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ORIGINAL RESEARCH ARTICLE

A REVIEW OF OPTIMIZATION APPROACH TO POWER FLOW TRACING IN A DEREGULATED POWER SYSTEM

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ABSTRACT

Power Flow Tracing (PFT) is known to be the best method in the allocation of charges to users of transmission systems, generators and loads, in a deregulated environment. The optimization approach to PFT produced better results than other methods because it considers the physical power flow results and electrical constraints of the system. A brief review of the optimal power flow concept, PFT techniques, and the deterministic and non-deterministic optimization methods applied to PFT are presented. The paper also highlighted the future trends of hybrid optimization approach to PFT. It is recommended that more research work should be directed on the hybrid optimization methods to solve PFT problems.

1.0 Introduction

The mechanism that helps to trace the contributions or share of each user in the power flow of a particular line or in the demand power of a particular load is known as Power Flow Tracing (PFT) (Morsali and Sheikholeslami, 2011; VinothKumar and Arul, 2013). PFT results in a comprehensive view of usage allocation problems in power systems which is an important tool in transmission cost and losses allocations (Khan and Agnihotri, 2014). Conventional wisdom believes it is not possible to trace the flow of power from individual generators to individual loads in transmission networks (Al-Rajhi and Bialek, 2002). However, under various assumptions and approximations, which include ignoring linear characteristics of generators and the operating constraints of generators and transmission constraints, several tracing schemes have been proposed (Azami et al, 2012; Islam et al, 2013; Khan and Agnihotri, 2013).

Tracing generators' shares accurately is difficult due to the nonlinear nature of power flow (Mustapha et al, 2010). Traditionally, some techniques such as Postage Stamp method, MW-Mile methodology and Contract Path method have been implemented for generators and loads tracing in the deregulated power systems. Postage stamp method allocates charges and losses proportionally to load and generators based on the active generation and load consumptions of the generator and loads respectively. Contract path methodology only choses a specific continuous path between generation and load for wheeling transaction, this selection is not based on load flow studies and it cannot clearly identify the facilities that are actually involved in the transaction. The MW-Mile method based its charges on the measure of transmission capacity that is used in the transaction (Narayana, 2017; Naresh et al, 2010).

These methods were found to be inefficient because users of transmission systems were not differentiated by the extent of use of the transmission facilities (Mishra et al., 2010). The methods did not consider physical power flow results and electrical constraints such as power directions and losses. The uses of power flow tracing methods have solved the problems of transmission usage allocation in a transmission system (Lim et al, 2006). PFT is the method of determining the extent of use of a power system network by both generations and loads. It makes it possible to decompose power flows and losses in a transmission line into generator and load constituent commodities (Abhyankar et al, 2005). Optimization approach to power flow tracing problem is the most efficient method because it provides fairness in allocation of charges, flows and losses to generators and loads with simple problem formulations (Mustapha et al, 2011; Khan and Agnihotri, 2013).

Optimization methods are classified into three broad categories: the deterministic, the non-deterministic and the hybrid methods. This paper presents a review of these optimization methods that have been applied to solve the power flow tracing problems in deregulated power systems. The objective is to bring researchers up to date and suggest directions for future research works.

Power Flow Tracing Techniques

The typical power-pool operators are faced with the challenge of how to allocate transmission usage and what should be the criteria for charging other utilities. Utilities in general consider locational signals, consistency, simplicity, accuracy and predictability, but, it is extremely difficult to accommodate all these considerations in a complex phenomenon like PFT (Chengaiah and Jyoshna, 2013). PFT techniques are mainly classified into the following (Khan and Agnihotri, 2013).

- Proportional Sharing Principle (PSP)
- Graph Theory
- Circuit Theory (Z-bus tracing)
- Optimization Approach
- Game Theory
- Relative Electrical Distance
- Equilateral Bilateral Exchange

The main differences of these methods lie with the way to treat losses, reactive power, loop flows and the arithmetic. The PSP satisfies Kirchhoff's Current Law and assumes that the network node is a perfect 'mixer' of incoming flows. In this respect, the principle is fair as it treats all incoming and outgoing flows in the same way (Bialek, 1997; Su and Liaw, 2007). This approach allocates usage to each transmission system user based on the extent of use of the system. This is determined as a function of magnitude, path and distance travelled by transacted power (Khan and Agnihotri, 2013).

Directed graphs are used in the Graph Theory method. The vertices of the graphs are system buses and the edges of the graphs are lines and transformers. The direction of each edge is the direction of power flow. The directed graphs of active power may be different from that of reactive power flow in edge directions (Wu et al, 2000). Graph theory is quite mature and suitable to tackle network topology related issues such as counter flows (Lim et al, 2006). Circuit theory method trace the power flow based on the converged alternating current power flow solution. The method uses the transmission network structures, the equivalent-current-injections and load equivalence admittances where all the electrical circuit theories are satisfied (Lin et al, 2006). The method allocates line losses according to the true contributions where counter flows can be fairly treated (Meng and Jeyasurya, 2009).

Optimization techniques came about since the contributions of generators satisfy simultaneously different objectives such as the real power balance flow at each line, generator real power outputs and real power balance at each node of the system. Optimization method offers accuracy in determining the generators contribution (Vlachogiannis and Lee, 2005). Inaccurate assumptions have been made in all other previous methods, ignoring various characteristics of the generators and operating constraints of transmission lines, which have resulted in the reduction of their acceptability, accuracy and flexibility in complex and large systems (Hasanpour et al, 2010).

Game theory provides a concept that is used when assessing the interactions of different agents in competitive markets and in the solution of conflicts that arise in that direction, such as those of electricity markets (Zolezzi and Rudnick, 2002). The concept of Relative Electrical Distance (RED) is based on the relative locations of load points with respect to the generator points in open access (Thukaram and Vyjayanthi, 2009). RED overcomes the limitations of other methods because it considers network configuration which is independent of the location of the slack bus (Thukaram and Vyjayanthi, 2008). Equivalent Bilateral Exchange (EBE) works on the linearized model of power system (Silva and Cuervo, 2008). The principle calculates agent's use of network using a simple direct current load flow model (Silva et al, 2005). EBE principle is characterised by independence from slack bus. Satisfaction of Kirchhoff's laws, counter flow acceptance or rejection, location dependent rates and low temporal volatility of transmission use rates and allocation of non-zero charges to all network users (Galiana et al, 2003).

Optimal Power Flow Concept

Optimization is the process through which the best possible values of decision variables are obtained under a given set of constraints and in accordance with a selected optimization objective function (Shrivastava and Siddiqui, 2014). Optimal Power Flow (OPF) concept was first introduced in 1960s to solve economic dispatch problems in power systems. The concept was developed using voltage and power flow as optimization constraints (Nazaran and Selvi, 2014). OPF optimizes specific objective function such as generation cost and total power loss by controlling power flow within an electrical network subject to a number of constraints due to system control and operational factors (Frank et al, 2012; Low, 2014).

Optimal Power Flow (OPF) is used to efficiently allocate power in the electrical network, under various operation constraints on voltages, power flows, thermal dissipation and bus powers. Due to the nonlinearity of the power flow equations, OPF problems are generally non-convex which make them hard to solve, in other words, there can be no general, efficient algorithm for solving the OPF (Bukhsh et al, 2013).

OPF, like Power Flow Analysis (PFA), determines the voltage, current and power injections in an electrical power system that is operating in its steady state. The difference between OPF and PFA is that OPF can have multiple solutions because it performs multiple power flow iterations (Frank

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et al, 2012). OPF problem is generally expressed as a nonlinear, non-convex, large scale static optimization problem with both continuous and discrete variables (Capitanescue et al, 2007; Frank et al, 2012).

Different OPF formulations have been developed to address specific instances of the problem using varying assumptions and selecting different objective functions, control and system constraints. Energy market calculations, transmission switching, distribution network configuration, capacitor placement, expansion planning, vulnerability analysis and power system restoration are some of the subsets of power system optimization problems that include a set of power flow equations in the constraints and are all classified as a form of OPF but given different names (Frank et al, 2012).

Variables are required to represent electrical states of the system in OPF formulations. The types of variables commonly used in the formulations of OPF are state control variables. State variables are continuous and mostly include bus voltage magnitude, bus voltage angle and real and reactive power injections at each bus. Control variables may be continuous or discrete and typically include a subset of state variables as well as variables representing control device settings such as transformer tap ratios (Soliman and Muntary, 2012; Frank et al 2012).

The general structure of OPF formulations is represented using the following standard form (Capitanescue et al, 2007; Frank et al, 2012):

$$\min f(u, x) \tag{1}$$

Subject to:

$$g(u, x) = 0 \tag{2}$$

$$h(u, x) \leq 0 \tag{3}$$

Where;

f(u, x) = objective function of the system's optimization goal

g(u, x) = system equality constraints

h(u, x) = system inequality constraints

The OPF objectives commonly used are the minimization of generation costs, with or without consideration of system losses, and minimization of system total loss. Other objectives include maximization of power quality and minimization of capital costs during system planning. In nearly all these cases, the objectives are functions of the system's real and reactive power generations (Frank et al, 2012).

OPF constraints are categorized into equality and inequality constraints. Equality constraints, g(u, x), include the power flow equations and any other balance constraints. The inequality constraints, h(u, x), include the minimum and maximum limits on control and state variable such as bus voltage and line current magnitudes (Lavaei and Low, 2012; Rao et al, 2014).

Classifications of Optimal Power Flow Problem Solutions

The first work on OPF was carried out by Carpentier in 1962 (Lavaei et al, 2011). The increasing need for OPF to solve today's deregulated industry and the unresolved problems of the vertically integrated industry gave way to extensive studies in literatures (Momoh et al, 1997; Lavaei et al, 2011). Evolutions of the OPF since inception and their applications have been reported in literatures (Pandya and Joshi, 2008; Amarnath and Ramana, 2008; Frank et al, 2012; Frank et al, 2013).

Numerous algorithms have been proposed, developed and applied to the highly nonlinear, non-convex large scale OPF problems in power system. The algorithms are classified as deterministic and non-deterministic methods (Frank et al., 2012; Khamees et al, 2016). Deterministic methods are classical or conventional methods based on mathematical programming approach (Narayana, 2017). Excellent progress has been made in the deterministic methods but the methods still have the disadvantages of, among others, differentiability and linearization requirements, getting stuck at local optimum, poor convergence, weak handling of qualitative constraints, becomes too slow for large number of variables and can only find single optimized solution in a single simulation run. The deterministic methods applied also have the limitations of that include not been able to model discrete power system variables and requirements of enormous computational efforts which tend to fail as the problem increases.

The non-deterministic methods, on the other hand, have the advantages of handling various qualitative constraints, find multiple optimal solutions in a single simulation run, solves multi-objective optimization problems and finds global optimum solution. The deterministic methods include the following (Pandya and Joshi, 2008; Amarnath and Ramana, 2008; Lavaei and Low, 2011; Frank et al, 2012; Frank et al, 2013):

Gradient method

Newton's method

Quadratic Programming method

Linear Programming method

Nonlinear Programming method

Nonlinear Programming method

Interior Point method

In Linear programming (LP) method, objective function as well as constraints with nonnegative variables are involved and their linearization is required which possess extra burden. Gradient method uses the first order derivative vector (i.e. gradient) of the objective function of a nonlinear optimization to determine improvement in the direction for the solution in the iterate steps. Gradient method has the advantage of being reliable, easy implementation, and guaranteed convergence but are slow compared to higher order methods (Narayana, 2017). Quadratic programming (QP) has its objective function being quadratic while the constraints are linear. QP is a special form of Nonlinear programming. Newton method is a second order method for an unconstrained optimization based on the application of second-order Taylor series expansion about the present candidate solution (Bansal, 2005).

Optimization problems involving nonlinear objective and/or constraints are referred to as nonlinear programming (NLP). NLP captures power system accurately, however, it involves much theoretical and computational challenges. Interior Point Method (IPM) solves both linear and nonlinear optimization problems which constraint the search to the feasible interior region by introducing barrier terms to the objective function. IPM is the most successful deterministic optimization method (Frank et al, 2012; Frank et al, 2013; Narayana, 2017).

The non-deterministic methods are the intelligent methods which have been developed to overcome the weak global search capabilities of the traditional methods. The following are some intelligent methods used in solving OPF problems (Pandya and Joshi, 2008; Amarnath and Ramana, 2008; Frank et al, 2013):

Genetic Algorithm (GA)

Particle Swarm Optimization (PSO)

Artificial Neural network (ANN)

Evolutionary Algorithms (EA)

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Chaos Optimization Algorithm COA)

Ant Colony Optimization (ACO)

Genetic Algorithm (GA) is an evolutionary search algorithm which use the mechanics of natural generations. It operates on encoded binary string where each string represents a chromosome that completely describes one candidate solution to the problem (Bansal, 2005). Particle Swarm Optimization (PSO) is a population based non-deterministic method based on naturally arising processes in socially organised colonies such as bird flocks and fish schools. The method exploits individual's population to explore promising regions within the search space (Bansal, 2005). Artificial Neural Network (ANN) is a computational tool based on biological neural network operations. Its principle of operation is based on the principle of parallel processing analogous to the operation of human brain. ANN is fast and can deal with stochastic variations of the scheduled operating point given increasing data (Bansal, 2005).

Evolutionary Algorithm (EA) include a numerous technique based on the principles of biological evolution which requires maintenance of a pool to mimic individual's evolution inside a population. EAs are efficient for problems evolving over time and solved repeatedly. Chaos is a common nonlinear phenomenon whose action is a complex action similar to randomness (Lu et al, 2006). COA is population based optimization method which uses chaotic maps based on ergodicity, stochastic properties and regularity of chaos. This method does not escape from local minima, unlike some optimization methods, by accepting some bad solutions according to certain probability (Mohammad and Roghiyeh, 2015).

Ant Colony Optimization was proposed in 1992 (Rahmat and Musirin, 2013). The method was inspired by the foraging behaviour of ants in their search for food. Ants frequently explore the areas surrounding their nests in a random manner when searching for food and when an ant finds a source of food, it evaluates the quantity and quality of the foods and deposits pheromone in their paths (Galal et al, 2013).

Two or more different optimization techniques can be combined into one algorithm to form hybrid method. Hybrid method is the combination of two or more different techniques or two or more high strength algorithms. The aim is to use the advantages of one method to overcome the disadvantages of the other methods or taking the advantages of their high performance characteristics which lead to powerful algorithms (Frank et al, 2012). Hybrid algorithms have produced the best results for many practical and academic optimization problems because of the exploitations of benefits of hybrid synergies (Blum et al, 2011). Hybrid methods are more robust and converge more quickly to optimal solutions than their individual components operating alone.

Hybrid optimization techniques started gaining popularity in the last two decades in their applications to various OPF problems. Hybrid optimization algorithms can be formed in three different ways (Blum et al, 2011):

Deterministic methods combined

Non-deterministic methods combined

Deterministic and non-deterministic methods combined

Interior Point Method (IPM) which is a deterministic method has been combined with Newton's method and Line Search which are also deterministic methods to form a hybrid optimization method by Han et al, (2009). The IPM was used in the computation of direction of descent for the objective function while the Newton's method and the line search technique were used to solve various auxiliary problems. The hybrid algorithm was found to converge to a Karush-Kuhn-

Tucker point of the OPF and it maintained feasibility in each iteration. The algorithm was evaluated using several test systems and the results were promising.

Hybrid PSO algorithm incorporating Chaos was proposed as an effective and efficient optimization algorithm for numerical functions. The two separate optimization methods are both non-deterministic methods combined to form a hybrid. Exploration process was performed by the PSO while the exploitation process was performed by chaotic local search. The hybrid algorithm was found to have superior search quality, efficient and robust on initial conditions. It was much faster than the heuristic methods individually (Liu et al, 2005; Wang and Lin, 2016).

A non-deterministic-deterministic hybrid optimization method was developed by Shengsong et al, (2002) which combined a chaos optimization algorithm and linear IPM. In this work, COA performed the global search while IPM was used for local search. The algorithm was reported to produce a more robust convergence and determined a global optimum solution compared to either algorithm separately.

Power Flow Tracing Optimization Problem Formulation

PFT problems are framed as optimization problems with objective function, equality constraints and inequality constraints. The power generated by a generator is equal to the sum of the total power contributed to loads and the total loss due to that generator (Chellam and Kilyani, 2014).

Mathematically, the unified optimal tracing problem is expressed as follows:

$$\min f(x,y) \quad (4)$$

Subject to:

$$A_d x = b_d \quad (5)$$

$$A_u y = b_u \quad (6)$$

$$y_k^i P_{Li} - x_i^k P_{Gk} \geq 0 \forall k \in \{1,2,\ldots,n_G\}, \forall i \in \{1,2,\ldots,n_L\} \quad (7)$$

$$[0,0,\ldots,0]^T \leq [x] \leq [1,1,\ldots,1]^T \quad (8)$$

$$[y] \geq [0.0\ldots.,0]^T \quad (9)$$

Where;

x = Solution vector to generation tracing

y = Solution vector to load tracing

A_d = Equality constraints matrices corresponding to generation tracing

A_u = Equality constraints matrices corresponding to load tracing

b_d =Right-Hand-Side of equality constraints for generation tracing

b_u = Right-Hand-Side of equality constraints for load tracing

N_G = Total number of generators

N_L = Total number of loads

P_{Li} = Real power at bus i

P_{Gk} = Real power injection by generator k

x_i^k = Real power fraction of generator k contributions towards load i

y_i^k = Real power fraction of load I contributed by generation k

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(4) is the objective function derived from the power-balance equation. Equation (5) and (6) represent the equality constraints for both generation and load tracing formulations. Equations (7) to (9) are the inequality constraints.

Power Flow Tracing Optimization

Deterministic Optimization Methods

The most famous optimization approach to PFT foundation was first proposed by Abhyankar et al, (2005a). The paper was devoted to constraint modelling of the approach. A multi-commodity network optimization approach was used for optimal tracing of power flows to introduce a linear constrained problem known as Optimal Tracing Problem. The formulation of the optimization problem required flow specification constraints, source and sink specification constraint and conservation of commodity flow constraints which were all modelled as equality constraints. The result was the formulation of a unified generic model for optimal PFT which can be solved with and objective function to achieve fairness in transmission costs, usage or loss allocations. The optimization formulation resulted in a sparse linear programing problem. The advantage of the linear constrained optimization is that all of the degree of freedom in tracing are retained and exploited. This work forms the basis for almost all the research works as all other works only applied the theories to solve different tracing problems. Only objective functions were required to be formulated while the framework provides the constraints modelling.

Different deterministic optimization methods have been used to solve the linear programing problems and the solutions have been applied to various power system problems. General Arithmetic Modelling System (GAMS) software was used to solve the programing problem and used to allocate loss and its cost between system loads by Amoli and Jadid (2008). The power flow optimization approach in this work was based on the work of Abhyankar et al., (2005a). In this work, proportional tracing and optimal real power tracing methods were used for allocation of loss and its cost considering congestion in the transmission lines. Power flow tracing analysis was carried out using the IEEE 14 bus standard system. The result was compared with the proportional tracing method, a non-optimization method, and it was concluded that optimization method was a better method than the proportional tracing method.

Abhyankar et al, (2005b) proposed a tracing compliant modified postage stamp loss allocation method. This was based on their established previous work that formulated the power flow tracing as a linear constraint optimization problem. The method computes a traceable solution that minimises deviation from the postage stamp allocation of losses. The paper considered the load allocation of three different methods which are optimal tracing method, postage stamp method and network usage method by proportional tracing. A specific case of Indian power system was used. The conclusion was that the tracing compliant postage optimization method achieved fairness to all users of the network. This same method was applied in the allocation of transmission fixed cost determination of the Indian power system and results showed it is better than the postage stamp method (Abhyankar et al., 2006).

The optimization approach to power flow tracing was used in tackling circular flows which terminates the graph theoretic approach when directed graph of power flow is cyclic. This paper tackled the problem of circular flow using the optimal power flow tracing approach developed by Abhyankar et al, (2005a). It was shown that optimization method converged to a solution even in the presence of circular flows due to the constraint modelling in the optimization method (Abhyankar et al,2006). A min-max algorithm which equalises allocations within constrained space and reaching equilibrium where it cannot be achieved in other methods was used to achieve fairness in fixed cost allocations. The method corresponded to solving a sequence of sparse linear programing problems for real power tracing (Abhyankar et al, 2007; Rao et al, 2010).

Non-Deterministic Optimization Methods

Various non-deterministic optimization methods have also been applied to power flow tracing problems. A Genetic algorithm for the determination of generator contribution to transmission systems was used by Mustapha and Sulaiman (2010) and Naresh et al, (2010). By treating voltage contribution as an optimization problem, the transmission usage allocation problem was traced by tracing the voltage contribution for the individual generator at each bus. In these papers, Genetic Algorithm (GA) is used to rework the power flow tracing using the approach of the traditional tracing. The Genetic Algorithm (GA) was used to compute an optimized result of voltage contribution to allocate power flow and loss in the power system. The formulation of PFT equations were based on the formation of branch impedance matrix and adjacency matrix in the MW-Km and MVA-Km methods. Transmission cost allocation using GA was compared with the traditional MVA-Km tracing method. It was shown that GA performed better than other methods; GA distributed the power flow effectively and minimises the net system transmission costs and losses.

Evolutionary Programing and Evolutionary Algorithms were employed for the generator and load tracing in deregulated the power system (Hamid et al, 2011a; Hamid et al, 2011b). The power flow tracing equations were solved using the evolutionary programming approaches were the optimal power flow tracing equation developed by Abhyankar et al., (2005) which are equations (4) – (9) above. The results of the stochastic optimization method were recorded to be better alternatives to traditional tracing methods due to problems of matrix inversion which can lead to an indefinite and undefined solution in the conventional problem. It was concluded that Artificial Intelligence based tracing solutions are fair and non-discriminatory with tolerable computation time and simplicity in computation.

Flower Pollination Algorithm (FPA) for real power generation tracing in a deregulated system was carried out by Kerta at al, (2015). The formulations were based on the objectives and constraints developed by Abhyankar et al, (2005a). FPA gave satisfactory results compared to traditional methods. The method is free from matrix inversion and independent of matrix singularity. It has fast computational time and is simple. Basha and Anitha (2016) used the Firefly Algorithm (FFA) for power flow tracing based congestion management in a deregulated electricity market. Non-deterministic optimization methods have the major disadvantage of premature convergence and been trapped at the local minimum.

Hybrid Optimization Methods

Many hybrid optimization methods have been employed in power flow tracing. Vlachogianis and Lee (2005) used the Vector Evaluation Particle Swarm Optimization (VEPSO) algorithm for the determination of generators contribution to a transmission system. Power flow tracing was formulated as a multi-objective optimization problem that combined the nonlinear characteristics of power system which include thermal limits of transmission lines and prohibited operating zones of generators. The multi-objective function has three objectives which are equal total contribution of generators to each transmission line; satisfactory real power balance between all generators contributions and the local generation and demand at each node; total contribution of a generator injected into the transmission system must be equal to the generator real power output minus local demand.

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Genetic Algorithm (GA) was incorporated into Least Square Support Vector Machine (LS-SVM) has been used to determine the shares of generators to loads and lines Mustafa et al, 2011). A circuit theory based superposition method was adopted in this work as a tracing, validating and testing process. The GA is used to find the optimal values of hyper-parameters of LS-SVM which adopts a supervised learning approach to train the LS-SVM model. The result showed the advantage of GA-SVM in better computational time.

Blended Crossover Continuous Ant Colony Optimization (BX-CACO) with simple and easy formulation steps has been used for load tracing (Hamid et al, 2012a; Hamid et al, 2012b; Hamid and Musirin, 2014). A hybrid mean calculated during solution update process is introduced in the ACO and crossover operation of GA was adopted. The formulations were based on the objectives and constraints developed by Abhyankar et al, (2005a). The method produced a wide variety of solution to prevent premature convergence problem in the original ACO. Mutation operation of GA was also introduced into Particle Swarm Optimization (PSO) to solve power flow tracing problem (Chellam and Kalyani, 2014) to prevent pre-mature convergence in PSO.

Conclusion

Power Flow Tracing is an important power system analysis in this era of power system deregulation. PFT provides the best way of addressing loss and cost allocation problems. This paper has briefly reviewed the best method of PFT. This work showed all the methods applied to power flow tracing problems which are deterministic, non-deterministic and hybrid methods. The hybrid methods combined the advantages of both the deterministic and stochastic methods to form the best optimization method. It was observed that so much works has been carried out using deterministic, non-deterministic and hybrid methods to solve PFT problems. It was also observed that no known work has been reportedly published to solve PFT problem using hybrid deterministic-non-deterministic optimization method. Research works are therefore encouraged to explore the advantages of a hybrid optimization approach to PFT especially methods that will combine deterministic and non-deterministic optimization approaches.

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