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A Comprehensive State-of-the-Art Survey on the Transmission Network Expansion Planning Optimization Algorithms

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ABSTRACT Long term planning in power transmission network expansion provides a well ordered and profitable extension of power equipment and facilities to meet the expected electric energy demand with an allowable degree of reliability. However, high quality and improved reliability in energy supply have to be balanced with the available funds. The need to expand transmission network can never be over emphasized. Transmission Network Expansion Planning (TNEP) is a periodical measure that must be carried out due to dynamic societies that attract extra energy demands. It is highly important to minimize the network reinforcement and operational costs while satisfying the increase in demand imposed by technical and economic conditions over the planning horizon. Several optimization algorithms for TNEP problems have been developed and applied over the past decades. This paper presents a comprehensive state-of-the-art survey on the TNEP optimization algorithms. The approach of this paper is in the area of highlights of the various available TNEP algorithms, their applications, viability, computational complexities and drawbacks, which can aid in the identifications of the proper methods that can yield an optimal solution to TNEP problem.

INDEX TERMS Algorithm, hybrid, meta-heuristics, optimization techniques, power network expansion planning, power system, transmission network expansion.

I. INTRODUCTION

Bulk energy supply network comprises of generators, transmission lines and loads, which generate, transmit and consume the generated power respectively. Power networks are mainly geographically vast and sophisticated interconnected network with several lines linked together in web-like manner under the control of a single network operator [1]. Power flow in transmission line must be in accordance with the laws of physics. For instance, the power flowing in transmission lines must be in proportion with the electrical characteristics and material properties of the lines. In order words, power transmitted in a line can be influenced by the material properties of other lines connected in the same network, which makes it possible to add or remove a line and upgrade the throughput of the system [1]. The technique of obtaining the optimal size, place and appropriate time for the addition of new resources to an existing power system is known as power system expansion planning [2].

Long term planning in power system is more of a general problem in energy system expansion and economic development planning.The central idea is to obtain a minimum cost technique for long term expansion of the generation, transmission and as well as distribution systems among a set of certain constraints such as weather, social, economic, technical and political constraints [3], [4]. One of the major strategic decisions in power systems is the transmission network expansion planning.Transmission network expansion planning (TNEP) has one major goal, which is to expand the existing network by integrating new power plants and new distribution links in order to prepare against the increasing future energy demand, thereby maintaining the system's reliability and efficiency [5]. Its nature is normally a mixed integer, non-linear, non-convex optimization problem which aims to optimal selection of the routs, types, and number of the new circuits to be added in order to face the expected

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future predicted load forecasting at minimum costs [6]. The commercial-based planning in transmission expansion takes into consideration, the existing economic status, system reliability constraints, security [6], [7] and the risk of planning strategies due to several uncertainties [2].

Due to the fact that its nature has a long-lasting and a deep impact on the operation of the system, it is always a problem when it comes to deciding the new lines to be included in an existing network in order to efficiently satisfy the system's objectives [4], [8].

TNEP involves the evaluation of which new lines to be added to the existing network in order to enable the system to satisfy forthcoming loads with the acceptable level of reliability [4], [9]–[11].

The major reasons for TNEP are due to large-scale grid upgrades necessary to accommodate renewable generations due to high demand in energy and as well as increase in cross-border capacity, which is good for economic growth [4], [12].

Integration of renewable energy sources in power network expansion planning is crucial due to emission reduction targets and clean energy supply to the grid [10]. However, renewable energy sources pose further challenges in TNEP process [13]. The renewable energy intermittent behaviour and the inherent uncertainties of long term TNEP demand the use of fast solution technique that can explicitly cope with the uncertainties [12].

Increase in uncertainty when combining significant share of renewable energy sources in large grid planning and finding the optimal design of large grid along with its modular development plan over a long period of time are the major issues tackled by [14].

Moreover, evacuation of power generated and the investment costs are becoming more of bigger problem than the generation expansions due to inadequate TNEP capacity and several uncertainties. [15].

Meanwhile, the prior work of the author, Hamam [16], states that a good security of power supply for any given period is when the total installed capacity exceeds the peak demand by a certain amount within the specified period of time. Such amount of extra capacity is known as reserve.

The allotment of energy storage systems is optimized in coordination with the transmission expansion by taking into consideration the operational costs, investment costs and risk costs [7]. Hence the main objective should be to determine the optimum expansion plan with regards to the new circuits (lines and/or transformers) and new energy storage systems to be added in order to allow a feasible operation with a minimized cost effect [7], [17]. Therefore, an ideal transmission network expansion planning is a type that should define, when, where, how many new extensions and new energy storage systems to be added to the existing system [4], [7], [9], [17].

Moreover, an optimal TNEP is the one that is capable of minimizing the total costs due to additional investment, production and reliability costs [18]. It is a non-detachable aspect of long term power system planning [4].

The numerous variables, which exist in energy system expansion problems give way to several mathematical models developments designed for a suitable systematic way of obtaining the optimal solution to long term planning in power network expansion. The planning must take into account the current and future technical and economic environment within which the power sector is expected to exist. Optimal solution is the minimization of the discounted cash flow, both operating expenses and available capital over the long term period. Such is expected to reduce the effects of uncertainties beyond the given period [3].

Most of the current TNEP models are usually oversimplified in certain aspects such as the use of reduced network equivalents, limiting expansion operation to adding new circuits in a given corridor and also limiting the planning horizon to one or few years, which do not always meet the requirements for a proper and practical TNEP. To overcome such challenges, improved models and algorithms capable of considering a higher degree of detail in the TNEP problem are needed [19]. Optimal TNEP parameters such as operation cost, reliability penalties and investment expenses should be taking into consideration for proper model development of the network planning.

Transmission lines and generation plants contingencies are described in the reliability aspect of the planning, while operation aspects incorporate a stochastic description of the hydro inflows, energy demand, fuel costs and renewable energy generation due to their unpredictable change in nature [10].

The contingencies can be expressed dynamically by the use of Progressive Contingency Incorporation (PCI) method, which have been developed and applied by several authors [10], [20].

It is a good practice to look into inter-state and inter-regional power flows to develop a proper and suitable transmission network expansion plans in line with the growing demand [11].

A review on the state-of-the-art shows that the strategy to find the solution of TNEP by classical mathematical optimization is normally slow, insufficient and tedious [21]. However, nature inspired algorithms, which are part of heuristic and meta-heuristic algorithms have proven their capability of providing better solutions to TNEP problems with less computational complexities over mathematical optimization algorithms.

This review paper was carried out based on the selected papers' subjects such as TNEP solution algorithms [22], electricity markets [22], [23], reliability [23], [24], Computational complexities and uncertainties [25]. Moreover, it is a good practice to set up criteria for choosing reference papers, such as the subject matter, journal and conference categories, novelty of papers and the year of publication [4].

The purpose of this paper is to review different optimization algorithms that have been developed and applied in TNEP problems. This will pave way for a proper recommendation of the most viable and low computational complex algorithm(s) for future TNEP applications. However the scope of this paper will not cover transmission network modeling, generation and distribution network expansion planning, power plants characteristics, energy storage system analysis, demand estimation, generation and load forecasts.

The criteria set for choosing reference papers are similar to that of Hemmati *et al.* [4], however, the novel approach of this paper is in the area of comparison of the previously applied TNEP algorithms, their applications, viability, computational complexities and drawbacks, which can aid in the identifications of the best algorithm(s) that can yield an optimal solution to TNEP problem.

The remaining part of the paper is organised as follows: First, Section II. presents some of the past related literature survey for TNEP problem. Section III. presents the review of TNEP optimization techniques along with choice of modeling techniques,reliability issues and uncertainties. Section IV. presents the mathematical optimization algorithms in solving TNEP problems. Section V. presents the meta-heuristic optimization algorithms in solving TNEP problems. Section VI. presents the hybrid optimization algorithms in solving TNEP problems.Section VII. presents the computational complexity of TNEP solution algorithms. Finally, section VIII. presents the conclusion and future work.

II. PAST REVIEW WORKS ON TNEP

Over the past decades, several researchers have come up with numerous reviews of related literature in the field of TNEP [4]. It is quite necessary to point out the methods and aspects through which some of the researchers followed in reviewing TNEP problem. This is to allow for visibility and identification of some uncovered area of interests for future implementation.

Lee *et al.* [26], classified and organised the existing TNEP algorithms into regulated and deregulated environment aspects. This was done so as to facilitate the present and future research works in TNEP field. The paper made two suggestion for future TNEP problem approach, viz: The unavoidable standard elements that are still needed in TNEP algorithms and the specific conditions and market regulations that can turn the algorithms from academic feasibility to commercial feasibility.

Hermati *et al.* [4], on the other hand, reviewed TNEP problem from different aspects such as distributed generation, solving methods, line congestion, reliability, modeling, electricity market,reactive power planning and uncertainties. The review results show a clear framework for further works in the field of TNEP. However, it was stated that there is no unique methodology nor approved pattern in solving TNEP problem. The solution to the problem differs from one system to another.

A critical review on TNEP was carried out in [8]. Its focus is mostly on recent developments. Current challenges to TNEP and the illustrations with some instances in a European context were analysed. modeling decisions and solution algorithms for TNEP classifications are proposed, which are linked to some of the main representative works in literature with more emphasis on the most current advances. The final aim of the article was to provide an overview of TNEP problem and its current circumstances, along with comments that can serve as a guide in selecting an appropriate modeling features and solution methods.

A review on TNEP was carried out by [8]. It was focused on recent developments such as regional plannings and renewable energy sources integration to the existing European grid. Several perspectives such as modeling, reliability issues, approaches for solving the TNEP problems, tools for optimization and electricity market was presented in [27]. The outcomes of the review offer a broad view of the planning problems and the approaches to the corresponding solutions, which could also provide related future directions of TNEP solutions.

III. REVIEW OF OPTIMIZATION TECHNIQUES FOR TNEP PROBLEMS

The escalating demand to lower production costs to resist global contest has driven engineers to look for Fuzzy methods of decision making, such as optimization techniques, to propose and manufacture both cost-effective and efficient products and systems [28]. Optimization techniques, which have reached its high degree of maturity in recent years, are being utilised in a wide spectrum of industries, such as electrical, construction, automotive, chemical, aerospace and manufacturing industries [28].

Optimization techniques, together with contemporary tools of computer-aided design, are used to improve the creative process of conceptual and comprehensive design of engineering systems. With fast growth in computer technology, computers are becoming more powerful, and likewise, the size and the complexity of the problems that can be solved using optimization techniques are also increasing [28].

Optimization techniques help in systematising this planning procedure and also help in alternative consideration of expansion schedules. However, the inclusion of reliability aspect does complicate the process because of reliability constraints [29].

Expressing an optimization model in general, demands the formulator to keep the model as simple as possible. It’s important to include only those decision variables, objectives and constraints that are essential for yielding the optimal solution to the problem [30].

Many TNEP techniques have been tested by many transmission network planners and numerous publications available in literature do have new improvements in TNEP problem’s solution strategies such as new optimization algorithms, availability of high speed computers and deregulated power sector uncertainty level [27].

Market-based TNEP model, which takes into consideration the wholesale electricity market with double-sided auctions is presented by [31]. In the paper, reliability-based transmission expansion and market-based approaches were compared in Long-term power system capacity expansion planning. Nevertheless, it was deduced from the paper [31], that the comparison lacks clear distinction between reliability-based transmission projects and value-based transmission projects as most transmission operations do bring economic benefits and as well as reliability to the system. Although reliability aspect was not considered in the planning model, yet the optimal investment plan to maximise the economic benefits could be identified by the market-based transmission planning. Social surplus, which is one of the economic theories was identified as a good indicator used to quantify the economic benefits of the transmission expansions. This is because it can indicate how efficient the market can work.

A new market-based TNEP model was compared with a traditional reliability-based TNEP model in [32]. Both models utilized Bender's decomposition and the overall problems of both models were decomposed into master and slave problems. The master problem makes the investment decisions, while the slave problem implements the expansion plans suggested by the master problem and provides feedback to the master problem concerning the operating state of the system. Both models were tested using a 5-bus system and again using a 30-bus system. The results showed that the traditional reliability-based TNEP model was overshadowed by the market-based TNEP model in terms of enhancing market efficiency, relieving system congestion and reducing load payments. However, the implementation of the investment decisions generated by the market-based planning was considered unnecessary.

A comprehensive view on TNEP is presented by Ramos and Lumbreras [12]. Benders decomposition and its accelerator technique along with a decision support system called semi-relaxed cuts were applied in the paper. The technique was earlier proposed in [10], [20] and Spanish transmission power system was utilized as a case study. The expansion planning time range is 12 years (from 2008 to 2020) and the Spanish transmission power system public data (from ENTSO-e and REE e-sios cases) is being used. The data consists of 1084 nodes and 294 power plants of different technologies including nuclear, diesel imported coal, hard coal, hydro, oil, wind and solar systems. Three case studies were presented, based on IEEE test cases and about 50% of the solution time was saved due to the simplicity and flexibility of the technique. It was shown that such can be implemented both in further TNEP academic research and in practical TNEP application.

A static optimization problem for long term PERLA network expansion was formulated by Alonso *et al.* [18]. The global annual cost, which aggregates the reliability cost, operation and the annualised investment cost was minimized using Bender's decomposition method. Multiplicity scenarios, which are characterised by the availability of components, the demand and the hydraulicity were considered. The popular transportation model was used to represent the network. The efficiency of the model was verified by detailed comparative analysis using more realistic network models and planning scenarios of Spanish systems.

It is stated in the paper [18], that several models were used and a large number of test cases were studied in the course of the system's analysis. Nevertheless, only the reduced version of Spanish system (46 areas and 87 corridors) was presented in the paper. It was stated also that different scenarios in the production cost and reliability aspects were tested as well as the original network's different simulated levels of insufficiency. The crucial aspects of the research are the representation of the power flow by a transport model, the use of continuous variables to model the naturally discrete investment decisions and the convenience of inclusion of the effect of losses in the production cost model.

The investigation of an advanced optimization and simulation techniques to tackle the very large and complex problem, which includes highly combinatorial aspects and stochastic behaviours of system components, while taking into account some control over the system is the approach of [14], in solving TNEP problem.

Moreover, a Monte Carlo approach was adopted to address the stochastic nature of the problem. The control over generation planning was not considered when solving the problem, rather the approach considered a transmission operator perspective.

In summary, optimization problem deals with finding the optimal choice out of a set of alternatives by either maximizing or minimizing set of functions in real time [33]. Energy aspect of optimization models are used in optimizing energy investment decisions endogenously and the results are normally the optimal solution for some input variables to satisfy certain constraints. It requires a relatively high mathematical knowledge and the processes must be analytically defined.

An innovative power transmission management paradigm that utilizes the power network properties is the optimal transmission switching [1]. The aim of switching off and on of power lines is to maximise economic efficiency of power generation dispatch on transmission network. Binary variables can be used to represent statuses of power lines during the formulation of the optimization problem for optimal transmission switching [5].

The mathematical optimization and its boundaries depend on the system's objective(s), decision variables and the constraints.

The tasks and steps that must be followed to come up with a well constructed optimization technique in solving any engineering problem start with the problem's scope definition. Followed by determining the decision variables and the system's constraints by the objective(s) of the task. Once the model is ready, a small set of the populated data must be fed into the model for a test. Adjustments should be made where necessary and advanced solution techniques could be developed if required.

A. CHOICE OF MODELING TECHNIQUES IN TNEP

The solution to TNEP problem entails the use of general network synthetics techniques, and the relaxed mathematical models using the active power and the voltage angle

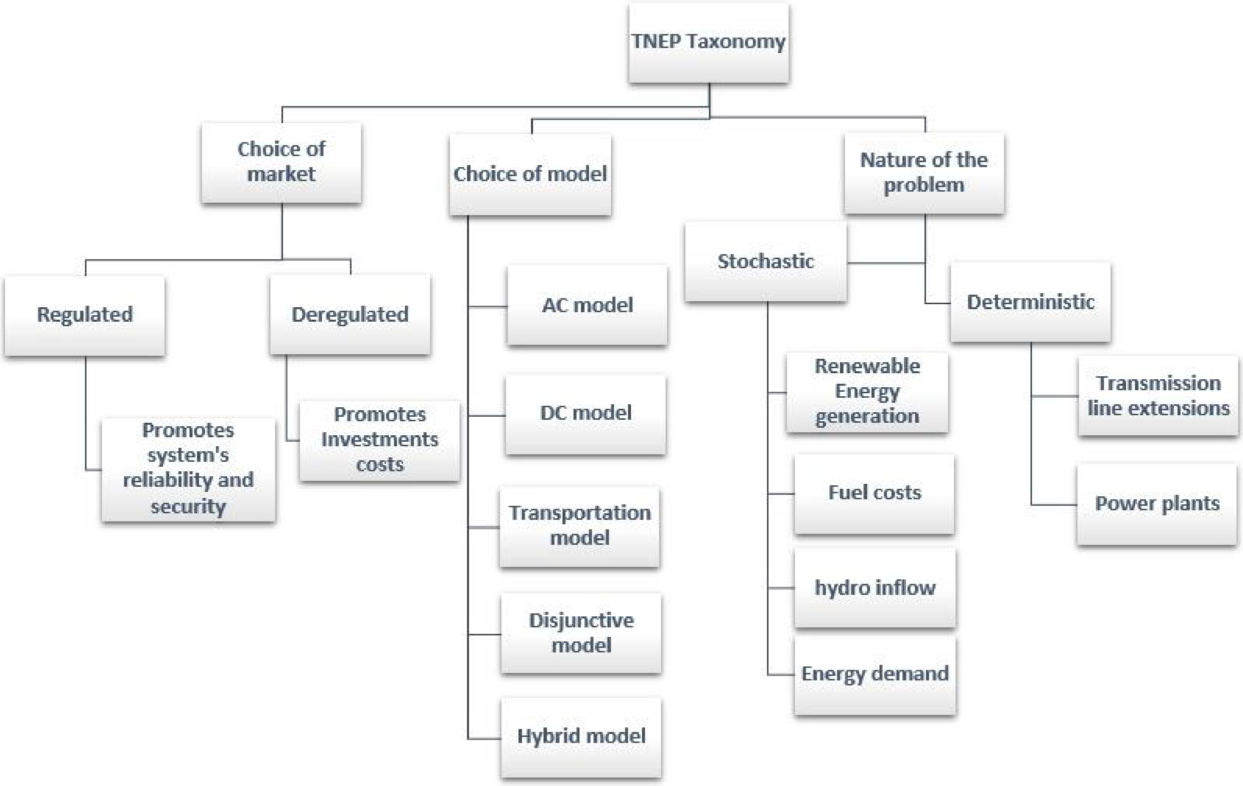

FIGURE 1. **Classification of TNEP based on choice of model, nature of market and nature of the problem.**

(active part) of the network. The data to be used for the problem is the present network topology (base year). Simplified classical models often used by researchers to solve network planning problem as shown in Fig. 1, are the DC model, transportation model, hybrid model, disjunctive model and the alternating current (AC) model [17], [34]–[37].

The DC model, which is capable of incorporating the electrical losses in the network modeling was used in [17]. The nature of the problem is a mixed integer nonlinear programming (MINLP) problem. Branch-and-bound algorithm was used to solve the problem. Moreover, the branch-and-bound algorithm used is an extension of the branch-and-bound method presented originally in [38], which was then applied in [17], with the advantage of extending it to more complex models. More exact power network model was used in the problem with the existence of non-linearity in the system.

Romero and Monticelli developed a hierarchical decomposition technique for the classical modeling approaches for TNEP problem [35]–[37].Transportation model was utilised in [39], [40], representing the power network, in which only the Kirchhoff current law is taken into consideration.

A modeling framework, which utilizes mixed integer linear programming algorithm with power system planning operation was developed in [11]. The model also takes into consideration the optimal transmission expansion plans in relation to fuel supply issues. However, the paper [11], failed to identify the particular type of model used in relation to the three classical types of TNEP modeling techniques. Indian power system operational data configuration for the year 1995 were used in testing the model [11]. The results show that optimal generation scheduling, streamlining of supply of fuel schedules, proper transmission line expansion strategies and prices policies can drastically minimize the system's costs, unmet energy in the system and need for capacity addition.

The transportation model adequacy was checked by the use of an optimal direct current load flow (DCLF) program named JUANAC. Linear programming becomes very useful when the system model is represented as a transportation model with the intention of solving the main problem using constructive heuristic algorithm or a branch-and-bound method. Illustrative tests were shown by the use of some electrical systems from literature [18].

An optimal plan obtained using transportation model is not altogether feasible for the DC model, because of the part of the constraints that are normally ignored. An additional circuits are normally needed in order to satisfy the active constraints in transportation model, which implies higher investment cost [37].

Some authors prefer transportation model in power flow calculations [41], while others use a linearized DC power flow model and hybrid model as a compromise between accuracy and computational requirements [35]. The full complexity of the AC power flow model was taken into account in works such as [42].

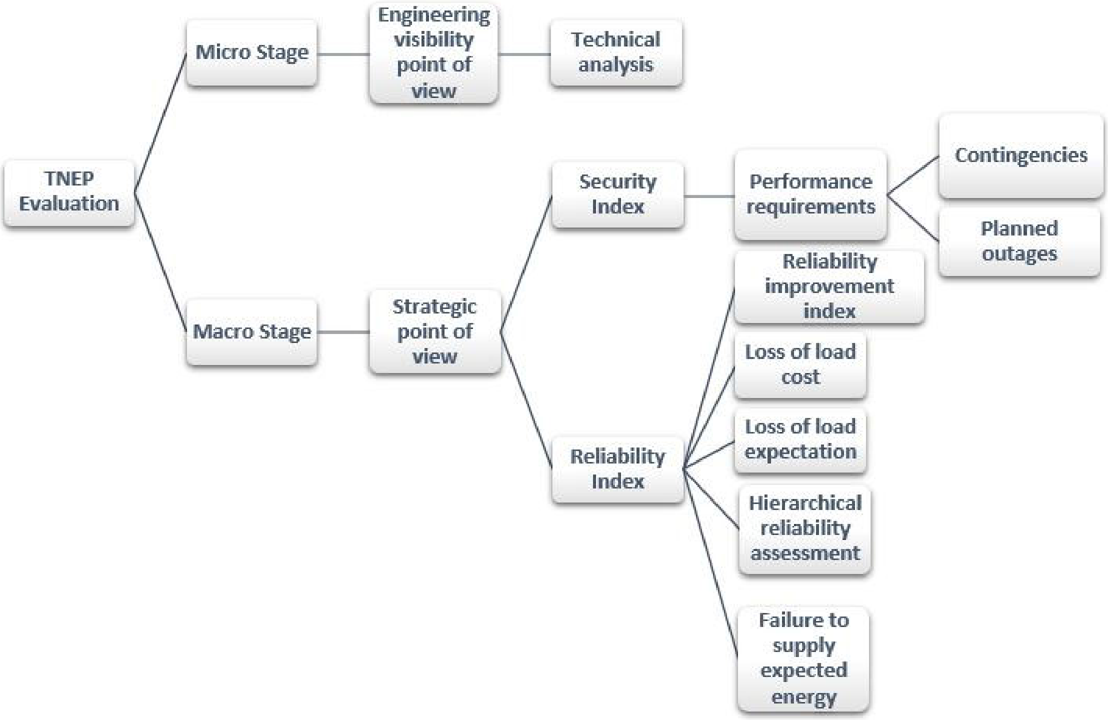

FIGURE 2. TNEP Evaluation in relation to reliability and security constraints.

Behavioral simulation model in which centralized and decentralized, as well as the hybrid model approaches was applied in [13]. The centralized market approach contributes in improving the system's reliability, while the decentralized market approach, promotes investment through usage charges and compensations as shown in Fig. 2. The hybrid method promotes investment timing, while reducing usage charges.

A linearized AC-TNEP model by means of special ordered set of type 2, is used in [43], to represent the mathematical model of the TNEP with reactive power planning network. The model was tested in IEEE bus test systems and the results show the robustness, effectiveness and computation efficiency of the proposed model.

B. RELIABILITY ISSUES IN TNEP

Power system's reliability is measured by the rate of interruptions of power supply, i.e. the rate of interruptions per customer per year, the average recovery time per failure per year, the probability of lingered power failure within a specified period and the expected overall interruption time per year [44]. Reliability evaluation should be included in any long term planning such as TNEP to guarantee trustworthy supply, hence, a proper plan should satisfy all reliability requirements [4].

Several researchers have come up with numerous techniques for transmission network expansion planning reliability analysis similar to those employed in generation expansion, such as long-term probabilities of failure/repair, and approximations for series and parallel paths etc. however, severe difficulties occur in TNEP reliability analysis due to multiple circuit interruptions and numerous power sources. Nevertheless, the use of Monte Carlo simulation, offers the feasibility of reliability analysis in TNEP problems [44].

Proper TNEP is evaluated in two stages as shown in Fig. 2: macro and micro stages [4]. The plan studies from strategic point of view is the macro stage, while the engineering feasibility point of view is the micro stage. Reliability analysis, adequacy and security of any TNEP are usually linked to the macro stage of the planning, whereas the technical analysis of the network are linked to the micro stage.

Reliability and security of the system under study can be incorporated in the problem formulation as constraints or as part of the objective functions. The reliability indexes are made up of the following: loss of load cost [45], loss of load expectation [23], failure to supply the expected energy [42], hierarchical reliability assessment [24], and reliability improvement index [46]. The security aspect looks into the performance requirements under certain contingency and planned outages are usually used as a constraint in TNEP problem [4], [39], [47], [48].

C. UNCERTAINTY ISSUES IN TNEP

The order and nature of occurrence of events are usually unknown in long term planning, thereby causing uncertainty events that are often hard to predict [49]. Major source of uncertainties in TNEP is the lack of access to relevant information involved in the process. Therefore, uncertainty in TNEP is a crucial aspect of planning, which must not be ignored.

The uncertainties in TNEP due to consumer behaviour and decision-making process are subject to influences of social-cultural and psychological as well as personal factors. The work of Sadikoglu [50] utilized Z-number concept in handling uncertainties in consumer buying behaviour analysis. Moreover, a hybrid probabilistic-possibilistic model was developed in [51], to indicate the dependency of customer performance with demand response(DR) operations by the use of two defined utility-based indices. Different types of uncertainties were synthesized in one framework and a Monte-Carlo simulation and optimal power flow methods were employed.

The uncertainties in TNEP also result from inaccurate load forecast. More accurate load forecast enhances a stable and reliable TNEP [15].

Moreover, renewable energy exploration is one of the important features of future energy system, but the randomness and the intermittent nature of renewable energy have introduced new challenges to planners [52].

An innovative scenario-based stochastic model that considers transmission, generation and reactive power planning to accommodate the uncertainty and variability of wind power system is presented in [52].

Robust TNEP in the presence of loads and wind power generation as two major uncertainties is proposed in [9]. Information-gap decision theory (IGDT), taguchi's orthogonal array testing (TOAT) and min-max regret criterion are the tools used in the proposed robust TNEP calculations. A modified 6-bus Garver transmission network test system was used as a case study and the results showed the validity of the proposed RTNEP, which are yet to be implemented in a large-scale and real TNEP problem and also in consideration of other types of uncertainties.

A study on the effects of uncertainties in power system models is presented in [53]. The methodology allows for worst-case analyzes, which is applicable to at least medium-sized networks. The case study shows that sensitivities of different generators to network parameter perturbations vary drastically, due to the effects of network topology, operating point and constraints. Moreover, even small parameter variations having significant effect on optimization results were also demonstrated.

An approach for coordinated and strategic transmission expansion planning under uncertainty with a multi-agent system is proposed in [54].

An algorithm known as Adaptive Robust Optimization (ARO) was proposed by Zhang and Conejo [5], to generate an effective candidate-line set for transmission expansion planning. The work takes into consideration, the short and long term uncertainties. Peak demand and available generating capacity of the system during the target year are grouped as long term planning uncertainties while uncertainties pertaining to different operating conditions is linked to short term planning uncertainties. The method provides a systematic method to obtain an effective candidate-line set. The results showed that the candidate line selection depends on the level of long-term uncertainty and the profile of short-term uncertainty. The work [5], states that the proposed technique portrays a high computational efficiency to yield an effective candidate-line set for transmission expansion planning operations when considering large systems. It can also effectively manage the size of the candidate-line set to achieve high accuracy with moderate computational burden.

IV. MATHEMATICAL OPTIMIZATION ALGORITHMS IN SOLVING TNEP PROBLEMS

Mathematical optimization in Engineering, Mathematics, Computer Science and Management Science (Operation Research) is the classical method of selection of the best solution to a problem or selection of the best element out of several alternatives, subject to certain criteria. It could be regarded as the first born among other types of optimization techniques [55].

A technique entails the application of an algorithm or combination of two or more algorithms to solve any engineering problem. It is a more general concept than an algorithm because it accounts for other resources such as availability of high speed computers and any other equipment in use. However, a set of instructions that describes the procedure to be taken in order to achieve a desired results in a finite number of steps for any set of input data is termed as an algorithm [56].

Over the past decades, different types of mathematical optimization algorithms have been developed and applied in solving different types of real world problems. However, this section of the review describes different types of mathematical optimization algorithms for TNEP problems up to the state-of-the-art as follows:

Linear Programming (LP) algorithm applied to the TNEP problem is presented in [57]. The paper adopted the LP algorithm that was used for power system operation problem presented in [58]. Two major distinct characteristics were developed in the formulation of the proposed model; i. the use of bounded dual simplex algorithm by the use of relaxation to solve the modified problem and ii. overall transformation of the problem for variables and the equality constraints reductions. However, despite the better computational performance, the proposed algorithm has a disadvantage of lacking the inverse of matrix B in an explicit manner.

Mixed integer programming was used in the analysis of some important issues associated with operation planning of Indian power network [11]. Emphasis was laid on spatial transmission network expansion plan for the active Indian inter-state grid network and the new links to be added. The method was also applied in fuel cost optimization and supply rescheduling to ensure efficient operation of various generating stations.

An approach for a solution to long-term power transmission expansion planning using mixed integer linear programming method is presented in [59].The general problem is a large-scale, mixed integer, nonlinear and non-convex type of problem. The nonlinear nature of the system was transformed into a linear equivalent by deriving a mixed-integer linear model, with the consideration of power losses and optimal convergence. The simulation was carried out using the Garver's 6-bus system and the results show the accuracy and the efficiency of the proposed solution method. The major contributions of the work of Alguacil *et al.* [59] are the formulation of the transmission expansion planning problem by revisiting mixed integer linear programming, which presented an efficient computational behaviour and precise modeling of power transmission losses using linear expressions.

A mixed-integer linear programming (MILP) approach that considers a security constrained loss modeling approach, generator costs and power losses for the multi-stage TEP problem is proposed in [60]. The peculiarities of the work are in the area of security-constrained loss modeling approach, the piece-wise linear generator cost model and a complete proposed planning framework along with the optimization and the security check sub-problems. However, the proper selection of the piece-wise linear sections proposed algorithm has not been tested in real system.

A TNEP problem with the corona power-loss effect added to the objective function was formulated in [61]. A non-linear programming algorithm was used to minimized the objective function. An unconstrained DC load-flow data were used as an initial guess, in order to avoid initial value selection of the unknown power flow variables problem. The results showed that Ohmic-power loss, corona-power loss and the total investment are less for a certain range of power tariffs.

Lumbreras *et al.* [10], applied Bender's decomposition method to solve the transmission expansion planning problem by improving some of the algorithms in order to foster the computational performance. Two case studies are used to demonstrate the proposed model. The first is descriptive test case, while the second is the real-time application.

A hierarchical decomposition algorithm for optimal TNEP is presented in [35]. The algorithm proved to be efficient in coping with non-convexity nature of the problem in finding the global optimum solution. The implementation utilised three different levels of network models: transportation, hybrid and DC (linearized) models. Each level of the models was considered as a relaxation point to the next level until the more accurate model was obtained. Practical results showed a significant reductions in investment costs, when compared to what was available in literature. However, the flexibility of the method to allow for the inclusion of the nonlinear power flow models as a fourth level network representation is yet to be confirmed and the utilization of the three network models consumes CPU time instead of the theoretical cross decomposition method that uses only single iteration process.

Branch-and-bound optimization algorithm for TNEP problem is presented in [39], [40]. Transportation model was utilised in representing the power network, in which only the Kirchhoff current law is taken into consideration, which made it possible to view the TNEP problem as an integer linear programming problem. Hence there was no further approximations in the process.

Application of interior point method (IPM) to solve problems of linear programming that appears as sub-problems in the solution of TNEP problem is presented in [62]. IPM is classified in three categories viz: the projection methods, affine-scaling methods and the primal-dual methods. Sánchez *et al.* [62], applied the primal-dual method to solve sub-problems in a standard TNEP problem. It was noted that the algorithm has good qualities to be used inside the field of transmission network planning. However, it is based on predictor-corrector approach or the use of the LP solution as the initial point for the resolution of next LP problem. Hence, it only represents the fundamental strategies for the improvement of the world.

Branch-and-bound optimization algorithm was further used to solve TNEP problem by the inclusion of the electrical losses in the network using DC model scenarios is presented in [17]. The nature of the problem is mixed integer nonlinear programming (MINLP) problem, which was solved by the help of interior point method. The method can easily converge towards the best-known solutions or to the optimal solutions for all the tested systems neglecting the electrical losses. However, there is no guarantee of convergence towards global optimization for MNLP problem except in the case where electrical losses are neglected. Nevertheless, modelinglosses gives a more accurate representation of the network, which may result in different expansion plans than those obtained in the absence of losses. The idea of neglecting losses could help in today's savings but tomorrow's investment adjustments could rapidly overshadow the initial savings [59].

A model for use in composite generation and transmission expansion planning problems was proposed in [63]. Distributed generation was taken into consideration. The problem was formulated as a mixed integer linear programming problem, and it was solved by a new heuristic algorithm. The minimization of the overall costs by finding the new transmission extensions and allocating the overall generation capacity in the grid nodes are the main objectives. Iran power grid as a large-scale network was used as a case study and it was shown that the proposed approach would be a powerful tool for a composite expansion planning in a large scale power system.

A single stage deterministic model based on game theory is proposed in [64], [65]. Generation and transmission enterprises are considered for analysis. It included the planning model of generation and transmission enterprises. It was stated in [66], that the optimization of coordination between GEP and TNEP has always been a difficult problem in power system planning. However, the proposed model according to [65], is capable of obtaining the equilibrium through solving mixed complement problem such as the discrete limit problem by deducing the quadratic programming model. The model was tested using a 3 bus system, which was also practically verified.

A decentralised coalition formation and cost allocation procedure by Kernel Oriented Algorithm (KOA) for TNEP problems is presented in [67]. It is a multi-stage system, an extension of the work of [68]–[70], based on Game Theory procedure. The algorithm was tested with a simple 6 bus problem and IEEE 24 bus with acceptable results. However, the approach failed in solving the allocation of sunk costs. A recommendation was made for further research on how sunk costs allocation could resolved.

A Constructive Heuristic Algorithm (CHA), an aspect of mathematical model for solving TNEP problem in a deregulated market was proposed in [71]. Multiple generation scenarios were considered in the proposed model in order to provide high quality solution with adequacy in power system operation. It finds its optimal solution in an iterative process and in each step, a circuit is selected and added to the system by a sensitivity index. The simulation results of the Garver and IEEE 24-bus tests systems demonstrated the possibility of using the algorithm in an open access system. The clarification of the core mechanisms for the representation of the possible generation scenarios forms the major contribution of the paper.

Dynamic programming is a deterministic search procedure that yields a powerful approach for solving numerous discrete sequential problems as well as quantitative and non-quantitative criteria without difficulty [72]. Dusonchet and El-Abiad [73], applied a method called Discrete Dynamic Optimising (DDO), which is the combination of the deterministic search procedure of dynamic programming [72], and probabilistic search as well as heuristic stopping criterion [74], to solve TNEP problem. The nature of the problem was expressed as a large finite Markovian sequential process over time. The algorithm was so designed to take advantage of any information known about the problem. However, the procedure is often limited in the number of stages considered and the number of alternatives considered at each stage.

V. META-HEURISTIC OPTIMIZATION ALGORITHMS IN SOLVING TNEP PROBLEMS

Meta-heuristic algorithms (also known as nature inspired algorithms [75]), have been proven to be the best methods severally applied in solving most of optimization problem. The methods are typically based on simulation of evolutionary algorithms, which is based on a principle of evolution (survival of the fittest), and simulations that mimic some natural phenomena such as genetic inheritance [29].

Transmission Network expansion planning (TNEP) is normally a complex optimization problem, to meet the demand of power consumers in an adequate quality level along the planning horizon, while maximizing profits by investment, operational, and interruption costs minimization [76], [77]. Over the past decades, optimization techniques based on meta-heuristics have show-cased good potentials in finding high quality solutions to TNEP problem. Their success is related to the ability to avoid local optima by exploring the basic structure of each problem. Many merits of using meta-heuristic algorithms in TNEP problem are linked to some available software tools, which can handle the complexity of the problem including mix-integer and non-integer variables with faster time-response. Some of the meta-heuristic optimization algorithms, which have been applied over the years in Solving TNEP Problems are as follows:

Cuckoo search algorithm proposed by Yang and Deb [78], was applied by Veeresham *et al.* [79], to solve the ever challenging AC based TNEP problem. The algorithm is based on the obligate brood parasitic behaviour of some cuckoo species with other birds. The algorithm's pattern is similar to many other meta-heuristic algorithms. There are three strategies of the cuckoo search algorithm: best solutions selection and keeping; host eggs replacement with respect to the quality of the new solutions; and host birds' discovery of some of the cuckoo's eggs and replacing it according to the quality of the local random walks, which is exploitation. The algorithm was tested by nine different TNEP models. However, the solution of cuckoo search algorithm based AC-TNEP models is still challenging when it comes to obtaining the optimal solution. Nevertheless, by reformulation and relaxation, obtaining the optimal solution is possible as proposed [79].

A dynamic TNEP technique is presented in [80], using a multi-objective optimization framework. The objective functions used are: congestion cost, investment cost and reliability. Genetic Algorithms (GA's) have demonstrated the ability to deal with non-convex, non-linear, integer-mixed optimization problems such as TNEP as stated in [81]–[83]. Moreover, a Non-dominated Sorting Genetic Algorithm (NSGA) approach was used to overcome the difficulties in solving the non-convex and mixed integer nature of the problems followed by a Fuzzy decision making analysis to obtain the optimal solution [80]. However, reformulation of the proposed model is needed in order for it to be applicable in a deregulated environment where there is no central planning. Meanwhile, A bi-level optimization is proposed to handle the reformulation problem.

The distinguish characteristic feature of GA with respect to the traditional optimization techniques is the ability to have simultaneous evaluation of many solutions. This is an added advantage that can enable a wide search and avoid potentially convergence to local optimum [29].

Improved GA with a population-based crossover operator is proposed in [84] for Transmission and Generation Expansion Planning (TGEP). The applicability of the proposed scheme for TGEP problem was tested on a 6-bus test system and the results show comparative performance in comparison with regular GA.

An algorithm to solve TNEP problems is proposed in [19], [45]. It is based on the meta-heuristic ant colony optimization (ACO). The algorithm was developed based on the ants' behaviour in finding the shortest cut from food sources to their nest. The shortest cut indirect communication is mediated by pheromones. The ACO meta-heuristic was firstly proposed in [85], [86], to solve combinatorial optimization problems. Later on, other applications adopted the method, especially those applications involving discrete optimization problems [87]–[90]. da Silva *et al.* [45], utilised the ACO for a multi-stage planning of transmission system with the influence of reliability on the decision-making process. However, the main drawback of the method points to the adjustment of a high number of parameters. Hence, a more comprehensive network dimensions analyses is still needed, (including different systems) to be done to correctly authenticate the performance of the algorithm.

Particle Swarm optimization (PSO) based approach to solve a multi-stage TNEP problem is proposed in [91]. It is a population based stochastic search method, which was first proposed by Kennedy and Eberhart in [92]. The nature of the problem is a large-scale non-linear combinatorial problem in a competitive pool-based electricity market. A number of cases, (which is based on the future demands of the system, multi-year time horizon, operating and investment costs, demand bids, the N-1 reliability criterion and the continuous non-linear functions of market-driven generator offers) were considered in the system modeling. A modified PSO model was applied to the Garva six bus system and to the IEEE 24-bus test system. The modified model performance was compared with to the basic PSO and a genetic algorithm (GA), it was confirmed that the modified PSO is capable of finding a better solution than the basic PSO and as well as GA.

An improved Harmony Search Algorithm (HSA) to solve TNEP problems was proposed in [93]. The algorithm has been applied for security constraints analyses over the past decades by various researchers [94]–[97].

Moreover, the algorithm was later improved by [93], to be used to overcome the difficulties in solving the non-convex and mixed integer nature of the TNEP problems. Adequacy and security aspects of reliability together with investment cost and congestion cost were considered as the core difficult aspects of the planning, which were solved by the use of the proposed improved HSA. The simulations results showed high accuracy and efficiency compared to GA. However, Its accurate and efficient potentials to be applied to a large scale power system has not been tested to a real world situation in TNEP process.

A meta-heuristic algorithm known as Simulated Annealing (SA) has been applied for TNEP problems in [98]–[103]. The approach proved effective when compared with other traditional optimization methods [103]. Some improvements were made on the algorithm by [103]. The major improvements done are: transition mechanism simplification, objective value calculation by increment, coefficient matrix of the linear equations generation by increment, tuning of the parameters by cooling scheme based on many tests, sparse matrix technology utilisation when the scale of system is great or median and the current optimal solution storage when accepting deteriorated solution. The improved SA according to [103], could be effective for hard optimization problems such as TNEP, because it has more chances of finding better solutions and searching for local optimal solution faster than other traditional optimization techniques. However, the convergence toward global solution in a large sized system is not guaranteed.

A heuristic algorithm known as Greed Randomised Adaptive Search Procedure (GRASP) solves wide variety of combinatorial optimization problems [104] in an iterative sampling method that has two phases for each iteration as presented in [105], for TNEP problem. The first phase is a construction phase that searches for a feasible solution for the problem, while the second phase, seeks for the improvements of the construction phase solution by a locally made search. The application of GRASP in TNEP problem was demonstrated using a real Brazilian Southeastern network system. The results were compared with the best known TNEP solution. However, the local search procedure, which is the second stage of the algorithm leads to certain difficulties that is related to pruning by comparison.

A clonal selection principle and a population based algorithm known as Artificial Immune System (AIS), proposed by Dasgupta and Forrest [106], was recently applied in TNEP problem in [15]. The algorithm was formulated based on human immune system, which is a parallel, distributed and highly evolved adaptive system that exhibits certain traits, such as immune recognition, immune memory, reinforcement learning, diversity, robustness and feature extraction. Its main search power depends on the mutation operator. The proposed approach was validated using a 6-Bus Ray Billinton Test System and IEEE 24-Bus Reliability Test System. The results were compared with two other heuristic algorithms and the efficiency of the AIS in terms of cost of new transmission line to be installed after TNEP was found to be better. However, the algorithm has not been tested in a real large transmission network.

A novel TNEP model and its application algorithm that considered surplus capacity and load factor of the transmission line was presented in [107], [108].The aim was to determine the best distribution of branch load factors and the minimization of the investment cost simultaneously, which is different from the traditional TNEP approach. Chaos Optimal Algorithm (COA) was proposed and used in solving the TNEP problem. The model effectiveness was tested in two typical systems. However, the combination of the surplus capacity with the balance between the system security, network investment with maximum surplus capacity were suggested for future work.

Tabu search (TS) was applied for the first time in a single stage (static) TNEP problem in [109], [110]. A DC power flow model was used and the formulation was based on the integer programming with an objective of minimizing the system overloads. The TS was applied to obtain an optimal expansion schemes progressively until the maximum number of iteration is reached. Further works applied TS in a more elaborate form by employing new heuristics in the search process [111]–[113],performing parallelism of the TS algorithm [111], [114] and considering the chronological of the

TABLE 1. Mathematical optimization algorithms in solving TNEP problems.

Mathematical optimization			
Algorithm	**Application**	**Viability**	**Drawback**
Linear Programming [22], [58], [59], [133], [134]	Applied in TNEP problem	The proposed relaxation method is very efficient for the analysed problem	It has a disadvantage of lacking the inversion of matrix B in an explicit manner
Non-linear Programming [62], [135], [136]	TNEP problem with Corona loss constraints	Good in solving a large-scale practical TNEP problem	It can easily run to a high degree of complexity due to the non-linear nature
Mixed Integer Linear Programming (MILP) [36], [48], [60], [61], [64], [137]	Multi-stage security-constrained TNEP problem	High potential to be applied to a large scale TNEP problems	The proper selection of the piecewise linear sections proposed algorithm has not been tested in real system
Branch-and-bound (B&B) [4], [17], [40], [41], [138], [139]	Solves the power system's TNEP with the incorporation of the electrical losses in the network modeling problem.	It can easily converge towards the best known solutions or to the optimal solutions for all the tested systems neglecting losses and without Bender's decomposition	There is no guarantee of convergence towards global optimization for MINLP problem except in the case where electrical losses are neglected
Benders Decomposition [7], [10], [12], [16], [18], [25], [33], [49], [140]–[142]	Solves the TNEP problems with high simplicity and flexibility	Good in dividing the co-planning problem into one master problem and two sub-problems and obtaining the optimal solution to TNEP problem especially in DC model	Inability to cope with non-convexity nature of TNEP problem
Hierarchical decomposition [36], [143]	Solves TNEP problems in three different network levels	Efficient for coping with non-convexity nature of TNEP problem	The utilisation of the three different levels of network models consumes CPU time and the inclusion of a nonlinear power flow models has not been verified
Adaptive Robust Optimization (ARO) [5]	For long- and short-term TNEP problem	It shows a high computation efficiency to generate an appropriate candidate-line set for a large scale TNEP problem	It results to increase in investment cost while attempting to decrease in the total cost throughout the iterations
Game Theory [65], [66], [68]–[70], [144]–[146]	To search the GEP and TNEP enterprises problem	Good in obtaining the equilibrium by solving mixed complement problem such as the discrete limit problem by deducing the quadratic programming model	It has only been applied in a 3-bus system. Its performance on large system has not been verified
Kernel Oriented Algorithm (KOA) [68], [147]–[149]	The allocation of transmission costs in a decentralised manner	It is able to form kernel-stable coalitions and the cost allocation procedure is performed at every step of the kernel- algorithm	The approach failed in solving the allocation of sunk costs
Interior Point method (IPM) [63]	Solves a sub-problem in the main TNEP problem	Good qualities to be used as a decision support system in TNEP	It is based on predictor-corrector approach or the use of the LP solution as the initial point for the resolution of next LP problem.
Heuristic Algorithm based on sensitivity index [72], [150]–[152]	Solves TNEP problem in a deregulated market	Finds its optimal solution in an iterative process and in each step, a circuit is selected and added to the system by a sensitivity index	It has not been tested in an open access system

TABLE 1. ***(Continued.)*** **Mathematical optimization algorithms in solving TNEP problems.**

Dynamic Programming [73]–[75], [153]	Solves TNEP problem expressed as a large finite Markovian sequential process over time	It provides a powerful approach for solving many discrete sequential problems such as TNEP problem expressed as a large finite Markovian sequential process over time	Its procedure is often limited in the number of stages considered and the number of alternatives considered at each stage

investments, the reliability worth and the Ohmic losses over the period of the planning horizon [109].

Fuzzy logic algorithm based on the divide to conquer, which is controlled by fuzzy system is proposed in [115]. The algorithm is capable of providing high quality solution with the use of fuzzy decision making and self adjusting mechanism that eliminates manual adjustment of the system's parameters based on non-deterministic criteria to guide the search to high quality solutions without being affected by premature convergence. However, it needs branch-and-bound method as a decision support system.

An expert system approach for short term multi-year TNEP problem was proposed in [116], with MW and ampacity rules. Enhancements to the fast decoupled load flow algorithm for on-the-fly reactive power management was proposed for the ac load flow convergence. The proposed enhanced algorithm is capable of detecting divergent load flow scenarios and can also self-correct it by restarting the whole process with higher degree of freedom in reactive power control. The analysis and comparative evaluation showed that the algorithm is Self corrective with the capability of arriving at a solution, which is close to the optimal and can deal with incomplete information about the system.

Wang et al [117], applied shuffled Frog Leaping Algorithm (SFLA) proposed by Eusuff and Lansey [118], which is based on threshold selection strategy for TNEP problem. It is fast and excellent with global search capability, which is good in solving sequential problem. The algorithm is capable of acquiring global optimization with a small calculation size and short computing time. Concurrently, Mehdi et al [119], applied the algorithm with focus on the problem of location, type and number of new lines to be added in the existing network to meet the demand such as the dotted lines shown in the 9-bus system in Fig. 3. The algorithm was found to perform excellently when compared with other meta-heuristic algorithm, such as PSO and GA.

A nature inspired algorithm known as Multi-Verse Optimizer (MVO), which was first proposed in [75] was recently adopted by [6] to solve TNEP problem in two realistic Egyptian networks. MVO has various advantages of being simple to handle and having adaptive control parameter. It can operate with high ability to escape the local optima stagnation. The superiority and efficiency in solving TNEP problem over other types of algorithms have proven to yield economic planning and secure transmission corridors.

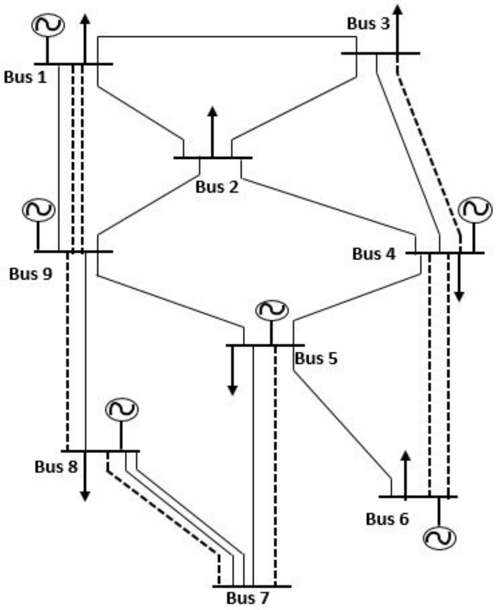

FIGURE 3. **Illustration of possible candidate-line extensions in a 9-bus system.**

VI. HYBRID OPTIMIZATION ALGORITHMS IN SOLVING TNEP PROBLEMS

The sole purpose of hybridization of different algorithms is to utilize the capabilities of the individual algorithms combined together to achieve a certain purpose in which a single algorithm will fail to achieve. For instance, hybridization of two algorithms such as Genetic Algorithm (GA) and Particle Swarm Optimization Algorithm (PSO) is for PSO to overcome the slow convergence of GA, and for GA to overcome the easy to fall into local optimum in high dimensional space and low local convergence rate in the iterative process of PSO [120].

Some of the hybridization of algorithms for TNEP problems are as follows:

A hybrid method consisting Real Genetic Algorithm (RGA) and Interior Point Method (IPM) was used to solve two simultaneous problems, which consist, the reactive power planning and transmission expansion planning problems via an AC model [121]. The idea of hybrid solution strategy is that the RGA was applied to solve the main TNEP problem, while the IPM solved the NLP reactive power planning aspect that evolved in the RGA process [122]. The aim was

TABLE 2. Meta-heuristic optimization algorithms in solving TNEP problem.

Meta-heuristic optimization				
Algorithm	**Application**	**Viability**	**Computational Complexity**	**Drawback**
Ant Colony optimization (ACO) [19], [46], [86]–[91], [154]	Multi-stage TNEP problems with the measure of influence of reliability on decision-making process	Capable of balancing the investment costs by the interruptions costs while searching for the least costs solution	Shows a good performance in term of computational time and quality of the obtained solution, compared to the traditional MILP approach	The main drawback points to the adjustment of a high number of parameters
Cuckoo Search [79], [80]	AC model based TNEP problem	Effective for global optimization problem	To obtain optimum values of all objective functions, the algorithm is capable of running 10 times with maximum of 500 iterations	Optimal solution of AC-TNEP models is still a challenge. Reformation and relaxation is still needed to obtain an optimal solution
Genetic Algorithm (GA) [4], [15], [81]–[85], [121], [125], [155]–[165]	Multi-objective TNEP optimization framework	Good in solving a non-convex and mixed integer nature of the TNEP problems with high convergence rate in the iterative process.	Improved GA finds the optimal solution in less computational time and finds a high-quality region at the first iterations and converges quickly to the optimal solution than the other nominal GA's	Expensive computational cost, often yields large number of variables and convergence becomes very slow. Not suitable for TNEP in a deregulated market, where there is no central planning
Particle Swarm optimization (PSO) [92], [93], [121], [154], [166]–[168]	Multi-stage TNEP problem	The rate of convergence is good due to fast information flow among the solution vectors and it is capable of finding a better solution than genetic algorithm	Capable of yielding optimal solution more rapidly in the fifth iteration	Its diversity decreases very quickly in the successive iterations resulting in a sub-optimal solution
Harmony Search Algorithm (HSA) [94]–[98]	For TNEP problems with adequacy-security considerations in deregulated market	The simulation results are accurate, efficient and has better convergence rate with less investment costs in TNEP analysis	It solves TNEP problem with less computational time than GA	Its (accurate and efficient) potentials to be applied to a large scale power system has not been tested to a real world situation in TNEP process
Simulated Annealing (SA) [100]–[104]	Hard optimization problems such as TNEP	Improved SA searches local optimal solution faster	Transition mechanism can be simplified and it searches for local optimum faster than Mathematical Optimization	Convergence toward global optimal solution in a large sized system is not guaranteed
Artificial Immune System (AIS) [15], [77], [78], [107], [169], [170]	For TNEP problem	Highly efficient in minimizing the Cost of New Transmission Lines to be installed after TNEP	The performance of AIS by considering lesser number of lines and length of new lines mainly for superior load and generation hikes is undoubtedly better than GA and BFOA for long-term TNEP	The algorithm has not been tested in a real large transmission network

TABLE 2. *(Continued.)* **Meta-heuristic optimization algorithms in solving TNEP problem.**

Bacterial Foraging optimization Algorithm (BFOA) [15], [171]–[173]	For TNEP problem	It is capable of having similar distribution processing, heedlessness to primary value and ability to accomplish global optimization	Undisclosed computational complexity	The efficiency of the BFOA in terms of Cost of New Transmission Lines to be installed after TNEP is poor compared to GA and AIS.
Artificial Neural Networks (ANN) [114]	For TNEP with a multi year perception model and a back propagation algorithm	Capable of determining the number of lines that should be added in each right-of-way in the network	Fast in performing a local search	It has only functioned as a decision support system with other algorithm for TNEP problem
Tabu Search (TS) [110]–[115]	For Dynamic nature of the TNEP problem	Capable of obtaining a better continuity of the solution in terms of reliability and losses in the performance of the expansion sequences over the planning horizon	Very favorable in terms of quality and corresponding CPU time	Needs other heuristics as decision support systems for the final solution to the TNEP problem
Chaos Optimal Algorithm (COA) [108], [109]	For TNEP problem	Capable of combining transmission surplus capacity and load factor of the transmission line in the plan	Undisclosed computational complexity	The main drawback is that investment may be higher than traditional cost-based planning model
Fuzzy Logic [116], [163], [174]	For TNEP problem	It has the ability to lead the search to high quality solutions without being terminated by premature convergence to poor local optima	Provides a self-adjusting mechanism that eliminates the manual adjustments of parameters that could lead to complexity	Needs branch-and-bound method for final decision making
Differential Evolution Algorithm (DEA) [131], [175]–[177]	For static and multi-stage TNEP problem	Effective and efficient in minimizing the total investment cost	Simpler algorithm with a good computational performance that is faster than GA for static and multi-stage TNEP	The effectiveness has not been applied in real world large-scale TNEP problem and also in a deregulated power network market
Expert system [117], [178]–[181]	For TNEP problem	Self corrective algorithm with capability of arriving at a solution, which is close to the optimal and can deal with incomplete information about the system	Undisclosed computational complexity	It is not able to arrive at the exact optimal solution rather it yields a solution which is close to optimal
Shuffled Frog Leaping Algorithm (SFLA) [118]–[120]	For discrete static TNEP problem	Capable of obtaining optimal location, type and number of the new lines to be installed	Introducing the technique to choose the candidate right-of-ways could reduce the calculation time for applying the proposed algorithm to large power systems.	The feasibility of the proposed algorithm has not been tested in a large scale TNEP system

TABLE 2. *(Continued.)* Meta-heuristic optimization algorithms in solving TNEP problem.

Greedy randomized adaptive search (GRAS) [105], [106], [182]	For TNEP problem	Quick to produce good quality solutions for a wide variety of combinatorial optimization problem. Due to its generality and simplicity, GRAS is a useful alternate approach that can be applied to many other kinds of decision problems	Computation times varied from 4 to 10 minutes, hence its computational effort is moderate	The local search procedure, which is the second stage of the algorithm leads to certain difficulties that is related to pruning by comparison
Multi-Verse Optimizer (MVO) [6], [76]	For selection of the types, routes and number of the added circuits in TNEP	Fast convergence characteristics in minimizing the total costs of the new circuits	Performs better than grey wolf optimizer, particle swarm optimization, genetic algorithm, and gravitational search algorithm in solving several engineering problems with less complexity	It has not applied in a multi-objective and large-scale TNEP problem.

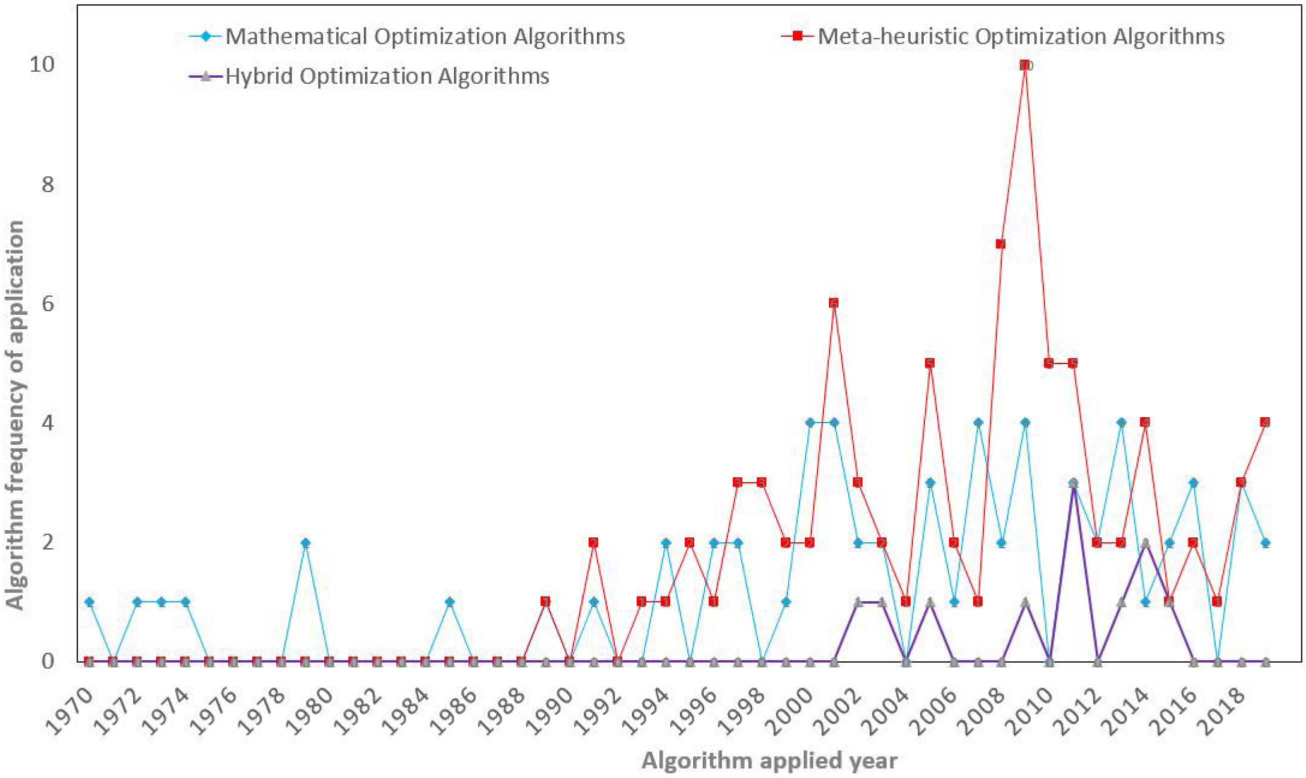

FIGURE 4. Graphical summary of the algorithms since 1970 as compared in table 1,2 and 3.

to obtain a significant quality solution to the problem. The proposed hybrid method was tested using the IEEE 24-bus system, the Southeast Network of Iran (SNI) and the 46-bus South Brazilian Network. The capability and the viability of the proposed method were confirmed by the obtained results, which was implemented even in real world. IPM provides a better computational performance for large scale problems than classical approaches such as simplex method. However,

TABLE 3. Hybrid optimization algorithms in solving TNEP problem.

Hybrid optimization				
Algorithm	**Application**	**Viability**	**Computational Complexity**	**Drawback**
Real Genetic Algorithm(RGA) and Interior Point Method(IPM) [122], [123]	Hybrid solution to TNEP and reactive power planning	Better computational performance for large scale problems and capable of solving TNEP problem in AC model	Provides a better computational performance for large scale problems than classical approaches	Inability to identify weak busses to install new reactive sources
Genetic Algorithm and Linear programming (GA-LP) [22]	Multi-year TNEP problem under a deregulated market	Provides a fair and efficient TNEP solution in a competitive environment	One time of iteration takes 18 s to execute in a sample problem containing 19 state variables, five equality constraints and 24 inequality constraints.	It is only applicable in a deregulated market
NSGA II and Fuzzy decision making [125]	Static TNEP to cope with new challenges introduced by deregulation of power system	A set of optimal solutions is produced, which provides more flexibility in network planning process, unlike the single objective methods	Limiting computational efforts to an acceptable level, requires the use of dc model of the network.	Inclusion of risk analysis and probabilistic reliability assessment in the algorithm are still challenging
NSGA II and probabilistic optimal power flow (POPF) [124]	Stochastic framework for transmission grid reinforcement in a deregulated market	It is good in determining the trade-offs between absorption of private investments, installation costs and reliability measures for several solutions	The simulation time for real large-scale networks with many uncertain variables can be reduced by:parallel processing, reduced number of contingencies,smart initialization of GA, and the use of MATLAB's MEX-files instead of M-files	The method is limited to a multi-stage multi-objective model
NSGA II and point estimation method [183]	Probabilistic multi-objective TNEP considering private investors' preferences, technical concerns, and random nature of power system uncertainties	The combination of Non-Dominated Sorting Genetic Algorithm II, as a widely-used robust multi-objective optimization technique, and point estimation method is capable of handling non-commensurable probabilistic objective functions	The computational burden increases when the size of the network increases	The timing query of these methods is escalated when applying to planning problem which is inherently a time-consuming procedure
Fuzzy logic and branch-and-bound [116], [163], [174]	TNEP problem for high quality solutions	They form a set of high quality topology that can suit the need for good initial population for meta-heuristics such as tabu search and evolutionary algorithms.	Provides many good solutions rapidly (78 seconds for the worst case) due to the intelligent branching strategy	Optimal solution for a large and highly complex problem is not guaranteed

TABLE 3. ***(Continued.)*** **Hybrid optimization algorithms in solving TNEP problem.**

NSGA-II and Chu-Beasley [126]	TNEP problem with multiple Generation Scenarios (MGS)	Capable of finding a set of Pareto optimal expansion plans for both variable and fixed demands in a multi-objective scenario	The proposed algorithm stands out over the basic NSGA-II, substantially improving computational effort and optimality	Further analysis by a decision maker scheme is still required for the final optimal solution
Genetic Algorithm, Table Search and Artificial Neural Network [114]	For TNEP with increased in load and additional generation requirements in terms of power losses and additional lines	Superior in dealing with a large-scale network problem with exponential increase in the size of the search spaces with the dimension of the network	Based on the quality of the final solution and computational speed, the method proved to be suitable for solving difficult optimization problems	There is a possibility of complexity in the process of hybridization

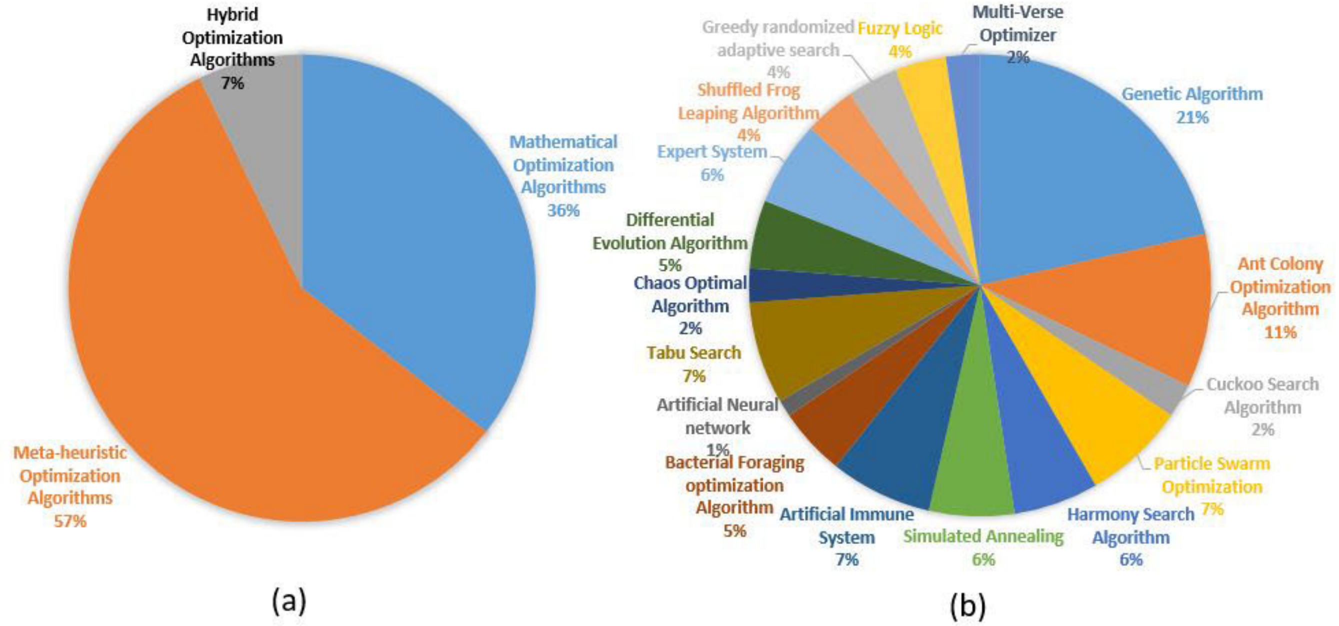

FIGURE 5. **(a) Graphical summary of frequently applied optimization algorithms in literature. (b) Graphical summary of frequently applied meta-heuristic optimization algorithms.**

the proposed algorithm can be improved by adding new indices to identify weak busses to install new reactive sources.

A multi-stage TNEP model in a deregulated market was proposed in [22]. The method was developed in order to solve difficult problems that arise due to deregulated nature of the market in question. In order to have an efficient and fair TNEP, operation costs, investment costs and load curtailment costs were considered to formulate the multi-year TNEP model in a deregulated market. The nature of the model is a complex mixed integer problem. Hence, a hybrid algorithm that combines GA and LP techniques was used to solve the model. The IEEE 24-bus reliability test system and other 6-bus system were used to test the model. The validation of the results was done by comparing it with the traditional model results.

A stochastic framework for transmission grid reinforcement in a deregulated market is proposed in [123]. The work is based on the integration of renewable energy resources into the power system with a case study of wind generation. A multi-stage, multi-objective TNEP technique was developed, which considered reliability, investment cost and absorption of private investment as the three objective functions. The NSGA approach was used, followed by a probabilistic optimal power flow (POPF), which considered the uncertainties of the power system. Moreover, a compromise-solution method was used to realise the best final plan based

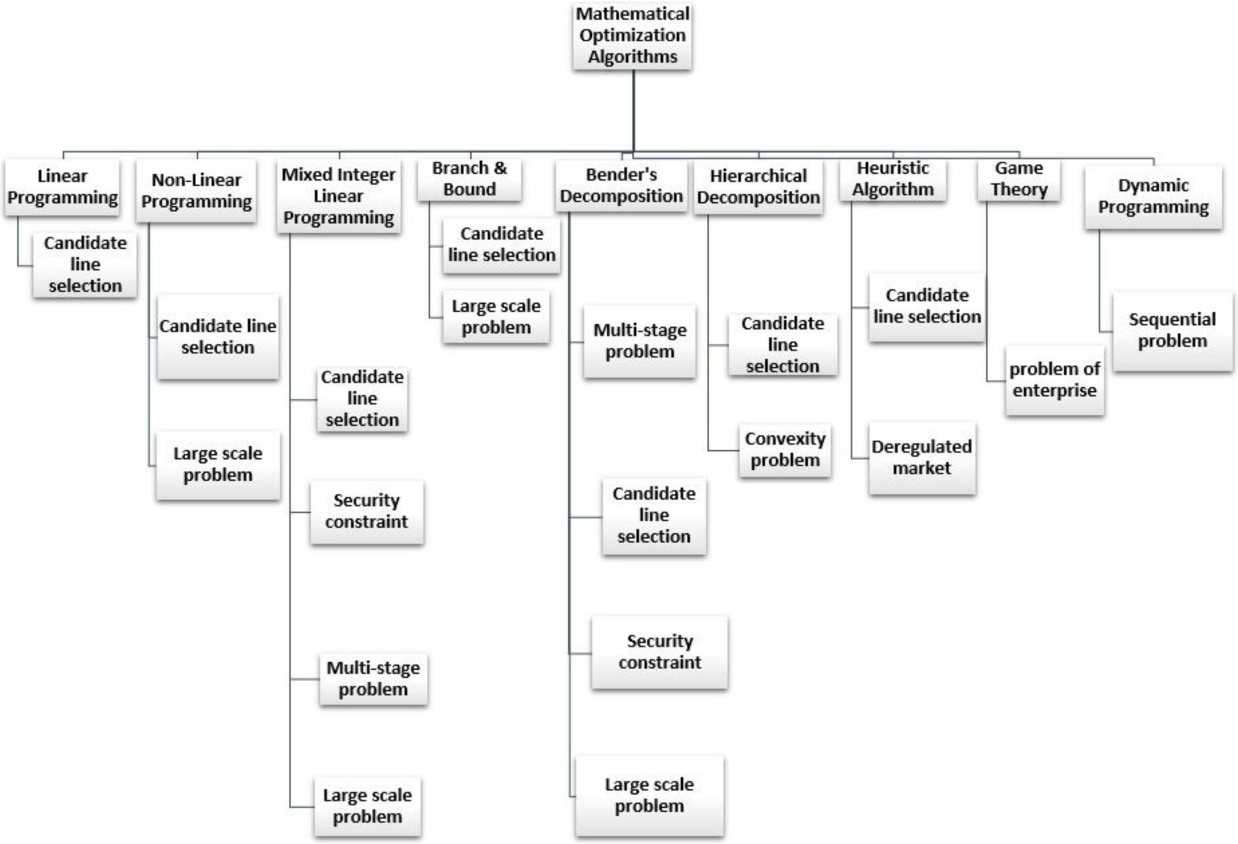

FIGURE 6. **Mathematical optimization algorithms and their suitable TNEP problem applications.**

on the decision-maker preferences. The feasibility and practicability of the proposed method was tested by using a 24-bus reliability test system (RTS).

A multi-objective optimization framework for a static TNEP to cope with new challenges introduced by deregulation is presented in [124]. Three objectives were considered in the problem formulation, which are reliability, investment cost and congestion cost. The nature of the problem is a mixed integer and non-convex optimization problems. The problems were handled by using a hybrid method that combines the the genetic based NSGA II algorithm and a Fuzzy decision-making analysis for an optimal solution to the problems. IEEE 24-bus test system was used as a case study to show the feasibility and the capability of the proposed algorithm, followed by a real life system application in northeastern part of Iranian national 400-kV network, in order to have an adequate comparison to the traditional method.

An enhanced constructive heuristic algorithm that combines fuzzy systems and the branch-and-bound algorithm for TNEP problem was proposed in [115]. The algorithm is based on the divide and conquer strategy that is controlled by fuzzy system. The aim of the method is to provide a high quality solutions by the use of fuzzy decision making process by leading the search without being affected by premature convergence for poor local optima.

Multiple Generation Scenarios (MGS) were considered in TNEP strategy in [125]. The approach taken in solving the problem is multi-objective evolutionary strategy using the features of NSGA-II and Chu-Beasley hybrid algorithm. Similar problem was earlier tackled by Escober *et al.* [126] in a single-objective approach and Rider *et al.* [127] solved similar TNEP problem by considering network security (N-1 contingency criteria). However, multiple power flow patterns needed to be analysed for a set of investment proposals to be obtained, which is why a multi-objective algorithm was proposed in [125]. The proposed algorithm was able to provide a set of Pareto optimal expansion plans for both variable and fixed demands with different levels of cost and load shedding when tested in IEEE 24 bus system.

VII. COMPUTATIONAL COMPLEXITY OF TNEP SOLUTION ALGORITHMS

The complexity of an algorithm is the duration taken by the algorithm to execute as a function of the length of the string that represents the input [128]. The concept has existed for thousands of years in different aspects of life. It could also be viewed as the process of producing an output from a set of inputs in a finite number of steps, while obeying certain rules that guide the process [129].

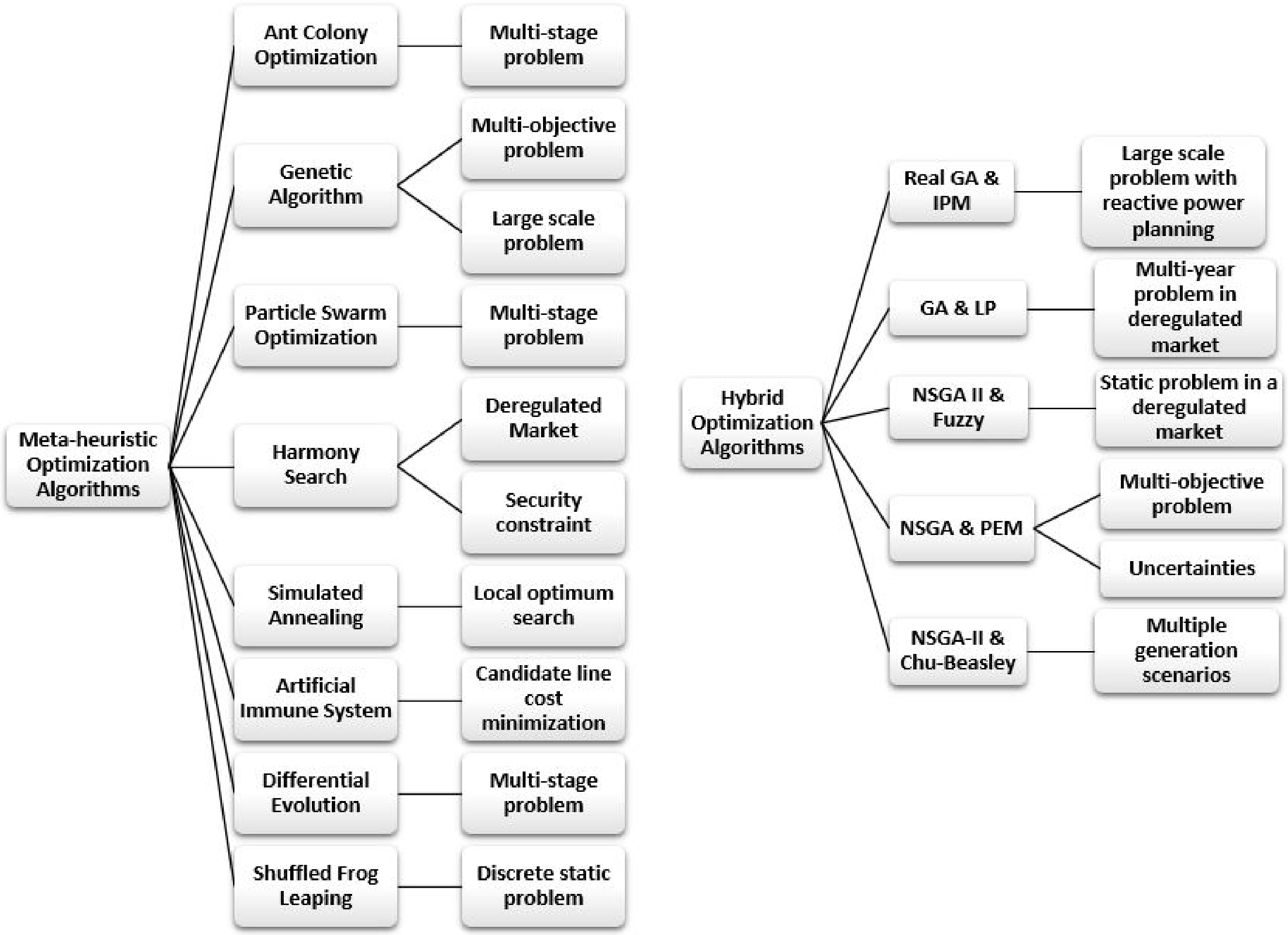

FIGURE 7. Meta-heuristics and Hybrid optimization algorithms and their suitable TNEP problem applications respectively.

The TNEP problem is inherently a large-scale, nonlinear and non-convex problem that has attracted attention from both academia and industry. Finding an optimal solution to TNEP problem over a planning horizon, requires the inclusion of some extensive parameters such as candidate circuits, network topology of the base year, investment constraints, electricity demand and generation forecast etc. These contribute more to the complexity of TNEP problem [130].

Mathematical optimization algorithms have proved the optimality in yielding the exact solution to TNEP problem. However, due to the complexity of TNEP problems, finding an optimal solution using only mathematical algorithms can be very challenging and time consuming [131]. Several meta-heuristic algorithms, and hybrid algorithms have been developed, which can solve the TNEP problem with less computational complexities.

Moreover, any given algorithm will take different amounts of time on the same inputs depending on its flexibility, simplicity and quick search for optimal solution to the problem. Hence, the details of the computational complexities of various meta-heuristics and hybrid algorithms for TNEP problem are listed in tables 2 and 3 respectively.

Table 1, shows the summary of different up-to-date mathematical algorithms, their applications, viability and drawbacks. While tables 2 and 3, show the summary of different up-to-date Meta-heuristic and Hybrid optimization algorithms, the applications, viability, computational complexities and drawbacks. Fig. 4, shows the graphical summary of the algorithms since 1970 as compared in table 1, 2 and 3. It can be noticed from Fig. 4, that meta-heuristic algorithms stand out to be the most frequently applied algorithms, especially in the last two decades. Fig. 5 (a) shows the graphical summary of frequently applied optimization algorithms in literature, while Fig. 5 (b) shows graphical summary of frequently applied meta-heuristic optimization algorithms. It can be noticed from Fig. 5 (b) that Genetic Algorithm is the most frequently applied meta-heuristic algorithm among others. Fig. 6 and 7, show the mathematical optimization, Meta-heuristics and Hybrid optimization algorithms and their suitable TNEP problem applications respectively.

VIII. CONCLUSION

Several algorithms for TNEP problems, which have been tested by many transmission network planners and numerous publications available in literature have been discussed in this paper. The paper has shown that there are new improvements in TNEP problem's solution strategies such as new optimization algorithms, availability of high speed computers and deregulated power sector uncertainty level.

Furthermore, it has shown that the major goal is to expand the existing network by integrating new power plants and new distribution links in order to prepare against the increasing future energy demand, thereby maintaining the system's reliability and efficiency. The commercial-based planning in transmission expansion takes into consideration, the existing economic status, system reliability constraints, security and the risk of planning strategies due to several uncertainties. Hence, a well-planned transmission network's expansion has to satisfy the above mentioned expectations. Moreover, the minimization of the network reinforcement and operational costs while satisfying the increase in demand imposed by technical and economic conditions over the planning horizon is eminent.

The numerous variables, which exist in energy system expansion problems give way to several mathematical model developments designed for a suitable systematic way of obtaining the optimal solution to long term planning in power network expansion. The planning must take into account the current and future technical and economic environment within which the power sector is expected to evolve.

The solution to the planning problem entails the use of general network synthetic techniques, and the relaxed mathematical models using the active power and the voltage angle (active part) of the network. The data to be used for the problem is the present network topology (base year).

The recommendation for future review is to classify the performance of each algorithm based on the type of TNEP modeling technique and the software in use. These could help to rank each algorithm's performance with regards to the network model and the suitable software. Moreover, it is recommended to engage in TNEP process that can incorporate the modification of the existing network topology of the base year by suggesting new generation points and exploring better transmission line corridors that can yield an optimal expansion over the planning horizon while considering all the necessary constraints.

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