits (whilst maintaining an exceptional convergence rate) which FPA's possesses has allowed it to make a seeming less transition into numerous fields and provide optimal solutions with minimal drawbacks [1], [7], [8]. Electrical power systems play an important role in modern society, as it provides the consistent and efficient supply of electricity, which is vital to the functioning of our civilization [3]. However, this field is plagued by various issues such as economic and emission dispatch, low renewable energy generation efficiency, poorly optimized distribution systems, and solving problems related to energy transmission, which include power flow, power loss and congestion management [9]–[13]. Various reviews have been carried out which investigate FPA techniques in various optimization fields. The authors in [14] provide a review of the engineering applications of FPA and its variants which include chemical engineering, civil engineering, energy and electrical power systems, mechanical engineering, electronic and communication engineering, computer science and others; however, the focus is not on the various types of modifications and hybridizations of FPA. A further review into the applications and variants of FPA is provided in [15]. Although various variants of FPA are mentioned, very little focus is given to the applications of FPA to solve real world complex problems. The distribution of published research on FPA from a variety of publishers, including IEEE, SpringerLink, and others, was determined in and displayed in Figure 1, which depicts the use of FPA and its variants in the fields of engineering and optimization.

Despite, the extensive research conducted on the use of FPA and its variants in optimization and engineering, a review which comprehensively discusses the problems faced in electrical power systems, has not been presented. As such, this paper aims to provide a comprehensive review of applications using FPA to successfully determine optimal results to non-deterministic polynomial-time hard problems in electrical power systems and an overall summary of FPA, including its characteristics, modifications, hybridizations, and applications in other fields of engineering.

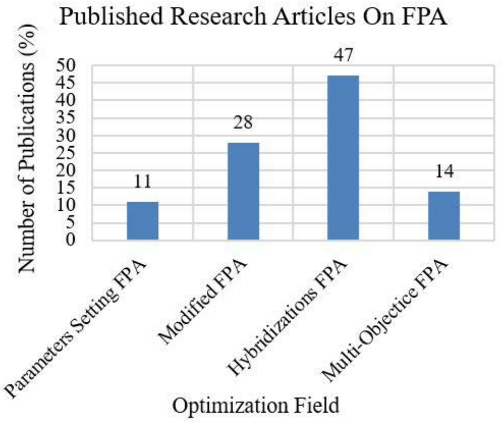

FIGURE 1. Distribution of published research on FPA [16].

Hence, this paper is organized in the following manner. Section II presents a brief overview of optimization algorithms. Section III of this paper introduces the concept of FPA and its parameters. Section IV describes the various types of modifications of FPA. Section V describes the hybridizations of FPA. Section VI-X presents the review of FPA in electrical power systems and other fields of science. Section XI discusses the distribution of published research in each of the fields mentioned in the review section and provides an analysis of FPA's performance in power systems. Finally, section XII concludes the paper.

II. BACKGROUND INTO OPTIMISATION ALGORITHMS

A. OPTIMIZATION PROBLEMS AND SEARCH TECHNIQUES

Throughout history, mankind has encountered many problems that require sophisticated methods or techniques to determine a solution. These problems, and the techniques developed to solve these problems, can date back as far as 2200 years ago when Archimedes utilized the method of exhaustion to compute the area inside a circle and developed the principle of buoyancy that is pivotal to fluid mechanics [17], [18]. As civilizations continued to evolve, standard approaches and methods to solving common problems were established. However, some methods cannot be applied to every problem and therefore, require new techniques that can be applied practically to provide a feasible result within a reasonable time frame. One such case is with regards to optimization, in which the aim is to determine the best solution from all possible outcomes to conserve resources or reduce costs [7], [8]. Some of the earliest well-defined procedures for determining optimum solutions come from conventional-based approaches. Presently, combinatorial optimization problems have become far too complex for such methods (e.g., calculus and linear programming) to solve efficiently [1], [6]. Thus, the need for non-conventional techniques such as heuristics and meta-heuristics has grown. While early forms of problem-solving may have existed in the form of heuristics and meta-heuristics (trial and error) as in the case of Archimedes method of exhaustion, the recent development into these forms of non-conventional approaches and their application to real-world problems has been widely observed [17], [18]. Figure 2 illustrates the various solution search techniques developed over the years.

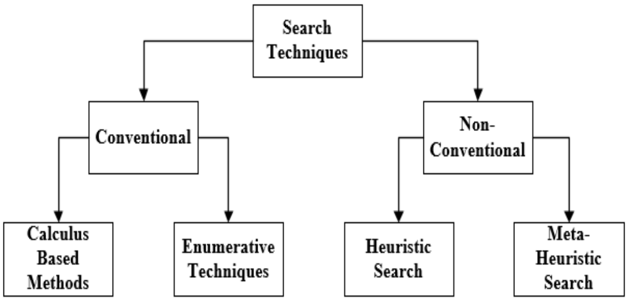

FIGURE 2. Search techniques used to solve optimization problems [17], [18].

B. NON-CONVENTIONAL SEARCH TECHNIQUES

In recent years, non-conventional search techniques have become popular for obtaining feasible solutions in polynomial time, as conventional optimization techniques are challenged by non-linearity and may be trapped in the local optimum [1], [19]. To address the challenge of non-linearity and multi-modality of optimization problems, approximate algorithms can be used instead. More specifically, one may use heuristics or meta-heuristics to determine optimal solutions with greater efficiency and without the search being trapped in the local optimum. Heuristics, like approximate algorithms, generate near-optimal solutions for non-deterministic polynomial-time hard problems (NP-hard) through trial and error [19]–[21]. However, unlike approximate algorithms, these algorithms have no known proof of their correctness and could potentially generate solutions that are unfeasible [6], [18], [21], [22]. It is, therefore, risky to apply such algorithms with loosely defined rules to optimization problems. However, they have proven useful for problems that do not have a known solution method or formulation [8], [20]. Heuristics can be an alternate method to exact solution methods that would otherwise be computationally intensive and are developed to address specific problems in optimization [20], [21]. In contrast to heuristic algorithms, metaheuristics are strategic problem-solving frameworks that guide underlying problem-specific heuristics to improve their performance by effectively combining exploration of a solution search space and basic heuristic methods in higher-level structures aimed at efficiency and can be modified to solve an array of optimization problems with little computational time [6], [21]. An important attribute of meta-heuristics that set it apart from other algorithms is the dynamic balance between exploration and exploitation of the solution search space, in which a good balance between these two characteristics results in efficient performance [6], [18]. However, like heuristics, there is no guarantee that an algorithm will work, though there are many meta-heuristic algorithms that have been successfully utilized in optimization. Some of these include Particle Swarm Optimization (PSO) [22], Simulated Annealing (SA) [23] and Genetic Algorithm (GA) [19]. With regards to the comparison of their performance to each other, there exists No Free Lunch (NFL) theorems in the field of optimization which imply that there is no universally better algorithm with regards to optimization problem solving, and one may either select an algorithm that is most suitable for a given problem or develop improved algorithms that solve most types of problems [18], [24]. This choice can be made based on comparative studies of algorithms in application, which evaluate an algorithms performance in a particular category of problems and compare the result with other popular algorithms used for the same problem. There are a variety of algorithms to choose from in the category of meta-heuristics, however, nature-inspired meta-heuristics have become powerful tools for optimization, especially NP-hard problems [1], [6].

III. THE FLOWER POLLINATION ALGORITHM

The Flower Pollination Algorithm (FPA), implemented by Xin-She Yang in 2012 [25], is an evolutionary, meta-heuristic algorithm inspired by the natural process of flowering plant pollination. The flow chart for FPA is shown in figure 3. The flower pollination process aims to transfer pollen between the same or different plant species for reproductive purposes [1], [7], [27], [28]. FPA focuses on the pollination process and aims to mimic its movements to produce an efficient and optimum system. Pollination occurs via two primary methods with the first being local pollination which consists of pollen from the same flower or different flowers from the same plant [1], [7], [27], [28]. Global pollination occurs when pollen from flowers of different plant species is involved. Global pollination occurs at long distances and requires pollinators to travel large regions over which this phenomenon occurs [1], [7], [27], [28]. The modelling of biological processes and algorithms requires complex variables to be considered. Simplification of biological processes is required to model the algorithm mathematically and form an algorithm. The FPA simplifies the natural flower pollination process into four idealized characteristics. The first rule being the global pollination rule, which is modelled after the natural global pollination process which consists of living organism and cross-pollination, with pollinators such as birds, bees etc. performing Lévy flights. The rule can be expressed as the phase that replicates global search through the solution search space in terms of Lévy flights [1], [7], [27], [28]. Pollination within the same flower (known as abiotic pollination) can be classed as local pollination, which can be demonstrated at the exploitation stage [1], [7], [27], [28]. This guides the search towards a better solution and is governed by the local pollination rule [1], [7], [27], [28]. The reproductive probability refers to flower consistency and is proportional to the degree of similarity between the flowers involved. This is governed by the reproduction probability rule, which imitates flower consistency behavior which replicates pollinators tendencies to fecundate certain flowers [1], [7], [27], [28]. The switch probability rule functions as an operator that regulates the switching process between global and local pollination. The switching probability (p) is defined as p ∈ [0, 1] [1], [7], [27], [28].

A. GLOBAL POLLINATION THROUGH LEVY FLIGHTS

To emulate the global pollination process, it is stated that each plant contains one flower, and each flower produces one pollen gamete [1], [7], [27], [28]. A solution x_i is equivalent to a single flower [1], [7], [27], [28]. In global pollination, the pollen traverses a long distance through pollinators. Lévy flight distribution is followed and used to determine the path taken by the pollinators. Lévy Flights, by definition, are Markovian Stochastic processes, whose individual jumps have lengths that are governed by the probability density function (PDF), decaying at a large distance [29]–[31]:

$$\lambda\left(\mathrm{x}\right) \approx |x|^{-1-\alpha} \tag{1}$$

where: $0 < \alpha < 2$.

Due to the deviation of their variance, long jumps occur on all scales showing groups of shorter jumps scattered by long excursions on all levels [29]–[31]. Lévy Flight distributions represent the limit distributions of random variables with diverging variance [29]–[31]. Thus, Lévy Flights are used to update the pollen as they can mimic the random path taken by pollinators in nature (during the global pollination method), this is expressed mathematically by [1], [7], [27], [28]:

$$x_i^{t+1} = x_i^t + L\left(x_i^t - g_*\right) \tag{2}$$

This uses the variable x_i to represents a single gamete [26]–[28]. The variable g_* represents the fittest gamete which is transported through global pollination [29]–[31]. t represents the current iteration and L denotes the step size corresponding to the strength of the pollination. L is drawn from the Lévy flight distribution and can be expressed as [1], [7], [27], [28]:

$$L \sim \frac{(\beta+1) \times sin\left(\frac{\beta\pi}{2}\right)}{\pi} \times \frac{1}{s^{\beta+1}}, \quad (s \gg s_o > 0) \tag{3}$$

β is the gamma function, which is initially selected before implementation [29]–[31]. The Levy distribution is valid for large steps where s > 0, this is used to emulate the steps taken within a global pollination process in nature [29]–[31].

B. LOCAL POLLINATION CONSIDERING FLOWER CONSTANCY

If a selected value is less than the switch probability P, the resulting type of pollination that occurs is local [1], [7], [27], [28]. This uses flower consistency within a small region to decrease the exploitation time and is shown by the following equation [26]–[28]:

$$x_i^{t+1} = x_i^t + \epsilon\left(x_j^t - x_k^t\right) \tag{4}$$

In this equation x_j^t and x_k^t represent individual gametes from plants at different locations. This indicates a local random walk if ϵ is drawn from a uniform distribution (0, 1) [1], [7], [27], [28]. Rule 4 (switch probability) is used to switch between local and global pollination, since flowers in nature may not occur far away from each other and are more likely to be pollenated by local gametes [1], [7], [27], [28].

C. ELITIST SELECTION

The candidate solution x_i^{t+1}, is obtained through either global or local pollination and compared with past solutions of x_i^t. If the fitness value of x_i^{t+1} is greater than previous x_i^t, it replaces the past solution otherwise the initial x_i^t remains in the population. This elitist selection operation can be represented by [1], [7], [27], [28]:

$$x_i^{t+1} = \begin{pmatrix} x_i^{t+1}, & if\ j\left(x_i^{t+1}\right) < j\left(x_i^t\right) \\ x_i^t, & else\ j\left(x_i^{t+1}\right) \geq j\left(x_i^t\right) \end{pmatrix} \tag{5}$$

The FPA can also be represented as a flow diagram [1], [7], [27], [28].

IV. MODIFICATIONS TO THE FLOWER POLLINATION ALGORITHM

The characteristics of FPA can be improved through modification. The nature of FPA allows it to be open to various enhancements and as such this section highlights the various modifications of FPA and their applications in many fields.

A. MODIFIED FLOWER POLLINATION ALGORITHM BASED ON OPERATORS (MFPA)

FPA determines new solutions based on either local or global pollination, which are the algorithm's core operators. FPA can easily be used to solve low-dimensional unimodal optimization problems but falls short in handling multi-modal optimization problems. To solve this issue, operators may be modified to produce an optimum solution. Yamany *et al.* [28] proposed a mutation to enhance the solution diversity of the basic FPA. The modification is expressed mathematically in [28] and allows for more efficient handling of large search spaces. The MFPA was tested against datasets in [28], and was compared to GA and PSO. The results in [28] demonstrate that MFPA operates more efficiently than GA and PSO and produces better quality solutions. Multi-level image thresholding is a crucial aspect required for image segmentation, with traditional methods being deemed highly costly due to the large amount of computational memory required for the Exhausting Search (ES) strategy [29]. Shen *et al.* [29] modified FPA by enhancing both the local and global pollination aspects to improve the exploration capabilities of the algorithm [29]. The modified flower pollination algorithm (MFPA) was tested by using a combination of real-life images and datasets shown in [29]. MFPA provided the greatest optimization and image quality and was compared to five other metaheuristic algorithms, including FPA, PSO, Cross Entropy (CE) [29]. In the field of renewable energy, development of accurate PV cell models is essential for efficient optimization but is difficult due to the non-linear characteristics of PV cells, which make accurate estimation of parameters, challenging [33]–[35]. Khursheed *et al.* [30] proposed a modification to FPA which doubled the base switch probability and added a dynamic step size function. The MFPA was applied to solve the non-linear optimization problem challenging PV cells and was tested on both single and double diode PV models. The tests in [30] found that the MFPA exhibited an increased convergence rate as compared to the standard FPA but lacked accuracy in single diode PV model test [30]. The use of super alloys in industrial processes has exponentially risen over the last decade, however the machining of these alloys with conventional processes is extremely difficult [31], [32]. Rao *et al.* [31] proposed MFPA to optimize the wire electrical discharge machining technique to process these alloys. The MFPA implemented in [31] aimed to use a two-stage initialization process to increase the speed and accuracy of the standard FPA [31]. The MFPA was tested using standard benchmark WEDM data against the standard FPA and Response Surface Methodology (RSM) methods and was found to outperform the algorithm in comparison and produce satisfactory results.

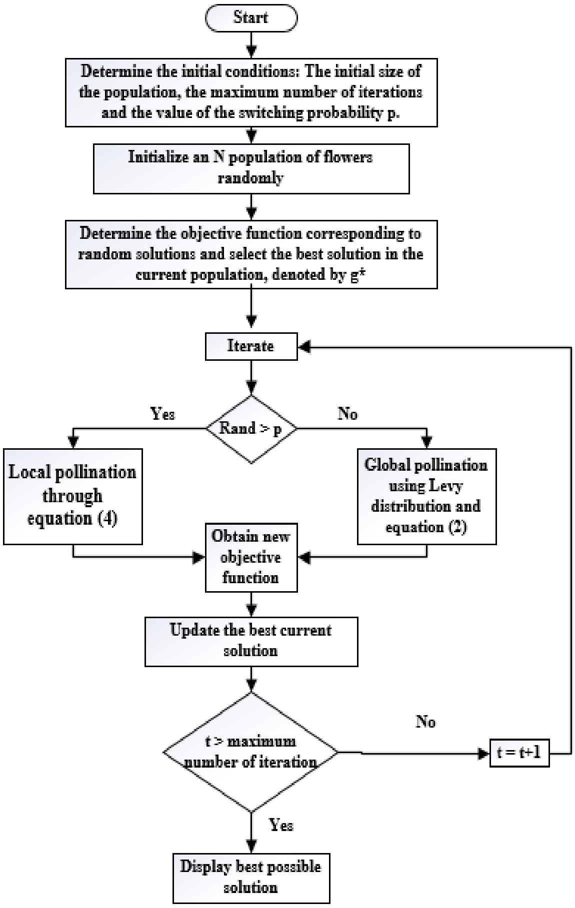

FIGURE 3. Flowchart of FPA algorithm [7], [27], [28].

B. THE ELITE OPPOSITION-BASED FLOWER POLLINATION ALGORITHM (EOFPA)

The MFPA presented in Yamany *et al.* report [28], produced satisfactory results, however the validity of the modifications to FPA in practical situations require more research. Zhou *et al.* [33] presented an elite opposition based FPA (EOFPA) and applied the algorithm to civil engineering design problems. The modifications are implemented by making changes to the global and local search function of the base FPA [33]. The EOFPA performance was validated by tests conducted in [33]. EOFPA had a faster convergence speed, increased stability and accuracy compared to the other population-based algorithms it was tested against [33]. In other fields, the quadratic assignment problem (QAP) is one of the most popular combinational optimization problems due to the numerous practical applications involved with it [39]–[41]. Abdel-Baset *et al.* [34] propose a EOFPA which aimed at modifying similar characteristics in [33], to improve global and local search functions. Abdel-Baset *et al.* [34] conducted a test using set benchmarks from the QAP library and compared EOFPA against the highest performing algorithms from various literatures. Both graphical and numerical results indicate that EOFPA exhibited the smallest convergence speed and produced the most accurate results amongst the standard FPA, GA and PSO algorithms [33].

C. BINARY FLOWER POLLINATION ALGORITHM (BFPA)

The original FPA was designed to solve continuous optimization problems; however, modifications are needed to solve combinatorial optimization problems [16]. The Binary Flower Pollination Algorithm (BFPA) models the search such that continuous optimization is implemented within a solution [35]. Rodrigues *et al.* [35] presented a comparison of BFPA against various other binary population-based algorithms (BFA, BPSO) on six datasets. The findings show that BFPA produced the most efficient results amongst the compared algorithms in [35]. The literature by Rodrigues *et al.* [36] applied BFPA to reduce the number of sensors used for person identification based on Electroencephalogram (EEG) signals. BFPA experiments results displayed in [36] showed that BFPA resulted in increased recognition rates, provided the best convergence and diversity of solutions as compared to the metaheuristic algorithms it was tested against. Dahi *et al.* [37] conducted tests to evaluate BFPA's performance in solving the Antennae Positioning Problem (APP). BFPA was tested using datasets with different dimensions and was compared with efficient algorithms in APP optimization. The results in [37] display that BFPA achieved the best solution in APP optimization and possessed the fastest convergence rates when tested against popular algorithms in the APP field. Single nucleotide polymorphism (SNP) is a genetic trait responsible for the differences in characteristics of individual living species [45], [46]. Rathasamuth *et al.* [38] implemented a modified BFPA that uses the cut-off-point-finding threshold and combined it with a GA bit-flip operator in [39]. The performance of the modified BFPA in [38] was assessed in terms of capability to identify SNPs with the highest genetic potential against various metaheuristic algorithms in the field. The authors in [38] found that the modified BFPA produced the fastest convergence rate, required the least number of iterations out of the compared algorithms, and achieved a commendable accuracy of 95%. The feature selection problem is a complex issue that plagues many industries. It involves the selection of features that maximizes a fitness function and is a crucial part in optimizing a function [35], [40]. Rodrigues *et al.* [35] conducted tests on numerical datasets in which BFPA is tested and compared to the performance of PSO, HS and FA to assess its ability in solving the fitness function. The results conclude that the BFPA algorithm was the slowest in terms of convergence speed but the most accurate [35]. These papers validate the use of BFPA and proves that modifications to FPA may result in better solutions to optimization problems as compared to established algorithms in those fields of application.

D. CHAOS MODIFIED FLOWER POLLINATION ALGORITHM (CHAOS-MFPA)

The Chaos Modified Flower Pollination Algorithm (CHAOS-MFPA) makes use of chaotic maps to replace the random sequences that generate the initial population in the FPA [41]. This improves the diversity of the initial population, by making the distribution more uniform [41]. Meng *et al.* [41] implemented and tested the ability of the CHAOS-MFPA to solve a variety of mechanical engineering design problems. It was found that the non-repetition of the chaotic sequences allowed for optimal solutions to be found in each case. Analog diagnostics makes use of a support vector machine (SVM) technique to identify fault samples [50], [51]. The SVM technique is vulnerable to the selection process problems described in [50], [51]. Cui *et al.* [42] implemented a Binary Modified Chaos-FPA (BCCFPA), which makes use of the chaos maps and cloud model to enhance the solution quality of the base FPA [42]. The BCCFPA was tested against various binary modified metaheuristic algorithms to determine which could produce the optimal solutions to the selection challenges present with the SVM technique [42]. The results display that the BCCFPA possessed the strongest optimization capabilities amongst the tested algorithms and overcame the premature convergence of FPA [42]. Kaur *et al.* [43] investigated the effectiveness of four variants of the CHAOS-FPA by conducting tests on nine benchmarks of high dimensional functions. The CHAOS variants examined used different chaotic maps, such as the logistic [44], sine [45], tent and dyadic maps [46]. The results in [43] showed that the CHAOS variants outperformed the standard FPA, with the sine map variant able to produce the best results in terms of accuracy but lacked the fast convergence speed that the dyadic map variant possessed. The CHAOS-MFPA is one of the most promising variants of the modified base FPA and is also one of the most used algorithms for optimization within various sectors of power systems. An in-depth review of

CHAOS-MFPA in power system applications is explored in greater detail in the review section.

E. MULTI-OBJECTIVE VERSIONS OF FLOWER POLLINATION ALGORITHM (MOFPA)

Engineering design optimization problems often contain conflicting objectives that can increase the complexity of the solution required [47]. Yang *et al.* [47] implemented the Multi-Objective Flower Pollination Algorithm (MO-FPA) to solve engineering optimization problems, through a random weighted sum method [16]. The paper [47] evaluated MO-FPA using various engineering optimization problems and found that despite the complexity, MO-FPA was found to produce optimal results. These findings were compared to various algorithms including the base FPA. Yang *et al.* [47] presented unique modifications to the MO-FPA by proposing several multi-objective test functions and two bi-objective design benchmarks. The algorithm in [47] was tested using various engineering design problems and was able to efficiently produce optimal solutions in each case, further validating MO-FPA for optimization in practical design situations. Emary *et al.* [48] implemented MOFPA for retinal vessel localization. The suggested method used FPA to determine the ideal clustering of the retinal images. This method was tested using a dataset in [48] and revealed that MO-FPA was able to increase the accuracy and sensitivity of the results. The benefits of modifying FPA are evident in the literature presented. Modifications allow for improvement on specific aspects of the algorithm which can be used to solve unique and complex problems found in various fields.

V. HYBRIDISATION OF THE FLOWER POLLINATION ALGORITHM

Every algorithm is prone to having limitations which creates the challenge of striking the right balance between global-wide searches and local searches [49], [50]. Some algorithms alone can meet the requirements, while others require a combination of the most desirable characteristics of two or more separate algorithms, to carry out a specific task [58], [59]. This forms the basic understanding on how hybridization is carried out. The approach combines two separate metaheuristic algorithms to produce a more efficient algorithm [51]. Hybridized FPA can solve discrete problems and find a balance between global and local searches [49]. Some optimization problems are multi-objective in nature, this means that a basic algorithm would not be able to compute a solution [52]. However, a modified or hybridized FPA would be able to provide a solution. The following section provides an understanding of the various methods as well as the different types of metaheuristic algorithms used to create a hybridized FPA. Some of the algorithms fall in different categories that represent a general type of algorithm, which is then combined with the FPA. Other algorithms are just stand-alone algorithms that are combined with FPA to produce a hybridized algorithm. Their individual advantages and disadvantages are discussed as well as their advantages and disadvantages when combined with FPA to form a hybridized algorithm.

A. TYPES OF HYBRIDISATIONS

1) LOCAL SEARCH

The local search algorithm is a form of hybridized FPA that uses SA. This algorithm has two main phases which are the annealing schedule and acceptance probability function. The SA algorithm is applicable to optimization problems since it allows the system to reach a stable state [23]. The combination of the SA algorithm with FPA can be mainly used for engineering optimization problems as well as to improve the local search convergence rate [16]. FPA is improved locally with the aid of the SA algorithm which produces an efficient search performance and high-speed global convergence. Another variant of the hybridized local search algorithm is the Clonal Selection Algorithm (CSA). This algorithm is popular in research conducted on the immune system and consists of a canonical form which is used to solve various problems. Some of which are solved better than other heuristic algorithms [53]. The hybridization of FPA with CSA creates what is called Binary Clonal Flower Pollination Algorithm (BCFPA). This improves the overall attribute selection of the problem and is done using a small number of attributes in a short time frame, thus providing greater accuracy [54]. Overall, the local search hybridized FPA can provide greater efficiency and higher performance with regards to its solutions. Characteristics of this algorithm include high-speed global convergence, high stability, high precision with regards to predictions and high accuracy when using a small number of attributes in a short time frame.

2) SWARM-BASED

Swam-based algorithms comprise of various metaheuristics combined with FPA. The resulting effect of these combinations differ on the type of algorithm that FPA is combined with. For example, FPA can be combined with the Harmony Search Algorithm (HSA) which aims at mimicking the improvisation process that musicians go through to find the right pitch and harmony [55]. The HSA-FPA algorithm can improve search accuracy and provide results efficiently [47]. Alternatively, FPA can be combined with the Artificial Bee Colony (ABC) optimization which is an algorithm that focuses on the foraging behavior of honeybees to conduct numerical optimization problems [65], [66]. This algorithm was first proposed to solve unconstrained optimization problems and displayed advanced performance in determining optimal solutions for this type of problem [56], [57]. The combination of FPA and ABC creates the Bee Flower Pollination Algorithm (BeFPA). This combination not only decreases simulation time and improves the robustness of the algorithm, but it also provides faster execution and greater quality of convergence to a global optimal solution [58]. In addition, BeFPA was able to solve the photovoltaic parameter determining problem as the combination resulted in faster execution, increased convergence rates, and a better optimal solution [33]. Kalra *et al.* [59] introduced a hybridized FPA by combining the standard FPA with a Firefly Algorithm (FA) which uses the bioluminescence trait of fireflies and its attraction behavior to solve multimodal functions [60]. The FA algorithm provides good performance on solving low-dimensional problems but is unable to solve complex high dimensional problems. The combination of FPA and FA algorithm can provide faster computations and convergence to global optimal solutions [36]. In addition, the hybridized algorithm has an improved ability of not converging prematurely [59]. Another hybridized, swarm based FPA algorithm is the combination of FPA with PSO. This algorithm is based on the hunting tactics that birds use and was proposed by Kenndey *et al.* [22] in 1995. The algorithm mimics these tactics by treating the bird as a weightless object with no volume and the required solution being food that the bird searches for, which allows the algorithm to manage both global as well as part searching [22]. The hybrid version of this algorithm can increase search accuracy and provide an accurate and efficient algorithm to obtain optimal solutions with better convergence rates [61].

3) DIFFERENTIAL EVOLUTION

The Differential Evolution (DE) algorithm, which focuses on the natural evolution characteristics of a population, was merged with the FPA to combine the characteristics of both algorithms, thus creating the DE-FPA [62]. The DE algorithm is robust in the sense that globalization takes place in evolution and was suggested by Storn *et al.* [37], to solve the Chebyshev polynomial fitting problem. A variation to the DE algorithm is one that can solve multi-objective optimization problems [63]. This specialized variation is termed Dynamic Differential Evolution (DynDE) algorithm and is capable of effectively solving the moving peaks benchmark function [64]. The standard DE algorithm has a simple methodology, efficient operation, and iteratively evaluates and updates the contender solutions in the population. The algorithm is guided by the norm pattern of evolutionary algorithms and is made up of steps for each iteration. Chakraborty *et al.* [41] presented a hybridized FPA which combined the DE algorithm with FPA and used five test functions to compare this hybridized algorithm with its individual counterparts. This combination of DE and FPA was made possible since the DE algorithm can find optima among erratically chosen trajectories but lacks the ability to move towards the global optimum. The algorithm also possesses a better capability in searching for a sufficiently good solution and can escape from local optima [62]. While the FPA algorithm is only able to provide global and local search strategies, the hybrid algorithm in [41] improves performance and uses a modified FPA that eliminates the need for the switch probability. Thus, increasing performance stability. The results of the five test functions in [41] show the DE-FPA outperforms both DE and FPA, demonstrating better stability and a smaller deviation. The algorithm also provides better performance and convergence rates which presents an advantage in real world applications, such as high-performance computing [41].

4) MULTI-SCALE RETINEX

This hybridized algorithm combines the Multi-Scale Retinex (MSR) algorithm with the standard FPA to form MSR-FPA. The main application of this algorithm is to improve the effectiveness of remote sensing image enhancement and remedy the deficiency that traditional wavelet algorithms face, such as losing bits of information when image enhancement is conducted [74], [75]. MSR is classified as a frequency domain enhancement technique which enhances Single Scale Retinex (SSR) and images that are taken in nonlinear lighting conditions. The advantage of MSR is that it can compute numerous scales with appropriate weights for greater enhancement. In terms of image enhancement, the MSR algorithm can preserve more detail but has a downside of producing unnatural color appearance [65], [66]. The algorithm is regarded as the most suitable for gray images. Due to the poor advantages and great disadvantages of the standard MSR, a hybridized MSR-FPA is formed in [67] and uses FPA to assign appropriate values to ensure an ideal weight at every scale of the Gaussian filter. This is done using global and local searches. The algorithm in [67] is found to be the best and most efficient algorithm for enhancement of gray images. This allows for further processes such as segmentation, classification, and feature extraction, as well as preservation of the original image [67]. Tests conducted by Shad *et al.* [67] to find a self-regulating proposal for image enhancement using MSR, incorporated FPA to obtain parameters by tuning MSR values. FPA used in combination with the MSR can converge to the global minimum. The experiments in [67] measured performance by recording the peak to signal-to-noise ratio (PSNR), mean standard deviation (SD) and the root mean square error (RMSE) [47], [48]. Based on the test results obtained MSR-FPA outperformed various other algorithms and provided better accuracy and reliable convergence rates. Figure 4 is a diagram that summarizes the MSR operation.

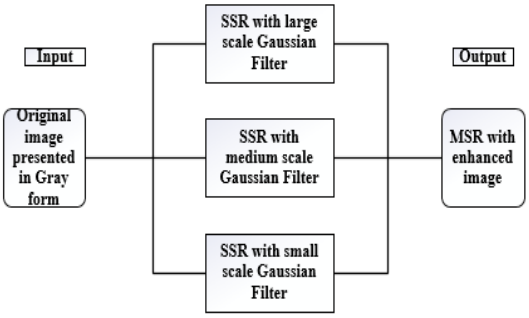

FIGURE 4. Process of MSR on a gray image [65], [68].

VI. REVIEW OF APPLICATIONS OF FPA IN POWER SYSTEMS

A. CLASSIFICATION OF APPLICATIONS

The applications of FPA in this paper are categorized into three subtopics of power systems, namely power generation, distribution systems, and transmission. In addition, other applications of FPA outside the field of power systems are explored.

1) POWER GENERATION

The power generation sector is responsible for the production of electricity with the primary source being various forms of fossil fuels. However, over the past few decades, the growing energy demand has caused an exponential rise in fuel costs, which in turn increased the operational costs of the power stations [13], [78], [79]. Within certain constraints, the economic dispatch problem (EDP) governs the active power output from distributed generators to maintain the demand [13], [78], [79]. Metaheuristic algorithms, such as the FPA are used to solve complex EDP to minimize costs and losses, while maintaining optimal power transfer [13], [78], [79]. The EDP is currently one of the major problems faced by generation systems. Fortunately, there are numerous metaheuristic algorithms displaying satisfactory performance as an optimization tool for this problem. FPA's unique switching, and exceptional convergence characteristics has made it a choice tool for solving the EDP [13], [78], [79]. The scheduling of hydro and thermal power plants in small durations are complex optimization problems in power generation systems due to drawbacks such as the time delay concerning hydro sub-system and the non-convex nature of thermal valve point loading [80]–[82]. Hydrothermal scheduling optimization is used to keep the cost of energy generated by thermal power plants to a minimum for the scheduled duration,which not only has obvious financial benefits for both the consumer and producers, but also for the environment [80]–[82]. The nonlinearity of the hydrothermal scheduling problem plays into the hands of metaheuristic algorithms in a similar manner as EDP, with the interesting features of FPA mentioned and the exciting prospect of hybridization and modifications to FPA, making its effect on hydrothermal scheduling optimization compelling [80]–[82]. The use of renewable energy sources is not perfect, in that their reliance upon specific weather conditions to ensure optimal efficiency are one of its key drawbacks [66], [83], [84]. One solution to the low efficiency rates of renewable Distribution Generation (DG) units are the inclusion of maximum power point trackers (MPPT) which allows for maximum power to be extracted irrespective of unpredictable weather conditions [66], [83], [84]. Researchers have employed numerous algorithms, namely the P&O and IC algorithms, to ensure the optimization of MPPT controllers for various forms of renewable DG units, however the conventional MPPT algorithms require many parameters to be initialized which increases its complexity and reduces accuracy [66], [83], [84]. This has opened the door for modern metaheuristic algorithms such as the FPA to revolutionize MPPT optimization [66], [83], [84]. The integration of renewable DG units in hybrid power systems impacts the system frequency, which in turn influences the overall stability of the system and may result in generation outages and load disconnections [85]–[87]. To assist in solving this problem, FPA optimized PID controllers have been employed to ensure that the nominal system frequency and steady state of a power system is maintained despite the inclusion of intermittent, renewable DG units at various nodes [85]–[87].

2) TRANSMISSION SYSTEMS

The transmission sector of power systems consists of the transportation of electrical energy from a generation site, this can range from a power station to an electrical substation [69]. In a substation, the voltage is either stepped up or stepped down and distributed for industrial and residential use or it can also be sent to other substations to obtain the required voltage [70], [71]. The transmission sector of a power system consists of the most widespread elements and represents the backbone of a power system. In terms of size and distance, the transmission sector is the biggest part of a power system [88], [91]. Transmission system operators (TSOs) oversee equipping and monitoring the system by tracking the state of the system during normal operation and detecting any abnormalities or disturbances [72]. Transmission can be done using 3-phase, 3-wire AC systems which is then split into sub sections known as primary transmission and secondary transmission [73]. Primary transmission can be found at the edges of the city. Due to the power loss in the transmission, lines which is proportional to the square of the line current, the voltage is stepped up [72]. Secondary transmission is found in the city and has the voltage stepped down at receiving stations and transmitted to sub-stations [92], [94]. Transmission lines have a mesh structure which allows for alternative paths for power to flow from the generators to the load points, increasing reliability of the system [74]. These systems can be of various types such as single, two and three phase AC systems as well as DC systems [73]. Scenarios that would impact the operation of a power system generally occur in or near the transmission network, therefore monitoring and employing various countermeasures needed to be taken into consideration, to ensure the stability and reliability of the power system, is vital [75]. The problems that the transmission sector of a power system face include large amounts of power loss in the transmission line which is termed as transmission line losses. This issue can be resolved by using FPA to determine optimal placement of Flexible AC transmission system (FACTS) devices [10], [76]. In addition, the optimal power flow problem in power systems, with the use of FPA along with SVC's, mitigates real power losses in transmission lines which allow the cost of real power generated to be reduced [9], [11]. Congestion in power systems is another problem that requires unique solution search techniques and occurs when transmission lines are operated beyond standard limits due to high demand resulting in a greater load. This problem can be resolved by using FPA and MFPA to provide optimized generator rescheduling, which is able to improve congesting management and power flow in transmission lines. The proposed FPA and MFPA used in the optimization of generator rescheduling, was able to find a solution in the fewest number of iterations, which saved on time and costs [12], [77], [78]. Total active power loss minimization and bus voltage profile improvement problem has also been resolved using FPA to solve single-objective optimization problems which provided a solution to the above-mentioned topic. The algorithm outperformed all other algorithms in reducing fuel costs, total active power and fuel costs that relate to valve effect and voltage profile improvement [13], [79]. These are just some of the issues relating to the transmission sector of power systems that the FPA can either improve or solve [73].

3) DISTRIBUTION SYSTEMS

Distribution systems aim at providing electrical energy to consumers and industrial areas at lower voltages, reliably and efficiently. However, studies have shown that approximately 70% of energy is lost in the distribution phase with only 13% of generated energy lost because of the joule effect [100]–[102]. Such losses have great financial and environmental implications, as well as affects the overall efficiency of the grid. Therefore, to meet the demands of energy generation whilst addressing key environmental issues, determining new methods to reduce power losses and improve the distribution network performance remains necessary and can be achieved by adopting reactive power compensation, network reconfiguration, distributed generation, and hybrid methods [100], [103], [104]. Although, all these proposed methods experience certain challenges. One such case is with regards to DG placement and sizing. Since the location and size of DG units greatly impacts the voltage profile, power losses, and power flow, the non-optimal placement and sizing of DG units within the grid can increase system losses and reduce the voltage profile past permissible limits [100]–[102], [104]. Therefore, to avoid the non-optimal placement, DG planning is essential. Incorporating DG into the grid can help reduce active power losses, but does not necessarily assist with reactive power losses, and so one frequently adopted method to suppress reactive power losses is through optimal capacitor or D-STATCOM placement and sizing within the distribution network [105]–[107]. Alternatively, minimizing the distribution system energy losses can be achieved by reconfiguring the network and involves changing the structure of the distribution system, which is also useful for restoring power to loads in areas where faults occur [30], [108]. Additionally, distribution network systems can be optimally scheduled to improve system performance [80], [81]. However, the above-mentioned methods are considered highly complex, and so FPA and its variants have been proposed as a possible tool for providing optimal solutions to these optimization problems.

VII. APPLICATIONS OF THE FLOWER POLLINATION ALGORITHM IN POWER GENERATION

This section discusses the applications of FPAs in electrical power generation systems. Table 1 provides an overview of such applications encompassing areas of problem solving and significant findings.

A. THE ECONOMIC DISPATCH PROBLEM

The literature [9], [82], [83] implement FPA on various sized power systems to investigate its effectiveness as an optimization technique to solve EDP. All three papers use MATLAB simulation software to conduct the experiment. Sarjiya *et al.* [9] conducted the test on an IEEE 30-bus test system, the results of the simulations are presented and analyzed [9]. However, it was found that FPA reduced the total fuel cost from the initial condition and enhanced the voltage magnitude of the system. FPA displayed the most efficient results amongst the metaheuristic algorithms it was compared to in [9]. However, FPA was only applied to a single generating system in the paper by Sarjiya *et al.* [9]. Maity *et al.* [82] implemented FPA on three different sized generation units. The results illustrated in [82] showed that in all three cases the fuel cost of the systems decreased after FPA was used to optimize the system. The third case that was considered, consisted of forty units. These papers confirm that FPA is efficient in obtaining the optimal economic fuel cost in various power generation systems. This is attributed to the algorithm's great convergence characteristics, computational efficiency, and robustness. The two papers [9], [82] discussed the application of FPA on various generation systems. Dhayalini *et al.* [83] integrated thermal generators with wind units and used FPA to solve the dispatch problem with the addition of a renewable energy wind farm connected to the generation system. The paper conducted tests on the wind farm and showed the comparison between the fuel cost before and after FPA was applied on the two thermal systems [83]. The paper found that system costs decreased and confirmed FPAs success and efficiency in economic dispatch problems to obtain an optimal solution in a variety of cases in power generation systems. In the literature [84]–[86], the initial population and switching processes was modified to form MFPA, and was applied by Sarjiya *et al.* [87] on a custom 10-generator system and Regalado *et al.* [13] who conducted the test on a standard IEEE 30-bus system. The results show that in both cases FPA and MFPA were able to reduce the costs of the system. However, MFPA was able produce a better optimal solution in both cases due to its faster convergence rate.

B. SCHEDULING OF HYDROTHERMAL STATIONS

Balachander *et al.* [88] provided a mathematical breakdown on the hydrothermal scheduling problem and used FPA on a test scenario, in which a single hydro and thermal power plant was used. The test results presented in [88] and [89] demonstrated FPA's superior search capabilities and potential to obtain global solutions in less settling time than traditional approaches such as GA, PSO, BFA. Sutradhar *et al.* [91] tested the validity of the MFPA to solve the Hydrothermal Scheduling problem. The literature [91] conducted the simulation on a test system in [101]. MFPA was compared to various algorithms (FPA, P-DE), and outperformed the above-mentioned algorithms significantly in terms of convergence time and accuracy. Dubey *et al.* [84] modified the base

TABLE 1. FPA in power generation systems.

References	Problem solved	Optimization technique	Important findings
[9], **[82]**, **[83]**, **[87]**, **[13]**	Economic Dispatch Problem - optimal sizing and placement of generating units in a power system to ensure efficient power generation through the minimization of fuel losses and correct active and reactive power outputs at each generating unit.	FPA MFPA	Modifications to the switching and pollination processes results in enhanced optimization [87], [13] .
[88], **[89]** , **[90]** **[91]** **[84]**	Scheduling of Hydrothermal stations - optimised scheduling of Hydrothermal stations in smart/ distribution grids to minimize operational costs.	FPA MFPA IFPA	Addition of a scaling factor and an additional exploitation phase can greatly enhance the performance of FPA in this sector [84].
[58], **[92]**, **[93]**, **[94]**, **[95]**, **[96]**, **[97]**	Conventional/Renewable energy generation optimization – use of FPA to optimize renewable/ conventional energy generation units.	FPA CHAOS-FPA MO-FPA	FPA to track the solar MPPT is advantageous due to it requiring far less parameters to tune [93], [95], [96].
[98], **[99]**, **[100]** **[80]**	Power System Frequency Stabilization – Use of FPA optimization to ensure frequency stabilization of system. Optimal integration of renewable energy generation sources into distribution grids.	FPA CHAOS-FPA	FPA was found to be an extremely effective algorithm for tuning of PID parameters and exceeded the performance of conventional PID optimization techniques [98], [99], [100] [80].

FPA through the enhancement of the local pollination process, with the addition of a scaling factor and an exploitation phase. The Improved Flower Pollination Algorithm (IFPA) was tested against various algorithms (including the standard FPA) on three different cases to determine the efficiency in solving the short-term hydrothermal scheduling problem. The results conclude that the IFPA can produce higher quality solutions with superior convergence characteristics on all cases [84]. The papers [88], [89], [91], [111] provide sufficient evidence which concludes that the use of FPAs strong search capabilities through global and local pollination techniques makes it a viable solution to solving the hydrothermal scheduling problem.

C. RENEWABLE ENERGY GENERATION EFFICIENCY

Generation of electricity through renewable energy sources has increased over the past decade. However, solar energy is limited by the availability sunlight and partial shading of solar modules negatively impacts the output power [58], [93]. Recent studies have shown the use of metaheuristic algorithms to optimize MPPT controllers to maximize PV power output under varying climate conditions. The literature by Ram *et al.* [58] and Elbehairy *et al.* [93] both implement FPA on MPPT controllers to determine whether global peak can be achieved. The tests in [58] and [93] were conducted on triple and single array solar panel systems, in which both tests utilized simulation software under different shading conditions such as low, medium, and high shading. The test results illustrated in [58] and [93] showed that FPA was able to detect the maximum power point at different conditions of partial shading. The literature in [93] compared the performance of FPA to PSO and demonstrated that both PSO and FPA methods have similar scope in reaching the Global Maximum Power Point (GMPP). However, FPA was able to produce the optimal global peaks under the strong shading conditions, which PSO could not achieve, thereby justifying FPA as a more suitable algorithm for this scope of work [93]. Murdianto *et al.* [94] investigated the prospect of adding a DC-DC BUCK converter to a DC microgrid to improve the grid stability. Murdianto *et al.* [94] tested the hypothesis by using FPA to optimize the MPPT tracking of a proportional integral (PI) controller in the system. The results in [94] displayed that a FPA optimized PI controller was capable of accurately tracking the MPP and thus resulted in a more stable system (due the regulated voltage). Murdianto *et al.* [94] also highlighted the fact that using FPA to track the MPP is advantageous due to the simplicity of the algorithm as compared to conventional techniques such as IC and P&O, as it requires far less parameters to tune [94]. Murdianto *et al.* [95] further investigated FPA MPPT capabilities by attempting to track the MPP of a SEPIC converter under partial shading conditions. FPA was tested against MPSO and Grey Wolf Optimizer (GWO) algorithms. The results in [95] highlighted FPAs superior MPPT capabilities and concluded that FPA was able to produce extremely accurate results in the least amount of convergence time. FPA proved in simulation to be an efficient method in finding the GMPP. However, the unpredictability of nature makes whether this method would produce desired results in a practical situation, unknown. Elbehairy *et al.* [93] implemented a practical PV unit system with the hardware implementation being described in [93]. The practical experiment made use of a MPPT controller optimized with the FPA under various shading conditions and concluded that FPA was capable of tracking MPP irrespective of shading patterns created [93]. This validates the practical use of FPA as a means of optimization to practically track the MPP. A modified Chaos FPA was developed and implemented by Yousri *et al.* [96]. The paper aimed to test the modified CHAOS-FPA against the base FPA to determine which algorithm can produce better results with regards to tracking GMPPT in solar generation units. Yousri *et al.* [96] conducted the simulation-based test on a solar generation unit under various shading conditions. The results obtained in [96] showed that C-FPA variants were able track the GMPP efficiently and assisted in producing a greater amount of power in a shorter space of time compared to FPA. Sun *et al.* [92] proposed a new wave energy converter (WEC) which uses FPA to achieve maximum power absorption under all conditions within a wave energy generation system. A complete model of a WEC system and controller was constructed in [92]. Simulation based tests conducted on a WEC system implemented on MATLAB in [92] found that FPA was able to increase the average power output under various conditions. Steam turbines are a key component to production of energy within conventional power plants and optimal tuning plays an important role in ensuring that the efficiency and lifespan of machinery remain sustainable [97]. Kumar *et al.* [97] proposed a closed loop speed control system through a fractional order proportional integral derivative (FOPID) controller for an industrial turbine [97]. The FOPID's parameters were tuned using the MO-FPA and the effectiveness of the optimization was assessed by examining the disturbance rejection, overshoot and rise time of the system. The results displayed in [97] show that the system produced satisfactory performance with an overshoot less than 1% and satisfactory minute rise and settling time values [97]. The most notable characteristic was the effective disturbance rejection of the system, thus highlighting MO-FPAs PID optimization capabilities [97]. Ren *et al.* [102] propose the use of the FPA to optimize Feedforward (FF) neural networks which provide valuable information on wind speeds to renewable energy (wind based) plants. Ren *et al.* [102] conducted the tests with reference to the predicted wind speed data outputted on conventional FF networks compared to that outputted on FPA and IFPA optimized FF networks. The modifications on the IFPA employed in [102], revolved mainly around the Lévy flight characteristics, with the improvements allowing for a global search trait of higher efficiency [102].

D. POWER SYSTEM FREQUENCY STABILIZATION

Hussain *et al.* [98] presented a hybrid power system and tested the ability of a FPA optimized PID controller against a PI controller to determine its effectiveness in optimizing an unstable system with DG units incorporated into the network. The test results in [98] show that both controllers were able to maintain the system frequency within the permissible limits. However, the FPA optimized controller outperformed the PI controller as it had optimal settling times and better search capabilities which allowed for better convergence and greater system stability. Joshi *et al.* [80] implemented the Chaos modified FPA to incorporate a large wind unit into a distribution network. The test results obtained in [80] show that CHAOS-FPA was able successfully obtain a stable system. The chaotic maps and random nature of the chaos modified FPA allowed it to achieve the lowest operational cost and greatest system stability amongst other metaheuristic algorithms tested against [80]. Jagatheesan *et al.* [99] aimed to solve the load frequency instability issues that exists within conventional power systems with the use of a FPA optimized PID controller. Jagatheesan *et al.* [99] conducted the tests on a power system consisting of three identical thermal generation plants. Power systems are subject to voltage fluctuations because of load disconnection, overcurrent, and overvoltage faults [100]. These voltage sags are extremely dangerous and may permanently damage the generators within the system. As such Sambariya *et al.* [100] attempted to optimize a PID controller for the AVR of a power system using FPA. The literature in [100] obtained the proportional integral derivative (PID) tuning parameters using FPA. The performance of the optimized controllers in [100] was tested for over 156 plant conditions and was compared with established literature in the field. The exceptional performance in terms of settling time, peak value and system stability were noted with comparisons to other optimization techniques, highlighting the FPA tuned PID systems superiority [100].

VIII. APPLICATIONS OF THE FLOWER POLLINATION ALGORITHM IN TRANSMISSION SYSTEMS

This section discusses the applications of FPAs in electrical power transmission systems. Table 2 provides an overview of such applications encompassing areas of problem solving and significant findings.

A. TRANSMISSION LINE PLANNING

Presently, the supply of electricity has decreased considerably due to unsuitable power system designs which are unable to satisfy the increasing load requirements. As a result, there is an increase in the number of private companies that assist in meeting the requirements, which would otherwise cause problems in the security of the power system, voltage fluctuations and system breakdown due to transmission line losses [10]. To solve these problems, new transmission lines are being built. However, this task is becoming more difficult due to governmental and ecological challenges [10], [76]. To preserve voltage stability, minimize transmission line losses and enhance power system security, flexible AC transmission system (FACTS) devices are used. These can be further categorized into thyristor-controlled series capacitors (TCSCs) which monitor and react much faster compared to other FACTS devices. TCSC is a better regulator of transmission line impendence and can reduce it by changing reactance values which in turn increases power flow in the system [10]. To ensure that the TCSC is optimally positioned in transmission lines to achieve maximum power flow, the fast voltage stability index (FVSI) factor is used [10]. FPA is employed to determine the optimal setting for the FACTS device. D.L. Pravallika *et al.* [10] suggested a method for optimal positioning of the TCSC in a network using the FVSI and the optimal configuration of the TCSC value using FPA. The paper [10] built a program using MATLAB, with the aim to reduce transmission line losses on an IEEE 14-bus system [10]. Tests were conducted to determine the:

- Fast Voltage Stability Index values for different IEEE 14-bus test lines.
- Incorporation of TCSC with Newton-Raphson (NR) method or with Flower Pollination Algorithm (FPA) method.
- Variable Values using FPA by TCSC and variable values without using FPA by TCSC.

The results observed and recorded in tables seen in [10] found that the optimal TCSC power flow based on FPA produced efficient results as compared to NR. Thus, the positioning of the TCSC using FPA decreased the response value by 9.5% [10]. An 11.76% power loss was also observed after the TCSC was used, which was further decreased by 40.3% after setting the FPA parameters [10]. This suggests that the use of FPA has a positive effect on the reduction of transmission line losses [10]. Thus, the paper by Pravallika *et al.* [10] confirms the good convergence rate and accuracy of FPA when positioning TCSC devices in a transmission network.

B. POWER SYSTEM MANAGEMENT

Modern power system's face a variety of difficulties due to their complicated function and multifaceted structure [11]. System Instability is a major challenge encountered by engineers and is primarily caused by the deficiency and overuse of current transmission lines [11]. The optimal power flow (OPF) principle has been applied as a continuity of economic dispatch [9]. OPF is vital in the scheduling of power system management, electricity tariff prices, maintaining system security, system stability and congestion [9].

To improve OPF in power systems, various factors apart of generation, transmission and distribution need to be improved. As such, this section will investigate how FPA is implemented to solve problems involving optimal power flow. Kumar *et al.* [11] and Sakti *et al.* [9] suggested methods to solve the Optimal Power Flow problem using the Flower Pollination Algorithm. B.S. Kumar *et al.* [11] outlined an approach to solve the multi-objective challenge of power system optimization. In the paper [11] a FACTS shunt device, called the Static Var Compensator (SVC), was used to achieve optimum power flow. The aims of this approach are to mitigate the loss of power in transmission lines and the cost of real power generation. The results presented in the study were obtained through simulation using MATLAB on an IEEE 14-bus method for OPF problems using FPA without SVC and SVC. In the method proposed by Kumar *et al.* [11], the simulation results showed that the total active power needed to be produced reduced by 1.19% and that the real power loss was reduced by 41.45% using FPA with SVC [11]. In the study [11], the results simulated were compared to results produced with the Genetic Algorithm (GA), and it was concluded that FPA was more efficient than GA. Sakti *et al.* [9] suggested the approach of using FPA to be extended to problems with OPF, with the key goal of minimizing the average cost of fuel while maintaining constraint conditions. Control variables used in this approach include generator generation of active power and voltage magnitude, tap-transform ratio configuration, and reactive power injection on shunt capacitance. These control variables were selected as they can be modified and therefore be used to obtain the lowest possible value of the objective function [9]. The method suggested by Sakti *et al.* [9] applied FPA to an OPF problem on an IEEE 30-bus test system with a total power of 283.40 MW. The simulation was conducted numerous times to ensure consistency and efficiency, with results for line active losses after FPA implementation being 9.045 MW. This result was then compared with other meta-heuristic methods. FPA proved to be 13.7% more efficient than Gradient Method (GM) with line losses of 10.486 MW and 0.13% less efficient than Artificial Bee Colony with line losses of 9.0328 MW. The two methods proposed in [9] and [11] are testament to the robustness and effectiveness that FPA has in enhancing the power flow in Power Systems.

C. CONGESTION MANAGEMENT

Congestion in transmission lines occurs when the line is operated beyond its standard transfer limits. This can occur due to the greater demand for electricity required by consumers, which strains the lines and forces them to work close to their MVA limit. Congestion impacts transmission reliability and system security, which can increase electricity tariffs. To resolve this problem, Congestion Management (CM) was introduced to reduce tariff accumulation for relieving congestion in transmission lines [12]. In [77] and [78], it is stated that congestion management is done by load shedding, using flexible alternating current systems (FACTS) and generator rescheduling. The chosen method is left at the discretion of an independent system operator (ISO). In this paper, generator rescheduling will be reviewed to determine the effects it has on improving congestion management in transmission systems. Verma *et al.* [12] explored the approach of generator rescheduling by focusing on equality and inequality constraints, where equality is the cost of rearranging the active power of the generator output and inequality is the set operating limits of the power system. These constraints are expressed as a mathematical model which considers the number of buses, generators, loads and transmission lines as well as other factors such as the real and reactive power that is produced and consumed. The test was conducted using

TABLE 2. FPA in power transmission systems.

References	Problem solved	Optimization technique	Important findings
[10], **[76]**	Transmission Line Planning – Optimal placement and setting of FACTS devices, such as TCSCs using the FVSI and FPA, to achieve maximum power flow, and regulate transmission line impedance and reduce it by changing reactance values.	FPA	It was found that the optimal TCSC power flow based on FPA produced efficient results as compared to NR. Thus, the positioning of the TCSC using FPA decreased the response value [10]. A power loss was also observed after the TCSC was used, which was further decreased by after setting the FPA parameters [10].
[9], **[11]**	Power System Management – Optimising the power flow in a power system using FPA with SVCs in order to mitigate the loss of power in transmission lines and the cost of real power generation.	FPA	It was found that that the total active power needed to be produced was reduced and that the real power loss was reduced using FPA with SVCs [11]. In addition, FPA was proven to be more efficient in solving OPF problems than Gradient Method, and less efficient than Artificial Bee Colony [9].
[12], **[77]**, **[78]**	Congestion Management – Optimising generator rescheduling using FPA to improve congestion management in power systems.	FPA MFPA	It was found that the FPA solution provided the least minimum congestion cost as well as a reduced power flow in both previously congested lines as compared to the other algorithms [12]. FPA successfully reduced system losses and congestion management costs in less iterations [12], [78].
[13], **[79]**	Bus Voltage Profile Improvement – Using FPA to solve single-objective optimization problems that are focused on valve effect, and voltage profile improvement.	FPA MFPA	The proposed MFPA solution had a minimum active power loss which is significantly less when compared to PSO and CSA [13].

a modified IEEE 30-bus and IEEE 57-bus systems, with each bus system having two test scenarios. FPA was used to optimize the generator rescheduling with the foremost solution discussed in [12]. In both these lines, power flow had exceeded the maximum MW allowed, which is 130 MW. More specifically, lines 1-7 had a flow of 147.46 MW and lines 7-8 had a flow of 136.29 MW. The overloaded lines had then been alleviated by applying optimal rescheduling of the generators using the proposed FPA. These results were tabulated in [12] and compared with other optimization algorithms results such as SA, PSO and RSM. It was observed that the FPA solution provided the least minimum congestion cost as well as a reduced power flow in both previously congested lines as compared to the other algorithms. This result was consistent in both test scenarios. FPA successfully reduced system losses and congestion management costs in fewer iterations [12].

D. BUS VOLTAGE PROFILE IMPROVEMENT

To improve OPF in power systems, various factors within generation, transmission and distribution need to be improved. In the literature [13], tests are conducted using the various optimization algorithms and are then compared with each other. This paper focuses on solving single-objective optimization problems and focuses on four main aspects, i.e., fuel cost minimization, total active power losses minimization and fuel cost minimization concerning valve effect and voltage profile improvement. The latter two single-objective optimization problems will be discussed as they relate to transmission systems. These single-objective optimization problems have been translated into a formula in which the combined active power losses determine the combined line active power losses. The improvement of load bus voltage is used to improve the system voltage profile and reduce the voltage changes. Tests are conducted on a standard IEEE 30-bus test system which consists of six generators and four transformers with off-nominal tap ratios [79]. The OPF problem was written mathematically to represent a single objective function composed of dependent state variables and independent control variables. The equality constraints related to load flow were provided as a formula that considers active power, reactive power, voltages, susceptance, phase difference and conductance between buses, the number of buses, and number of generator buses. The inequality constraints were written as a formula and considers generator limits, tap limits transformer, compensator limits, voltages at loading buses and power flow line limits [13]. The MFPA used in [13] focused on two factors; looking for the foremost initial condition, which looks for a closer solution while simultaneously looking at the opposite guesses; this allows for the best initial condition to be chosen and an appropriate solution point, as well as eliminating the need for the switch probability, which improves the switch between local and global searches. It is tabulated against other optimization algorithms the active power losses using the minimization function. The proposed MFPA had a minimum active power loss of 2.8877 MW which is significantly less compared to PSO and CSA, which had an active power loss of 3.0745 MW and 3.0437 MW, respectively. There is also graphical analysis done by [13], which shows the convergence profile of the various algorithms used. MFPA progress time does not deviate from the other optimization algorithms, which stipulate that the changes done to the standard FPA do not affect its capability to deal with similar computational problems. A deviation of 5% to 10% from the nominal voltage profile is acceptable; the bus voltage profile is an excellent indicator to determine the quality and system security [13]. The voltage profiles from various optimization algorithms and the power flow solution were analyzed in [13] with voltage limits marked at 0.95 p.u. and 1.05 p.u., and buses from 1-30 showing their voltage p.u. values. MFPA shows better results and lies almost exactly in the middle of the two limits. It is noted by [13], that the load bus voltage profile formula does not give data pertaining to the voltage deviation distribution among the system. This resulted in the authors developing a MATLAB interface that was able to display the voltage bus map. This map displays the IEEE 30-bus single line power system diagram and each bus p.u. value from 0.95 p.u. to 1.10 p.u. This map indicates that the voltage profile estimated by the MFPA does not exceed 1.025 p.u. or go below 0.965 p.u. indicating a stable bus voltage profile. Thus, the MFPA was able to reach convergence using fewer iterations and a reduced processing time. Overall, the MFPA performed better than the basic FPA and was able to find fitter initial solutions as well as improve switching probability.

IX. APPLICATIONS OF THE FLOWER POLLINATION ALGORITHM IN DISTRIBUTION SYSTEMS

This section discusses the applications of FPAs in electrical power distribution systems. Table 3 provides an overview of such applications, encompassing areas of problems solved using FPA and its variants as well as significant findings.

A. Distribution System Planning

Distribution generation (DG) is electrical power generation that is located near the consumer [103]. This form of generation is tasked with supplying the grid with active power in the event of load instability [104]. The increasing interest in optimally placing DG units and determining the optimal size is largely attributed to its ability to improve voltage profile and minimise power losses [105]. Research has estimated that approximately 20% of new generation installations are DG [106]. However, non-optimal placement of DG can instead reduce voltage profile and increase system losses [106].

Sizing is another important topic that must be planned before installation as changing the DG size with varying demand is not economically feasible [106]. One approach to searching for optimal locations and sizes of DG is to use meta-heuristic optimization techniques. Several works such as [104]–[106], [108], [109], [110] have utilized this method for DG placement and sizing using popular meta-heuristic algorithms including the recently developed FPA. Authors in [105], [106], [109], [110] applied FPA to determine the optimal location and size of DG in distribution systems. The approach by Reddy *et al.* [105] involved determining the optimal size and location of four different types of DG for IEEE 15, 34, and 69-bus systems using FPA, to minimize the total active power loss. The vector index method was used in [105] to minimise the search space. The results in [105] showed that FPA successfully reduced power losses, achieving the best results with a DG capable of injective both real and reactive power. Oda *et al.* [106] evaluated FPA on IEEE 33, 69, and 136-bus test systems with single and multi-DG allocations. FPAs performance was compared in [106] to other popular optimization algorithms used in DG placement and sizing, such as artificial bee colony (ABC), backtracking search optimization algorithm (BSOA), and clonal search algorithm (CSA). The results verify that FPA is efficient and robust, outperforming ABC, BSOA, and CSA in optimal DG sizing and placement demonstrated in [106]. Prasetyo *et al.* [109] explored optimal placement of PV based DG in Semanu substation, Gunung Kidul Yogyakarta, to reduce PV penetration that may reverse power flow, in addition to improving the voltage profile. FPA was chosen as the optimization algorithm in [109] and reduced active power losses by approximately 68% in a small computational time. While the objective is to choose an optimal location and size of DG units to reduce active power loss, one must keep in mind that power losses include reactive power as well. Recent works indicate that optimal placement of capacitors (in conjunction with DG) to suppress reactive power losses, can greatly increase system efficiency [104]. The literature [104], [108], and [110] indicate that optimal placement of capacitors (in conjunction with DG) to suppress reactive power losses, can greatly increase system efficiency. The work presented in [108], [110] explored the optimal placement of DG with shunt capacitors simultaneously using the FPA to decrease power losses and increase the voltage profile. Sudabattula *et al.* [108] used the algorithm to optimally place multiple capacitors and 1 DG unit using a 69-bus system under different load conditions and effectively achieved the main objective of improving voltage profile and reducing losses. Manimegalai *et al.* [110] tested various DG and capacitor combinations on an IEEE 33-bus system using FPA and found that the best result was achieved using multiple DG with capacitor. However, studies have shown that capacitors can be replaced by D-STATCOM with effective results [113]. A more recent approach to improving voltage

TABLE 3. FPA in power distribution systems.

References	Problem solved	Optimization technique	Important findings
[105], **[107]** , **[108]**, **[104]**, **[106]**, **[109]**, **[110]**	Distribution network planning - optimal placement and sizing of DG units in distribution systems together with optimal placement of Capacitors and D-STATCOMs in distribution networks to supress reactive power losses, optimal placement of transformers in distribution networks to reduce installation costs, maintain high efficiency of operation, and satisfy customer expectations.	FPA	FPA with loss sensitivity factor (LSF) is so versatile that it can be imposed on different distribution systems effectively [104]. FPA is simple to implement, converges to a better solution and provides preferable performance over other algorithms in terms of voltage profiles, active and reactive power losses, and net savings [105], [108], [107], [106], [109], [110].
[80], **[81]**	Distribution system operation - optimised scheduling of microgrids in smart, distribution grids.	FPA-GSA CHAOS-FPA	CHAOS-FPA exhibits a lower standard deviation (S.D.) than FPA [80].
[27], **[111]**	Distribution system automation – optimal placement of sectionalising and tie lines for distribution network reconfiguration (DNR), minimising load balancing index (LBI) of a radial distribution network (RDN).	FPA MO-FPA	FPA and its variants yields better solutions in less computational time compared to other optimization algorithms used for this application [27], [111].
[112]	Voltage and reactive power control – optimal capacitor placement and sizing in distribution networks to reduce costs and power losses.	FPA	FPA outlasts other algorithms in determining optimal solutions to the size and location of capacitors in a distribution system [112].

profile was explored by Vittal Bhat *et al.* [104], in which DG placement and sizing was searched for simultaneously with D-STATCOM placement in RDS using FPA with LSF, which is an important aspect to consider when determining the selection of buses for DG and D-STATCOM installation. The system was tested on 15, 33, and 69-bus RDS, and achieved optimal results using FPA, thereby producing greater efficiency in the distribution network. Transformer placement is another difficulty encountered in distribution network planning by power utilities, as installation cost, customer satisfaction, and high efficiency of operation are some of the variables that need to be considered [107]. Huang *et al.* [107] explored the placement of distribution transformers in a low-voltage grid with FPA as the proposed method of approach with the above variables in mind. Several other approaches such as tabu search involved complex processes, and popular search algorithms such as PSO require adequate selection of parameters for satisfactory performance [107]. With regards to FPA, tuning of only two control parameters is sufficient for satisfactory performance with less computational time [108]. Huang *et al.* [107] validated the effectiveness of FPA in distribution transformer placement using two grid networks and found that the algorithm converged to better quality solutions compared to other published methods on this topic.

B. DISTRIBUTION SYSTEM OPERATION

Conventional electrical power grids have been reconstructed to form smart grids which use information and communication technologies (ICT) to allow for more efficient and reliable operation of power systems [80]. The future development of such smart grids will consist of many DG microgrids for grid-connected power generation [81]. Many of these DG units consist of renewable energy sources that are unpredictable and volatile. For example, PV generation is dependent on solar irradiance which can be obstructed by clouds. Wind farms require strong currents of air, which is not always available, to produce electrical energy. Therefore, research in optimised scheduling of distribution network systems with microgrids has become vital. Zhan *et al.* [81] utilized FPA of gravitational search mechanism to determine the optimal reactive power distribution of a distribution network with a PV microgrid. However, reactive power optimization is related to active power optimization of the network with a PV microgrid, and so the optimization of the scheduling was performed separately with active power optimization performed first. FPA was combined in [81] with the gravity search algorithm to accelerate its convergence speed and improve exploration. The algorithm in [81] reduced network loss by 14.7% and improved voltage qualification rate. In another paper, Pandya *et al.* [80] modified FPA using Gauss map chaotic equations to optimally schedule distribution energy resources (DERs) in an attempt maximise profits of an aggregator. The proposed CHAOS-FPA in [80] was tested on a 33-bus distribution network and its performance was compared to FPA, cuckoo search algorithm (CSA), and differential search algorithm (DSA). Results in [80] illustrate that CHAOS-FPA has a lower standard deviation in comparison to FPA, CSA, and DSA and produced the greatest increase in profits from all other algorithms used in [80].

C. DISTRIBUTION SYSTEM AUTOMATION

Distribution systems consist of two categories of lines i.e., sectionalising and tie lines [27]. Distribution network reconfiguration (DNR) involves rearranging the structure of the system by optimally changing the position of these lines to maintain the radial topology [27], [111]. Network reconfiguration can provide better solutions to minimise power losses in a distribution system and can restore loads in areas that experience a fault [111]. However, DNR is highly complex and requires innovative techniques to solve. Proposed methods include the heuristic and meta-heuristic algorithms to search for an optimal solution. Salman *et al.* [111] explored DNR using FPA with a graphical user interface (GUI) to minimise power losses in a grid. The proposed method was tested on an IEEE 33-bus system using MATLAB software for the simulation. The use of FPA was compared to other popular meta-heuristic algorithms such as PSO and MPSO. The results in [111] confirm FPA's efficiency in searching for an optimal solution as it reduced power losses by 31.12% in 14.3 seconds compared to MPSO, which took 52.23 seconds to reduce losses by the same percentage. The voltage improvement of the system in [111] after applying FPA to reconfigure the network was approximately 2.64%. Although network reconfiguration can minimise power losses considerably in a distribution network, DNR alone cannot increase the voltage profile of the system to an optimal level [27]. Ganesh *et al.* [27] presented a reconfiguration methodology that utilises a combination of FPA and CSA to form the multi-objective modified Flower Pollination Algorithm (MO-MFPA), which was then used to decrease power losses, improve voltage profile, and minimise the load balancing index in a radial distribution network with PV based DG and D-STATCOM. The suggested method was tested on an IEEE 33, 69, and 118-bus distribution system. To compare the performance of MO-MFPA in [27], the algorithm was compared to MO-FPA. Results from the simulation confirm that MO-MFPA yields better solutions and that MO-MFPA in [27] optimally reduced power losses and minimised the LBI whilst improving the voltage profile considerably in all three bus distribution systems.

D. VOLTAGE AND REACTIVE POWER CONTROL

Capacitor placement and sizing on its own is also a challenging task. Many proposed meta-heuristic techniques and allocation methods have failed to reach optimal costs as they lack certain strategies to handle the limited discrete nature of capacitor bank sizes when seeking to optimize the system and computational performance [112], [114]. Abdelaziz *et al.* [112] suggested the use of FPA to determine optimal placement and sizing of capacitors in distribution networks to decrease power losses. The algorithm was tested on IEEE 15, 69, and 118-bus systems and its effectiveness was compared to numerous other algorithms including PSO, GA, and harmony search algorithm (HSA). The proposed scenario of testing in [112] involved FPA selecting the optimal location from the initial candidate buses based on higher Power Load Index (PLI), which is used to reduce the research area. The test results in [112] concluded that FPA gave the highest power loss reduction and net savings in comparison to PSO, GA and HAS.

X. APPLICATIONS OF THE FLOWER POLLINATION ALGORITHM IN OTHER FIELDS

This section discusses the applications of FPAs in other engineering field. Table 4 provides an overview of such applications encompassing areas of problem solving and significant findings.

A. MICROBIOLOGY

In the field of science, the need for innovative optimisation techniques is imperative to obtain solutions to optimisation problems as efficiently as possible. Mohamed A Tawhid *et al.* [115] recently proposed the development of a hybrid algorithm consisting of FPA and GA to minimise the molecular potential energy function and is referred to as the hybrid flower pollination and genetic algorithm [115]. Algorithm (HFPGA). Minimising the molecular potential energy function is required to understand the 3-dimensional structure of proteins. Some of the current methods of minimising the molecular energy function are futile as they are costly and time-consuming. This serves as a reason to develop a nature-inspired algorithm to obtain solutions to these problems. The HFPGA numerically demonstrates its efficiency compared to other types of algorithms.

B. CHEMICAL ENGINEERING

The Flower pollination algorithm is a relatively new method of solving optimisation problems in the field of chemical engineering. However, there are some studies conducted by researchers about the applications of FPA in chemical engineering. Merzougui *et al.* [116] applied FPA for phase equilibrium calculations of a Liquid-Liquid Equilibrium system in which the algorithm had been utilized for parameter identification of UNIQUAC and NRTL models from ternary and quaternary systems. A modified FPA had also been presented and compared to the standard FPA. Numerically the modified FPA performed better than the standard FPA. Zainudin *et al.* [117] combined FPA and Taguchi design to produce a hybrid algorithm to resolve problems related shrinkage of triaxial porcelain composed of palm oil fuel ash.

C. MECHANICAL ENGINEERING

In the field of mechanical engineering, many hybrid flower pollination algorithms have been developed for optimisation problems to obtain efficient design solutions. The flower pollination algorithm was modified and utilized in the design of tubular columns to minimise the material and construction costs [41]. Speed reducer designs require the total weight of

TABLE 4. FPA in other fields.

References	Problem solved	Optimization technique	Important findings
[115]	Microbiology - minimisation of Non-Convex Potential Energy function of molecular structure.	HFPGA	The experimental outcomes showed that the suggested algorithm comparatively performs better to obtain the global minimum of the potential energy function [115].
[116], [117].	Chemical engineering - Optimization of food-related thermodynamic problems, minimising the size of triaxial porcelain.	FPA MFPA	Numerically the modified FPA performed better than the standard FPA [116], [117].
[41]	Mechanical engineering - Tubular Column material and construction cost minimisation, Speed Reducer weight minimisation.	MFPA	The modified flower pollination algorithm provides an efficient solution to this minimisation problem as compared to other nature-inspired algorithms [41].
[118]	Civil engineering - truss structure weight minimisation, optimal tuning of mass dampers.	FPA	The results numerically show FPA is far more efficient than other metaheuristic algorithms [118].

the device to be minimised. The modified flower pollination algorithm provides an efficient solution to this minimisation problem as compared to other nature-inspired algorithms.

D. CIVIL ENGINEERING

Efficient optimisation techniques are vital in the field of civil engineering since many of related design problems tends to be non-linear with uncompromised constraints. These constraints include cost, physical and architectural requirements which often leads to a design problem of severe complexity. Bekdas *et al.* [118] investigated the use of the FPA to minimize the weight of trusses and sizing design variables. The algorithm had been applied to minimize both two and three-dimensional truss weight minimization problem. The results numerically show FPA is far more efficient than other metaheuristic algorithms. Nigdel *et al.* applied the flower pollination algorithm to optimize design of tuned mass dampers. This optimization includes the optimum mass, period, and dampening ratio.

XI. DISCUSSION

A. DISTRIBUTION OF PUBLISHED RESEARCH ON FPA AND ITS VARIANTS IN ELECTRICAL POWER SYSTEMS

Figure 5 shows the distribution of published research regarding the use of FPA and its variants in electrical power systems and other fields of sciences. Majority of the literature pertaining to the applications of FPA and its variants, was reviewed in the power generation category, followed by the distribution systems and lastly transmission systems. The least amount of published research reviewed in this paper belonged to other fields of science and engineering, since the focus lies mostly with reviewing literature pertaining to the use of FPA, its modifications and hybrid algorithms, in the field of electrical power systems.

Figure 6 illustrates the distribution of published research of FPA in four power generation categories. From Figure 6, majority of the research in the power generation section foused on conventional/renewable energy generation optomization, which entails the use of FPA to ehance the efficiency of MPPT technology as with conventional turbines through the optomization of PID controllers for the equipment. The remainder of the research reviewed focused on the use of FPA in solving complex problems such as the ELDP and optimal scheduling of hydrothermal power plants. The performance of FPA in determing a solution in both above-mentioned categories proved extremely effective and efficient. A significant decrease in fuel costs was made possible through optimization using FPA. The final aspect of interest was the use of FPA in grid stabilizaton, which had the least amount of literature dedicated to it, as the use of FPA as a means of PID optomiation is still relatively newer than the other sectors of power generation. With this in mind and the results thus far noted as promising, this sector may one which be may be further looked into in the future.

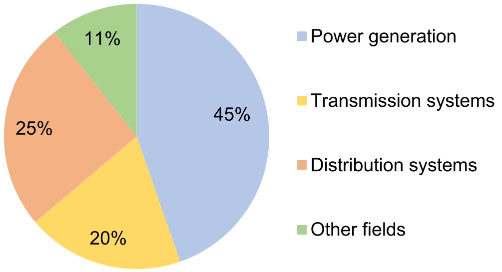

FIGURE 5. Distribution of published research on FPA in electrical power systems and other fields.

Figure 7 illustrates the percentage of articles reviewed in the transmission systems categories. Power system management, transmission line planning, and bus voltage profile improvement contained an equal percentage of reviewed publish research while congestion management contained the highest amount. Operating transmission lines beyond standard transferable limits to meet with the growing

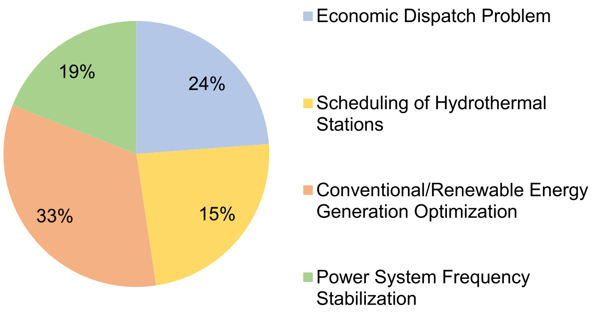

FIGURE 6. Distribution of published research on FPA reviewed in power generation.

demand of electricity, greatly affects the reliability of transmission systems. Therefore, relieving the transmission lines of this excess energy through congestion management, is vital in improving the longevity of the system. Thus, congestion management receives a great deal of attention.

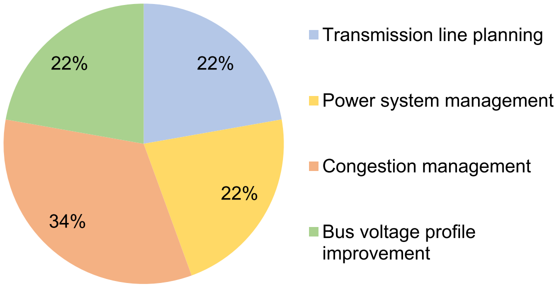

FIGURE 7. Distribution of published research on FPA reviewed in transmission systems.

Figure 8 illustrates the distribution of published research in the four distribution systems themes. It can be seen from Figure 8, that a large portion of reviewed research focused on distribution network planning, which entailed the optimal placement and sizing of DG units, capacitors and D-STATCOMs in distribution systems as well as the optimal placement of transformers in distribution networks. The balance of the research reviewed focused on distribution system operation and automation, as well as voltage and reactive power control. Since power system networks are expanding to accommodate the growing demand for electricity, the optimal placement of DG units, capacitors, D-STATCOM and transformers to maintain high efficiency of operation and reduce installation costs, is key. Therefore, seeing majority of the research falling in the category of distribution network planning is unsurprising. Although, it must be pointed out that voltage and reactive power control, while entails the optimal placement and sizing of capacitors and D-STATCOMs in distribution systems which forms part of distribution network planning, papers reviewed in this category included the optimal placement of DG units in conjunction with capacitor and D-STATCOM placement and sizing, simultaneously. Therefore, a separate category was dedicated to only the optimal placement and sizing of capacitors and D-STATCOMs in distribution systems, in an effort to reduce costs and power losses, in existing networks.

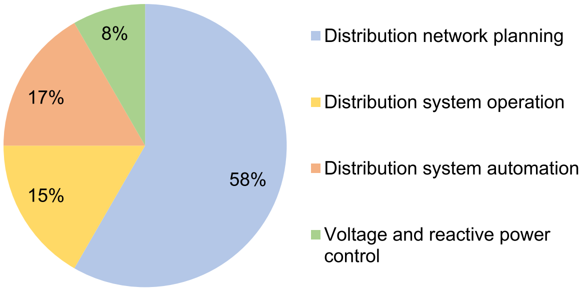

FIGURE 8. Distribution of published research on FPA in distribution systems.

B. ANALYSIS OF FPA AND ITS VARIANTS IN ELECTRICAL POWER SYSTEMS

1) POWER GENERATION

The use of FPA in power generation optimization, providing a solution to the Economic Load Disptach Problem, optimal scheduling of Hydrothermal stations, low renewable/ convetional energy generation efficiencies, and power network stabilizing, has proven itself to be extremely effective and reliable. FPA's commendable convergence charecteristics in conjuction with its global and local search capabilties allow for it to provide optimal solutions regardless of the size or complexity of the network. One of the key findings from the assesment of FPA in solving the ELDP, was that despite the base algorithms high efficiency in producing optimal solutions, modifications (MFPA) to the switching and pollination processes resulted in even better optimum solutions [13], [87]. These enhancement set FPA apart from conventional metahiuerstic algorihms employed to solve the ELDP, and provides higher optomization efficiencies whilst still allowing the user to benefit from the fast converge charecteristics of the algotihm [13], [87]. The scheduling of Hydrothermal power stations in smart grids proved a difficult challenge for engineers to implement whilst ensuring that operational costs were minimized. As such metahueristic algortihms such as FPA were employed to assist in providing optimal solutions to the hydrothermal scheduling problem. Assessment of research confirmed that FPA was once again able to use of its impresive convergence and local/global serach capabilities to offer reliable and efficient optizmation of hydrothemral scheduling, which ensured that fuel costs were significantly reduced. The key finding was that the inclusion of a scaling factor and an additional exploitation phase can greatly enhance the performance of FPA in this sector [84]. The unpreidctability of weather has largely contributed to poor efficines of renwable energy generation tehcnology, as such MPPT were employed to resolve this issue. Numerous algorithms had been employed to optimize MPPT devices, such as the P&O and IC, all of which thus far come with their own drawbacks which limits the ability to efficienly track the MPP. The P&O and IC methods performed poorly compared to FPA and MFPA, with FPA/MFPA requiring far less parameters to tune to track the MPP, whislt still providing higher efficiencies [93], [95], [96]. Frequency stabilization is key component in eletricity genration, as one must ensure that not only does the frequency remain stable at the plant but also once power is injected into the grid, which are connected to numerous frequency sensitive loads. As such the use of PID controllers to ensure that the frequency remains constant had been employed, with the benfits of the FPA already extensively highlighted. FPA was found to be an extremely effective algorithm for tuning of PID parameters and exceeded the performance of conventional PID optimization techniques [80], [98]–[100].

2) TRANSMISSION SYSTEMS

The use of FPA in transmission line planning, power system management, congestion management and bus voltage profile improvement, was found to be an effective tool in efficiently providing optimal solutions. In transmission line planning it was observed that the optimal TCSC power flow based on FPA produced more efficient results compared to NR. Thus, the positioning of TCSC using FPA decreased the response value [10]. In addition, a power loss was also observed after the TCSC was used, which was further decreased after setting the FPA parameters [10]. It was also observed that FPA with ε-constraint outperformed TVDFPA and SFPA in terms of determining optimal solutions with less computational effort [119]. Thus, it is confirmed that the ε-constraint flower pollination algorithm is more reliable and can effectively improve the economic reliability of the transmission line maintenance scheduling [119]. The tests conducted determined the fast voltage stability index values, using TCSC with both FPA and NR, and variable values using FPA and without FPA. The positioning of TCSC using FPA decreased the response value but there was a power loss observed after TCSC was utilized. The total real power generated, and the transmission line losses were also found to be reduced. In addition, the total active power needed to be produced and real power loss, was reduced using FPA with SVCs [11]. FPA proved to be more efficient in solving OPF problems than GM, and less efficient than Artificial Bee Colony [9]. FPA provided the least minimum congestion cost as well as a reduced power flow in both previously congested lines as compared to the other algorithms [12]. FPA successfully reduced system losses and congestion management costs in less iterations [12], [78]. In addition, congestion management can be achieved using flexible alternating current systems also known as FACTS devices. Tests were conducted on modified IEEE 30-bus and IEEE 57-bus systems, using FPA which is used to optimize the generator rescheduling. The overloaded lines were alleviated using FPA, which provided the least minimum congestion cost and reduced power flow. Further observations showed that the proposed MFPA solution had a minimum active power loss which was significantly less when compared to PSO and CSA [13], [79]. The MFPA used in bus voltage profile improvement concentrates on two factors, one looks for a closer solution while simultaneously looking at the opposite guesses. This allows for the best initial condition and eliminates the need for the switch probability. The use of MFPA greatly reduced active power loss compared to PSO and CSA, with its progress time deviation between 5-10%. A similar result is seen in the voltage bus profile improvement in which the proposed MFPA achieved a smaller minimum active power loss when compared to PSO and CSA.

3) DISTRIBUTION SYSTEMS

The use of FPA in distribution network planning, system operation, system automation, and voltage and reactive power control has proven itself as an efficient and reliable alternate approach to solving complex optimisation problems when compared to other popular meta-heuristic algorithms. FPA's better convergence characteristics allow it to provide optimal solutions with little computational effort despite the size and complexity of the system [104]–[110]. One particularly interesting finding with regards to the implementation of FPA in distribution network planning, was the inclusion of LSF in FPA. This incorporation of LSF to optimally locate and size DG and D-STATCOM allowed FPA to be imposed in various distribution systems effectively [104]. Together with its low complexity with regards to implementation, and better convergence characteristics compared to other popular meta-heuristic algorithms, FPA successfully provided better voltage profiles, PLR, and net savings in fewer iterations compared to its meta-heuristic counterparts. While FPA outperformed other meta-heuristic algorithms in distribution network planning, system automation, and voltage and reactive power control, modifying or hybridising meta-heuristic algorithms is a common practice when trying to improve the convergence rate, explorative, and exploitation characteristics of an algorithm. The use of FPA-ES when determining the optimal location and size of capacitor banks in distribution systems produced optimal solutions with less computational effort than the standard FPA [114]. Similarly, the modification of FPA using Gauss map chaotic equations to optimally schedule distributed energy sources in a smart grid resulted in a higher profit being attained whilst producing the lowest standard deviation in comparison to DSA, CSA, and FPA [80]. Overall, FPA and its variants have proven its robustness and effectiveness in achieving an optimal solution with little computation effort compared to many other meta-heuristic algorithms in the category of distribution systems [27], [111].

XII. CONCLUSION

The Flower Pollination Algorithm was developed using the interesting features presented by the evolution of flowering plants. This robust and efficient algorithm can be used to solve many multi-objective optimization problems, which are challenging in both industry and engineering. Since its inception in 2012, FPA has been well received by the science and engineering community for its performance in solving optimization problems more efficiently than other popular nature-based algorithms reviewed in other works of literature, such as Genetic Algorithm and Particle Swarm Optimization. FPA and its many variations have outperformed many prevalent algorithms used for solving complex optimization problems in power systems and with promising results. Some of these problems include the well-known economic dispatch, distribution generation and optimal power flow problem in power systems. With its successful application in multiple engineering fields, the prospect of FPA, and its variations, benefiting other fields of science as well as electrical power systems, is highly probable.

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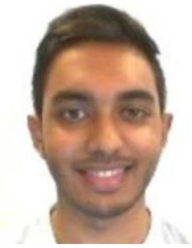

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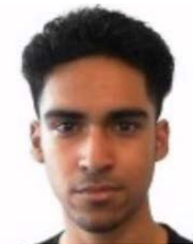

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