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A Comprehensive Review on Optimal Location and Sizing of Reactive Power Compensation Using Hybrid-Based Approaches for Power Loss Reduction, Voltage Stability Improvement, Voltage Profile Enhancement and Loadability Enhancement

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ABSTRACT With the modernization of power grids, the network optimal utilization is essential to ensure that voltage profile at each bus is maintained within an acceptable range, voltage stability of the system is enhanced, power losses in lines are minimized, reliability and security of system are improved and etc. These can be achieved by introducing reactive power compensation devices such as Flexible Alternating Current Transmission System (FACTS) devices, Custom Power (CP) devices, synchronous condenser, capacitor bank and etc in distribution or transmission networks. Optimal location and sizing of the reactive power compensation devices are significantly important to ensure sufficient investment onto this device. Recently, most of conducted studies had focused on the techniques for determining the optimal location and sizing of various reactive power compensation devices in the power system using various indices proposed in the literature to access the power loss, voltage stability, voltage profile and line loadability. However, no review paper had discussed on the application of the existing indices adopted in the available techniques for solving the optimal location and sizing problems for all types of reactive power compensation devices. In this paper, current literature survey on optimal location and sizing of reactive power compensations had been discussed which includes analytical, conventional, metaheuristic and hybrid based approaches. The main objectives are to reduce power losses, to mitigate voltage deviations, to increase voltage stability and to improve reliability and security of the system.

INDEX TERMS Optimal allocation, Reactive power compensation, Analytical approaches, Metaheuristics, Optimization.

I. INTRODUCTION

The role of the grid has been evolving day by day towards more decentralized by maximizing the distributed energy resources with an advanced automatic control and communication techniques which is known as smart grid system. By modernizing the grid towards smart grid system, the electrical utilities are able to deliver the optimal amount of information and load control, reduce power losses and costs, promote energy conservation, manage peak demand, integrate the high levels of multiple distributed energy sources with variable output and etc in order to enhance the reliability, resiliency, security and efficiency of the system [1].

With the emerging modernization of the power grids and the use of multiple renewable energy sources, the optimal utilization of the networks is crucially important due to the cost of construction and the development of transmission and distribution networks is high. Moreover, the power system problems such as voltage profile issues, voltage instabilities, excessive power losses, heavily loaded lines, reliability problems, power quality and etc must be mitigated to enable a high performance infrastructure in the smart grid system [2 – 4]. These problems can be obviated by introducing the Reactive Power Compensation (RPC) in transmission and distribution system. The voltage support via RPC is necessary especially with the presence of non-dispatchable intermittent renewable power sources to alleviate voltage fluctuations at a given transmission or distribution bus [5].

The optimal number, size and location of RPC to be installed in the transmission and distribution system must be determined to satisfy all power system problems in modernizing the electrical power grid [6-7]. The location of RPC can be deployed at any buses or lines in the power system as its performance are varied on different transmission or distribution buses or lines. However, to maximize the overall performance of system and to ensure adequate investment of the reactive power compensation devices in the network, the most appropriate type of RPCs with the optimal placement and sizing is essential to provide an effective control [6-9]. This is known as optimal RPC placement and sizing problem and this problem is a critical component in reactive power planning (RPP) or known as VAR planning [10-11]. The selection of location, size and number of RPC are typically based on economic feasibility, security, reliability and quality of supply as well as availability perspective. The techniques for solving optimal allocation of RPC problems are categorized in fourfold; (i) analytical, (ii) arithmetic programming or also known as conventional optimization, (iii) metaheuristic optimization and lastly, (iv) hybrid based approaches.

A comprehensive review on optimal placement and sizing of Distribution Static Compensator (DSTATCOM) is done in [6]. Various approaches such as analytical, Artificial Neural Network (ANN) and metaheuristic methods with combination of sensitivity approaches namely; voltage stability index and power loss index for selecting the optimal allocation and sizing of DSTACOM had been discussed in this paper. The allocation objectives and constraints were also presented in this review work. However, the review work only focused on numerous methodologies available in literature for selecting optimal location and sizing for DSTATCOM. In [12], the review works are extended for multi-type of FACTS devices and focused on various metaheuristic optimization approaches for optimal placement and sizing. The authors of this paper highlights 49 of the current research works that consisted of various objective functions, constraints, approaches, type of FACTS devices, studied cases and contingency occasions.

In [13], a review work for solving FACTS devices allocation problem using a popular, powerful and well-established metaheuristic optimization approach namely, Particle Swarm Optimization (PSO) had been deeply discussed.

Various perspectives from the viewpoint of objectives and PSO itself (PSO variant, parameter selection, multi-objectives, constraints and discrete-variable) had been comprehensively reviewed. Numerous application of PSO-based techniques for solving FACTS allocation problems are available in literature such as normal PSO, non-dominated sorting PSO, hybrid PSO with differential evolution (DE) and evolutionary programming (EP), multi-objective PSO (MOPSO), enhanced leader PSO (ELPSO), perturbed PSO, evolutionary PSO (EPSO), hybrid evolutionary strategy EPSO (ES-EPSO) and hybrid PSO gravitational search algorithm (PSO-GSA), hybrid PSO genetic algorithm (PSO-GA) had been also reviewed in this work.

Throughout all the review works available in literature, there are no specific work that focused on the application of the existing indices adopted in available techniques for solving the optimal location and sizing RPCs. Hence, this paper presents a comprehensive review on various available indices which are adopted in optimal location and sizing techniques; analytical, conventional, metaheuristic and hybrid-based approaches for power loss reduction, voltage stability improvement, voltage profile enhancement and loadability enhancement.

II. REACTIVE POWER COMPENSATION TECHNOLOGIES

Various different emerging technologies are available to compensate the problem of reactive power circulation and these can be divided in two categories; conventional topologies and power electronic based topologies. The conventional topologies of reactive power compensation (RPC) also known as traditional topologies, utilize the non–power electronic based technologies either employing rotating machine or mechanical switch. Synchronous condenser is an example of rotating machine in RPC conventional topologies that works similarly as synchronous motor, however, it is used to produce the reactive power to regulate voltage at grid. In past decades, the synchronous condensers were once broadly used for reactive power compensation before the introduction of power electronic based devices. This type of compensation is rarely used nowadays due to the high power losses, contribute a part in short circuit current, slow response in balancing speedy load changes and high cost [14]. There are two types of synchronous condensers; traditional or conventional synchronous condenser and superconducting synchronous condenser (SuperVAR). The conventional synchronous condenser consists no mechanical load and its field is regulated by voltage regulator to provide the

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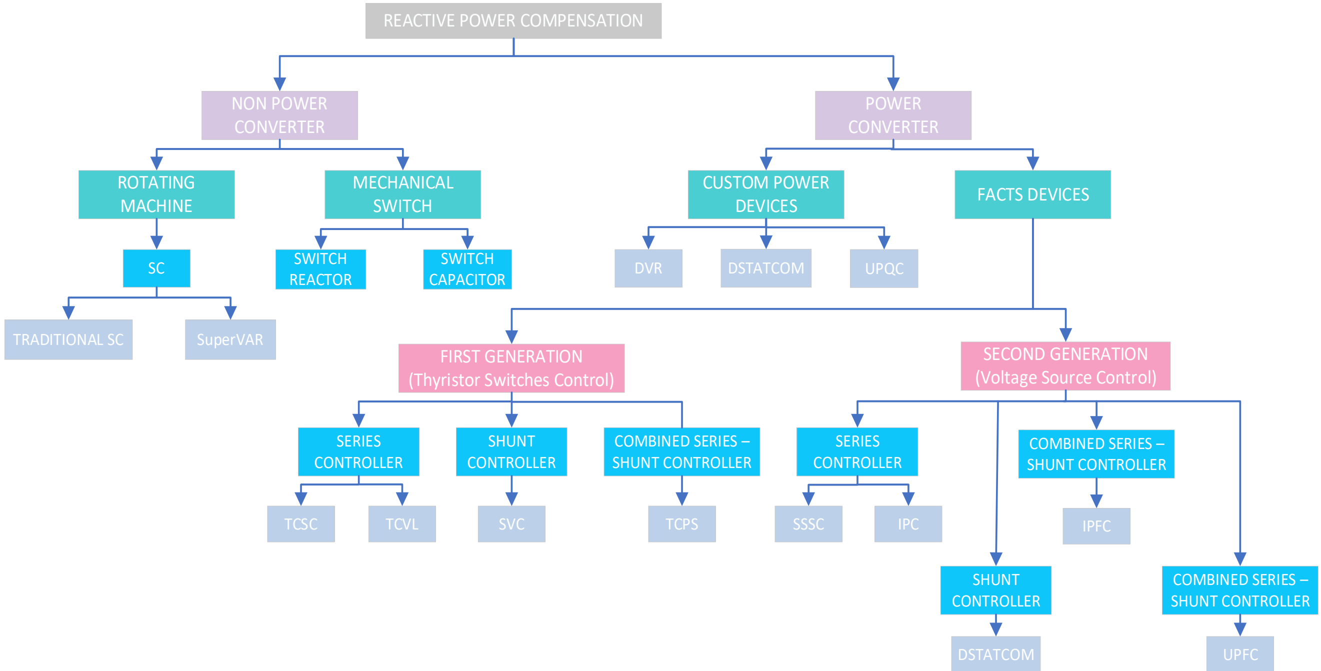

FIGURE 1. **The reactive power compensation technologies**

reactive power support for maintaining the voltage and power factor at a specific level [15].
be easily installed in any power transmissions and distribution lines compared to other reactive power compensation devices [16]. These devices are incorporated only with static elements such as capacitors and reactors that are directly connected at a high voltage busbar system or transformer and can either be fixed or turned on and off according to load and voltage conditions [16-17]. Series reactors capable to decrease the power flow in lines and reduce the short-circuit levels at selected location of the network whereas, series capacitors are able to shorten the electrical length of line which consequently increased the power flow in lines [18]. Series capacitors will be fully employed during the maximum loading to alleviate the overloading in transmission lines and it will be bypassed during minimum loading to prevent from overvoltages in transmission lines due to excessive capacitive effects [19]. It also reduces the losses in lines by reducing the line reactance which significantly enhance the voltage at the receiving end with low power factor [20]. Series capacitors is known as self-regulating device since the reactive power compensation increases with the increment of load [21]. However, series capacitors provide rise to resonance resulting which is not suitable for motor and industrial loads. Besides, precaution is required when switching off the series capacitor before turning off the loads as it provides rise to ferroresonance [22].

The thyristor controlled devices were introduced later to alleviate the limitations of conventional RPC by providing additional fast response times, reduction in power losses and less maintenance requirements [23]. These were further

The mechanically switched capacitors or reactors are commonly utilized since they are relatively low-cost and can improved with introduction of voltage source converters (VSC) for controlled techniques. These power electronics based topologies are known as Flexible Alternating Current Transmission (FACTS). FACTS devices can be categorized into two generations based on the technological features. The first generation utilizes thyristors while the second generation uses VSC as the controlled switch [24-25]. The second generation offers better performance compared to the first generation as the VSC based controllers are free from the drawback of resonance phenomena that are encountered by thyristor based controllers.

Due to the expansion in the electric power distribution systems and the use of electronic devices in all levels of end users, the quality of electric power delivered to load has been affected. Hence, the consideration on introducing distributed-FACTS (DFACTS) devices or also known as Custom Power (CP) devices in distribution networks for power quality improvement has become essential. CPs are similar to FACTS since it has similar technical base, however, its performance goals are different between these two devices [6]. FACTS are used to alleviate all problems in transmission system which includes increasing energy utilization efficiency, controlling demand flexibly, enhancing voltage stability, regulating voltage, controlling power flow and reducing power losses while CPs are used to mitigate all problems in distribution system especially in enhancing system reliability and solving power quality issues such as power factor, voltage profile and voltage stability [6-7]. The classification of RPCs is according to connection itself; series connected controller, shunt connected controller, combined series-series connected controller and combined series-shunt connected controller [12]. Further details on RPC can be found in [24-28].

III. IMPACT OF REACTIVE POWER COMPENSTATION INTEGRATION IN DISTRIBUTION AND TRANSMISSION SYSTEM

The modernization power system nowadays is facing a bigger challenge to satisfy the rapidly growing demand for electricity. This caused the transmission and distribution systems to operate beyond the transfer capacity which leads to overloading in networks or known as network congestion. In a large and complex modern power system, the increment in demand of electrical load may force the system to operate closer to the stability limit. At this stage, the generators and transmission lines are exceeding their physical limits and this triggered the system frequency and voltage at respective bus to drop. As a result, a voltage collapse may occur in the system. Numerous major blackouts have been reported in various countries in Europe, USA and Asia due to this abnormal low voltages phenomenon which leads to voltage collapse in most parts of the power system [29]. Large disturbances frequently led to cascading events and may end up with a total blackout if these cascading events are not properly mitigated. Lack of reactive power reserves are one of the main contributions towards these cascading events [30-31]. As the world is moving towards renewable and sustainable energy systems, reactive power requirements are now becoming obligatory to ensure both generation and consumption are balanced across the entire grid [32].

Reactive power is essential in power systems to support the real power which is transmitted from generation to load side via transmission and distribution lines. RPC or VAR compensation is known as the management of the reactive power to enhance the performance of alternating current (AC) power in an electrical power system. Load compensation and voltage support are two main aspects viewed in any problems related to RPC. The methods of generating reactive power at load side are known as compensation. It is predominantly aimed for enhancing system power factor, balancing the real power supply, compensating voltage regulation and eliminating the harmonic current components generated by nonlinear loads. On the other hand, voltage support in general is essential for reducing voltage fluctuation at bus to enable the delivery of power in networks [28,33-34]. At distribution level, both load compensation and voltage support are required for solving the end user problems especially problems related to the power quality; to increase the power factor, to balance the real power drawn from ac supply, to compensate the voltage regulation and to eliminate current harmonic components due to nonlinear loads [28,33-34]. For transmission system, the reactive power compensation is required to reduce voltage fluctuation, upgrade transmission lines, increase loadability of the system, enhance stability of system, maintain voltage profile within the acceptable range, improve transmission efficiency, controls steady state and temporary overvoltages and prevent networks from catastrophic blackouts [28].

RPCs are capable to increase power transfer capability in lines, boost stability margin, provide fast and reliable real and reactive power flow control, improve control of grid in both steady state and transient state conditions and mitigate power quality problems. The power flow control services provided by RPCs are capable to alleviate network congestion, minimize operation cost, reduce power losses and voltage deviation by minimizing the reactive power dispatch, enhance available transfer capability and minimize load curtailment [35]. Another essential role of RPC in power system is for voltage security improvement and it has been reported that inadequate reactive power supply is one of the causes of major blackouts [36]. Due to the increased usage of sensitive loads, renewable energy systems and power electronics equipment, the power quality issues have become more complex at all power system levels and without a proper mitigation technique, the poor power quality may increases power losses, undesirable behavior of equipment and inference with nearby communication lines [37]. Power quality problems can be effectively improved by RPCs especially in minimizing voltage sags, providing harmonics isolation for nonlinear load and improving power factor. Furthermore, significant improvement in power system stability which specifically enhances the damping of oscillation, improves transient stability and voltage stability are also offered by RPCs [38]. All these advantageous can be fully maximized with a proper location and sizing of RPC integration thus optimized the operation of power system under both normal and contingency occasions.

IV. OPTIMAL LOCATION AND SIZING TECHNIQUES

RPCs technology has been effective and viable in mitigating all problems in both transmission and distribution systems. It capable to control the key parameters of power grids and improve the characteristic of the power systems. The cost of installing RPCs in the networks are high, hence a proper location and sizing is essential to ensure adequate investment of the devices. The integration of RPCs with an appropriate location and sizing in power system may provide additional improvement in the overall system's performance especially in enhancing voltage profile at bus, minimizing power losses and enhancing the voltage stability and loading margin. Besides, the economic viability aspects based on reliability, quality and availability are the additional features which highlight the needs of obtaining the optimal location and sizing of RPC in power systems.

Solving the optimization problem in which related to searching for the best or optimal location and sizing of RPC has greatly drawn the attention of many researchers over the past decades. In most research work, more than single

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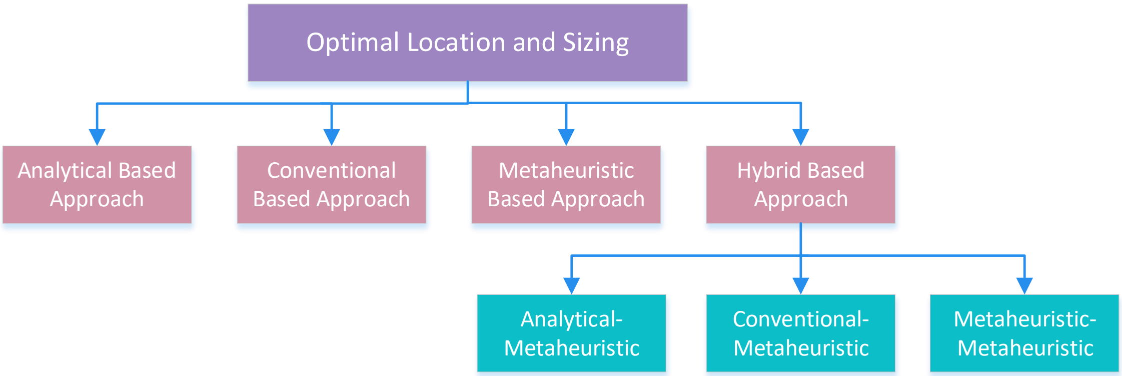

FIGURE 2. Classification of Optimal Location and Sizing Techniques

objective is considered in solving the optimal location and sizing of RPC and this is known as multi-objective optimization problem. The formulation of multi-objective for optimal RPC optimization problems are expressed using mathematical sum approach, weighting functions, fuzzy goal programming techniques and Pareto concept. The common objective functions presented in most recent research works are aimed to minimize power losses, enhance voltage profile, improve voltage stability and boost system loadability. Several different factors such as real and reactive power balance, bus voltage and phase angle bus limit, generation cost, power flow limit, voltage stability limit, real and reactive power demand limit, thermal limit, DG limit, loading factor limit, real and reactive generator limit, cost of RPC, RPC capacity, number of RPC limit, current limit, power factor limit, total real power limit and total reactive power limit are frequently considered in most studies as the constraints of the optimization problem.

The optimal location solution alone is represented as integer decision variable while for both optimal location and sizing solutions are considered as mixed-integer optimization problem. The optimization solutions are typically comprised of several local optima and due to that, it is also classified as multi-modal optimization problems. Hence, the optimal location and sizing optimization problems are considered as non-linear multi-modal, multi-objective, mixed-integer and highly constrained optimization problem [12, 40-41, 43]. The optimization goals can be achieved by evaluating the power system under the following circumstances; (i) N-1 contingency such as line tripping or generator outage, (ii) load variation, (iii) load growth, (iv) generation variation and, (v) load model characteristic. These events are likely contributed to sudden and large changes in current configuration and state of power system which may leads to severe violations of the operating constraints such as overloading in line, high voltage deviations in bus and excessive power losses [39]. Study related to all these events are essential to allow the system operates defensively with a fast corrective action taken for all potential severe violations.

Various techniques for solving optimal location and sizing of RPC had been proposed in literature that can be categorized into four groups; (i) analytical approaches, (ii) conventional optimization based approaches, (iii) metaheuristic optimization approaches and, (iv) hybrid approaches as shown in Fig. 2 [6, 12, 40-41]. Analytical approaches or sensitive based approaches are simple, reliable and computing efficiency algorithms that is used to identify the optimum solutions with lack of consideration of nonlinearity and complexity of the system [6, 12, 40-42]. It could provide an optimal or near-optimal global solution [42]. In order to reduce the computational procedure, these algorithms utilize some approximation for solving the optimization problems. Due to that, these approaches are lack of computation accuracy and lack of ability on dealing with both optimal location and sizing simultaneously [41]. It requires high extensive computational burden and storage in order to provide high calculation precision [42].

Traditional or conventional optimization techniques such as linear programming, non-linear programming, dynamic programming, sequential quadratic programming (SQL), newton raphson (NR) and many others provide an excellent convergence characteristic [41]. The algorithms are generally start with randomly determined the initial solution and reach towards the optimal solution in every iteration. These algorithms are broadly categorized into two main clusters: direct search methods and gradient based methods. The traditional optimization approaches have no guarantee that the final solution obtained is a globally optima solution since it is dependent on the value of initial randomly chosen [44]. Besides, in most of traditional approaches especially gradient based approaches, the algorithms are not capable to solve the optimization problems which consist of discontinuous objective functions as they may trap at local optima points [45]. Furthermore, the algorithms are complex in which they are difficult to be implemented effectively and not suitable for solving various constraints optimization problems [12, 41, 44, 46]. Mixed integer linear programming (MILP) and Mixed integer non linear programming (MINLP) are the two most common conventional optimization techniques for solving the optimal location problem in various type of RPC which can be found in [47-52]. Since these traditional optimization techniques are incompetent to solve the multi-objective nonlinear problem and have more chances to trap into local optimum, hence, metaheuristic algorithms were introduced to compensate these problems [53].

Metaheuristic algorithms are dynamic algorithms that are independent in solving any problems and capable to provide a global optima solution. The algorithms are typically a nature-inspired method which can be further group into three mainstream disciplines: (i) biology inspired algorithms, (ii) physics-based algorithm and, (iii) chemistry-based algorithms [54-55]. The biology inspired algorithms are clustered based on three concepts: (i) evolutionary, (ii) swarm-based intelligence and, (iii) plant-based intelligence algorithms. Evolutionary algorithms are generic population-based metaheuristic optimization which start with initializing random population. The algorithms are inspired by the biological evolution, for example, mutation, reproduction, recombination and selection that evolved a population of solutions to solve the optimization problem iteratively and the best individuals are passed to the next generation until termination criterions are met [32, 56]. Genetic algorithm (GA), evolutionary programming (EP), evolutionary strategies (ES) and genetic programming (GP) are categorized under evolutionary algorithms and among these algorithms, GA is extensively used in literature for solving reactive power optimization problems.

Swarm-based intelligence algorithms are based on the imitation of animals' social behavior with no centralized control. The agents are acted on local information and interactions with other agents and their environment to achieve a common goal [56]. The behavior of agents and self-organizing interaction between agents in nature capable to solve complex optimization problems [54]. Particle swarm optimization (PSO) is the baseline algorithm for most of swarm-based algorithms and also one of the most preferred algorithms in solving reactive power optimization problems. Besides PSO, ant colony optimization (ACO), wolf search algorithm (WSA), cat swarm optimization (CAT), cuckoo search algorithm (CSA), bat algorithm (BAT), firefly algorithm (FA), bacterial foraging optimization algorithm (BFOA), artificial bee colony (ABC), whale optimization algorithm (WOA), bee colony optimization (BCO) and grey wolf optimization (GWO) are the common optimization algorithms for solving optimal location and sizing problems that were used extensively in the literature.

Plant intelligence based algorithms are developed by inspiration from plant intelligence based on the behavior of plants. Plant growth simulation algorithm (PGSA) and flower pollination algorithm (FPA) are the two algorithms that had been covered for solving RPC optimization problem. PGSA is inspired by the growth process of plant phototropism while FPA is developed from the pollination behavior of flowers. Majority of nature-inspired algorithms generally falls under biology-inspired algorithms, however, there are some metaheuristic algorithms are inspired by physic or chemistry-based algorithms. These algorithms have been developed by inspiring certain physical or chemical laws such as gravity, electrical charges, river systems, music and etc [57]. Simulated annealing (SA), harmony search algorithm (HSA), gravitational search algorithm (GSA), chemical reaction optimization (CRO), improved harmony

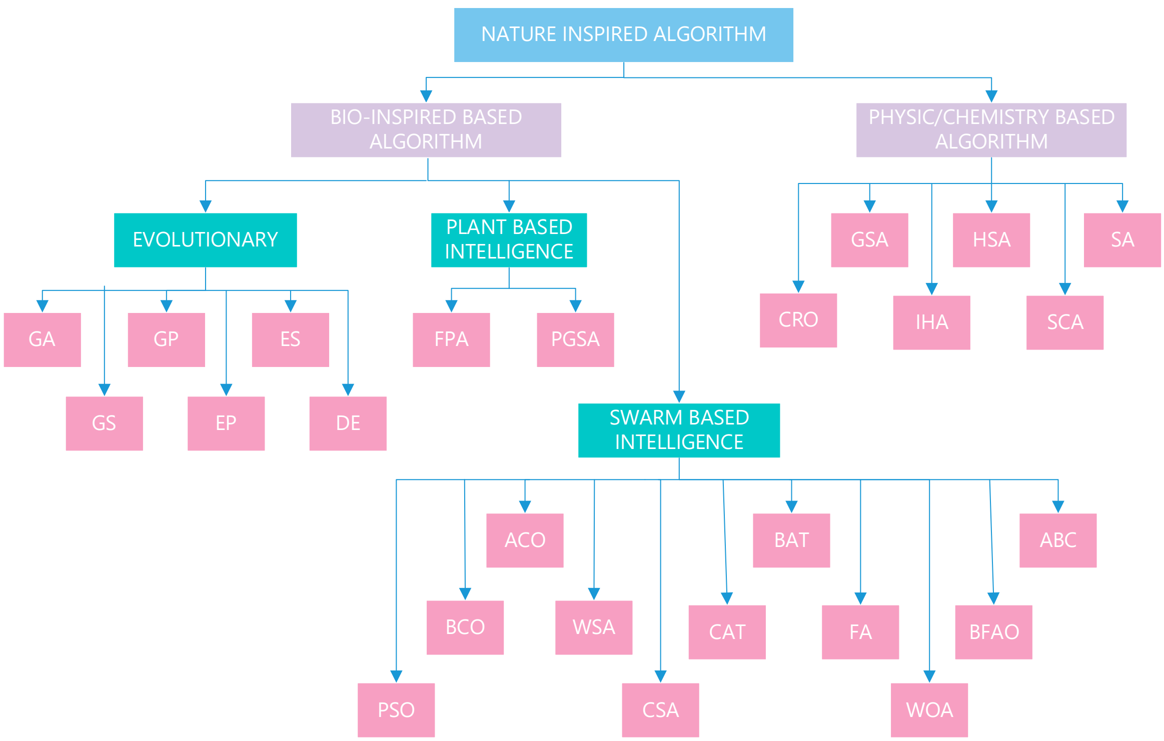

FIGURE 3. **Taxonomy of Nature Inspired Algorithm commonly used in solving optimal location and sizing problem**

algorithm (IHA) and sine cosine algorithm (SCA) are among the well-known physic or chemistry-based algorithms that are generally used for solving the reactive power compensation optimization problems. Fig. 3 illustrates the taxonomy of nature-inspired algorithms.

The combination of analytical-metaheuristic approaches or traditional-metaheuristic approaches or metaheuristic-metaheuristic approaches are known as hybrid-based approaches. The utilization of either analytical or traditional techniques helps to reduce the search space of the proposed metaheuristic optimization techniques [12]. As a result, the structure of algorithms is simple and less computation time consuming to solve the optimization problems. The combination of analytical and metaheuristic approaches is preferred in literature due to the deployment of analytical approaches which are simple and reliable. This approach is also known as two-stage approach. The candidate locations of RPCs are pre-determined initially by using analytical techniques and finally, the optimal location and sizing is obtained using metaheuristic algorithm [6, 12-13, 112, 116, 118]. In some two-stage approaches, the optimal location and sizing of RPCs are determined separately whereas the best location is obtained using analytical approach and the best sizing is determined using metaheuristic technique.

V. ANALYTICAL APPROACH

The pre-identification and estimation of the candidate buses/lines for optimal RPC location through analytical approaches are essential to reduce the search space for solving optimization problems. These potential or candidate locations are known as critical, unhealthy, weak, vulnerable or severe lines/buses which are prone to cause other transmission networks to be more stressed and complicated. In most research work done in literature, these weak lines/buses are typically located far from the generating source.

The results obtained from analytical approaches may not lead to optimum solutions due to the facts that results are differ according to network topology, configurations and contingencies such as load increment or variation and generator or line tripping. These limitations can be solved with metaheuristic algorithms in which the algorithms help to obtain optimal location, number and sizing of RPC based on the objective(s) adopted in the objective function. In this section, the common indices to determine the candidate locations for RPC which were proposed by researchers are listed.

A. POWER LOSS

The increment of reactive power demand in distribution system creates manifold challenges especially in loss profile management due to most of the loads consist of reactive loads. This significantly increases the current flow in transmission and distribution system which also increases the I^2R and I^2X losses in lines. As reported in [58-59], about 13% of power delivered from generation to load side is lost as ohmic losses at the distribution level. According to [60], 70% of total power losses in power system occurs at distribution system while the rest of 30% occurs at transmission and sub-transmission system. By integrating capacitor, custom power devices or FACTS devices into the network, the power losses produced by reactive currents can be reduced. The reduction of total power losses is significant in order to alleviate the sag problem, increase the capacity of line loading as well as reduce the heating effect in cable. The investigation in reducing power loss is one of the most common criteria in selecting the possible location of FACTS devices [61]. The location which offers the highest reduction in total losses is chosen as the most suitable location for installing reactive power compensation.

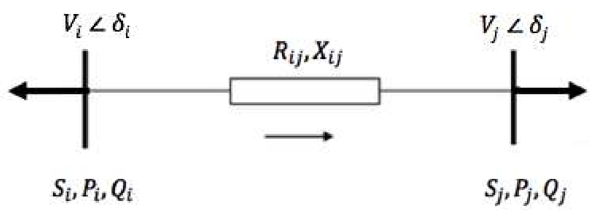

FIGURE 4. The sending and receiving two-bus model representation

Where:

R_{ij}, X_{ij}, Z_{ij}	=	the line resistance, reactance and impendence between bus i (sending end) and j (receiving end)
S_i, P_i, Q_i	=	the apparent, real and reactive power at bus i (sending end)
V_i, V_j	=	the magnitude bus voltage at bus i (sending end) and bus j (receiving end)
nl	=	number of lines
δ	=	phase angle between sending and receiving bus, $\delta_i - \delta_j$

Several power losses' indices were proposed in literature to examine both real and reactive power losses in each line and overall system losses. The mathematical formulation of power losses is derived using a power transmission concept in two bus model representation of a single line of an interconnected network as shown in Fig. 4. The real and reactive power losses in line are extracted from the following set of equations.

$$P_{loss(ij)} = \left(\frac{P_j - jQ_j}{V_j^*} \right)^2 * R_{ij} = \frac{P_j^2 + Q_j^2}{V_j^2} * R_{ij} \quad (1)$$

$$Q_{loss(ij)} = \left(\frac{P_j - jQ_j}{V_j} \right)^2 * X_{ij} = \frac{P_j^2 + Q_j^2}{V_j^2} * X_{ij} \quad (2)$$

And the total real and reactive power losses of the entire system is determined by summing up all line losses as follows;

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$$P_{(totallosses)} = \sum_{t=1}^{nl} P_{loss(ij)} \quad (3)$$

$$Q_{(totallosses)} = \sum_{t=1}^{nl} Q_{loss(ij)} \quad (4)$$

The following indices proposed in literature to evaluate the optimal placement for series and shunt RPCs are briefly discuss in this section.

1.0 TOTAL SYSTEM LOSS SENSITIVITY FACTOR METHOD

The sensitivity factor approaches are based on the principle of linearization of the original set of nonlinear equation around the initial operating point which aimed to reduce the number of solution space [62]. This approach has been extensively used for capacitor placement and has gained popularity recently in determining distributed generation (DG) locations for power loss reduction [63-64].

1.1 LOSS SENSITIVITY FACTOR (LSF)

The sensitivity indices were proposed in literature based on the control parameters for RPCs, with respect to series reactance for series compensation and reactive power injection for shunt compensation. Loss sensitivity factor (LSF_{bus}) are proposed by utilizing the sensitivity of total transmission line losses (P_{loss}) with respect to the control parameters of RPC for optimal location. The loss sensitivity factor with respect to shunt compensation was computed using total real power losses in system, also known as exact loss formula [65-66]. This index is commonly used for determining optimal location of DG which can be found in [67-70].

$$P_{loss} = \sum_{i=1}^{n}\sum_{j=1}^{n}\left[\alpha_{ij}\left(P_iP_j + Q_iQ_j\right) + \beta_{ij}\left(Q_iP_j - P_iQ_j\right)\right] \quad (5)$$

For each bus, the sensitivity factor can be expressed as partial derivatives of total system real power losses with respect to the reactive power output of the shunt RPC as,

$$LSF_{bus} = \frac{\partial P_{loss}}{\partial Q_j} = 2\sum_{j=1}^{n}\left(\frac{r_{ij}}{V_iV_j}cos(\delta)Q_j + \frac{r_{ij}}{V_iV_j}sin(\delta)P_j\right) \quad (6)$$

For series compensation, the loss sensitivity index was formulated using the real and reactive power losses in line which are expressed using real and reactive power flow from sending and receiving bus.

$$P_{(lineloss)} = V_i^2G_{ij} + V_j^2G_{ij} - 2V_iV_jG_{ij}cos(\delta) \quad (7)$$

$$Q_{(lineloss)} = -V_i^2B - V_j^2B + 2V_iV_jG_{ij}cos(\delta) \quad (8)$$

Where, $B = B_{ij} + B_{sh}$, $G_{ij} = \frac{r_{ij}}{(r_{ij}^2 + x_{ij}^2)}$, $B_{ij} = -\frac{x_{ij}}{(r_{ij}^2 + x_{ij}^2)}$

Hence, the loss sensitivity with respect to control parameter of series compensation which is placed between buses i and j are formulated and can be express as,

$$LSF_{line(1)} = \frac{\partial P_{lineloss}}{\partial x_{ij}} = (V_i^2 + V_j^2 - 2V_iV_jcos(\delta_i - \delta_j))\left[\frac{-2r_{ij}x_{ij}}{(r_{ij}^2 + x_{ij}^2)^2}\right] \quad (9)$$

$$LSF_{line(2)} = \frac{\partial Q_{lineloss}}{\partial x_{ij}} = (V_i^2 + V_j^2 - 2V_iV_jcos(\delta_i - \delta_j))\frac{r_{ij}^2 - x_{ij}^2}{(r_{ij}^2 + x_{ij}^2)^2} \quad (10)$$

$$LSF_{line(3)} = \frac{\partial P_{lineloss}}{\partial \delta} = 2V_iV_j\sin(\delta_i - \delta_j))\frac{r_{ij}}{(r_{ij}^2 + x_{ij}^2)^2} \quad (11)$$

$$LSF_{line(4)} = \frac{\partial Q_{lineloss}}{\partial \delta} = -2V_iV_j\sin(\delta_i - \delta_j))\frac{r_{ij}}{(r_{ij}^2 + x_{ij}^2)^2} \quad (12)$$

Two criterions have been set for the optimal location of RPC using these sensitivity approaches. For shunt compensation, the shunt RPC should be located at the most negative sensitivity index bus, LSF_{bus} and only load buses are considered for the placement of RPC. However, for series compensation, the series RPC should be located at the most positive sensitivity index, LSF_{line} and the series RPC should not be located between two generation buses although the index is the highest.

1.2 POWER LOSS SENSITIVITY (PLS)

The next loss sensitivity indices were formulated using the real and reactive power losses in line from equation (1) and (2). These indices reduce the search space which significantly help in obtaining quick results for the optimization process [71-73]. The indices can be expressed as partial derivatives of the real and reactive power losses in line with respect to the reactive power injection at the receiving bus as,

Real power loss:

$$\frac{\partial P_{loss}}{\partial P_j} = \frac{2P_jR_{ij}}{V_j^2} \quad (13)$$

$$\frac{\partial P_{loss}}{\partial Q_j} = \frac{2Q_jR_{ij}}{V_j^2} \quad (14)$$

Reactive power loss:

$$\frac{\partial Q_{loss}}{\partial P_j} = \frac{2P_jX_{ij}}{V_j^2} \quad (15)$$

$$\frac{\partial Q_{loss}}{\partial Q_j} = \frac{2Q_jX_{ij}}{V_j^2} \quad (16)$$

By utilizing the base case power flow results, the indices are calculated and arranged in descending order for all lines in a given system and the normalized voltages for each bus are obtained by dividing the base case voltages with 0.95. The buses which are at the highest rank and with the normalized voltage less than 1.01 are considered as the candidate buses for RPC integration. In literatures, the study involving these indices were mostly examined in radial distribution system which consisted only single line connected between two buses. However, for mesh networks, these indices are suitable for examining the best location in series RPC due to its capability of identifying the weakest lines.

1.3 COMBINED POWER LOSS SENSITIVITY (CPLS)

The combined power loss sensitivity (CPLS) index as proposed by [74] helps to indicate the candidate nodes for RPC placement by estimating the sensitive or critical buses directly to reduce the search space. Integrating RPC in the network does not only impacts the reactive power losses since the RPC supply reactive current which contributes to the increment of real power losses as well. Hence, CPLS is proposed with consideration of both real and reactive power losses. By utilizing the real and reactive power loss sensitivity indices as in equation (13) – (16), the combined power loss sensitivity with respect to real and reactive power are formulated as below,

$$\frac{\partial S_{loss}}{\partial P_j} = \frac{\partial P_{loss}}{\partial P_j} + j\frac{\partial Q_{loss}}{\partial P_j} \tag{17}$$

$$\frac{\partial S_{loss}}{\partial Q_j} = \frac{\partial P_{loss}}{\partial Q_j} + j\frac{\partial Q_{loss}}{\partial Q_j} \tag{18}$$

And the loss sensitivity matrix (LSM) is obtained as follows,

$$LSM = \begin{pmatrix} \dfrac{\partial P_{loss}}{\partial P_j} & \dfrac{\partial P_{loss}}{\partial Q_j} \\ \dfrac{\partial Q_{loss}}{\partial P_j} & \dfrac{\partial Q_{loss}}{\partial Q_j} \end{pmatrix} \tag{19}$$

The candidate nodes for RPC placement can be determined by this index and buses which provide higher index and are highlighted as the potential location for RPC placement.

2.0 POWER LOSS INDEX

The power loss index (PLI) is an efficient approach which is used to determine the best location of STATCOM and it is sensitive to the total active power loss reduction. The FACTS device is injected at all bus except voltage bus and the total real power losses and loss reduction are obtained from base case load flow. The total reductions of real power loss are normalized into a range of 0 for low reduction and 1 for high reduction. Bus which offers the highest PLI value (PLI = 1) will be the priority to be the candidate bus for installing FACTS devices. The power loss index is determined using the following equation:

$$PLI(i) = \frac{M(i) - M_{\min}}{M_{\max} - M_{\min}} \tag{20}$$

Where :

$M =$ reduction in power loss,

$M_{\min} =$ minimum power loss reduction,

$M_{\max} =$ maximum power loss reduction,

$N =$ number of buses, $i = 2, 3, ..., N$

B. VOLTAGE STABILITY INDICES

Voltage stability is defined as the ability of the system to maintain the nominal voltage at all buses close to the normal operating condition after the fault occurrence [75]. The voltage instability occurs in the system due to insufficient reactive power supply or unnecessary reactive power absorption that leads to voltage collapse especially when the system is heavily loaded. The system is not able to retain generation and network schedule at this point. Therefore, an adequate reactive power support is crucially important for maintaining the voltage stability of the system.

Voltage stability indices (VSIs) are defined as indicators to detect the voltage collapse points in a power system. VSIs are capable to identify the weak lines and buses in the network under both offline and online mode via static analysis or phasor measurement units, provide the information on the stability of line connected between two buses at various loading conditions, determine the optimal placement and sizing of RPC and DG, and as a real-time indicator for voltage instability via Phasor Measurement Unit-Wide Area Measurement system (PMU-WAMS) [76-79]. Analyzing the voltage stability for a given power system involves two aspects; proximity which indicates how close is the system to approach voltage instability and mechanism that contributed to voltage instability such as the key factors of contributing the voltage instability, voltage weak points and areas involved [80]. Proximity provides an indicator of voltage security while mechanism produces useful information on how to prevent voltage instability occurrence for system modifications or operating strategies.

Voltage stability studies can be analyzed using different approaches, either static or dynamic approach [81]. Although voltage stability is dynamic phenomenon and the studies can be done using an extended transient or midterm stability simulations, however, these simulations does not provide sensitivity information or degree of stability and also time consuming since it requires to be tested under different system conditions and large number of contingency scenarios. These can be done using steady state analysis. Static voltage stability approaches are based on the steady state analysis model that are based on the power flow equation or linearized dynamic model described by steady state.

The classification of the static voltage stability analysis methods are based on the main idea of VSIs formulation; maximum transferable power through single line, existence of solutions for voltage equation, PV curve, Lyapunov stability theory, jacobian matrix and maximum power transfer theorem [79]. In [82], the classification of VSIs are based on system variables-based, jacobian matrix-based, and PMU-based (observability-based and local measurement-based). However, it is more preferable to categorize VSIs based on its type; line VSIs, bus VSIs and overall VSIs [79].

System variables-based indices which includes line VSIs, bus VSIs and overall VSIs are extracted based on two bus system model. They are less time consuming, preferable in identifying the weak or stress line bus in one area and react to the overall system load change [79-80]. Jacobian matrix based indices are not recommended for online application due to the nonlinearity characteristic at a collapse point and require high computation time. They do not accurately measured the collapse point due to the nonlinearity behavior whenever near to the collapse point [80]. PMU-based indices are more on monitoring voltage stability state which offers completely different application from the two mentioned indices [80].

In most studies involving VSIs either using analytical or optimization approaches, the RPC placement and sizing are determined based on two procedures. In the first procedure, the weak lines and buses are identified and ~~the~~ listed as candidate locations for RPC. Based on the candidate lists, the optimal location and sizing are obtained by evaluating the voltage stability margin improvement based on the VSIs calculated. Thus, overall VSIs are not preferred in solving optimal location and sizing problems due to this type of VSIs that are not capable to determine weak buses and lines and it requires more computational efforts. However, in term of accuracy, overall VSIs are better than bus and line VSIs. Various techniques were proposed in literature referred in [79, 82].

1.0 LINE STABILITY INDICES

The voltage stability analysis for line VSIs is examined in lines. The formulation of the line indices is based on power transmission concept of two bus models as illustrated in Fig. 4 where the shunt admittances are neglected. Hence, most of the indices were formulated using the same theoretical base with difference assumptions made; neglecting some parameters such as line resistance (*R*), shunt admittances (*Y*), phase angle differences between sending and receiving voltage (δ) and etc. Furthermore, the discriminant of the voltage quadratic equation in most of indices are set to zero or greater than zero.

Under normal loading condition, all line VSIs will be measured less than 1.00. The system is more stable if the value of indices in every line is measured closer to zero and if the value of indices is measured closed to 1.00, then the system is much more prone to voltage instability. Line with the highest index is classified as critical line and will be nominated as the potential location for RPC integration. In this section, the most well-known line VSIs which have been proposed in literature are concisely explained here.

1.1 LINE STABILITY INDEX (L_{MN})

The L_{mn} derived by Moghavemmi et al. in [83] is based on the power transmission concept in an individual line network to assess the overall system stability. By utilizing the power flow in line, the power flow at the receiving end as shown in Figure 4, and the index are obtained as follows,

$$L_{mn} = \frac{4X_{ij}Q_j}{\left[|V_i|\sin(\theta-\delta)\right]^2} \le 1 \tag{21}$$

1.2 LINE STABILITY FACTOR (LQP)

Mohamed et al had proposed LQP that is formulated based on a power transmission concept in a single line [84]. The formulation starts with deriving the power equation in a power system and the line stability index can be obtained as,

$$LQP = 4\left(\frac{X_{ij}}{V_i^2}\right)\left(\frac{X_{ij}}{V_i^2}P_i^2 + Q_j\right) \tag{22}$$

1.3 FAST VOLTAGE STABILITY INDEX (FVSI)

Musirin et al. in [85] developed the fast voltage stability index (FVSI) from the same power transmission in two bus system concept and the index is defined as follows,

$$FVSI = \frac{4Z^2Q_j}{V_i^2X_{ij}} \tag{23}$$

1.4 VOLTAGE STABILITY PROXIMITY INDEX (VCPI)

VCPI is derived by Moghavvemi et al in [86] is simply based on the maximum power transferred through a single line. The maximum real and reactive power that can be transmitted to the receiving end are labelled as $P_{i(max)}$ and $Q_{i(max)}$ while P_j and Q_j are determined from the power flow calculations,

$$VCPI_{(P)} = \frac{P_j}{\frac{V_i^2}{Z_{ij}}\frac{\cos\phi}{4\cos^2\frac{\theta-\phi}{2}}} \tag{24}$$

$$VCPI_{(Q)} = \frac{Q_j}{\frac{V_i^2}{Z_{ij}}\frac{\sin\phi}{4\cos^2\frac{\theta-\phi}{2}}} \tag{25}$$

1.5 LINE COLLAPSE PROXIMITY INDEX (LCPI)

Tiwari et al derived LCPI based on the transmission line proximity index (PI) model of two port network using ABCD parameters [87]. The formulation of LCPI is described as follows,

$$LCPI = \frac{4A\cos\alpha(P_jB\cos\beta + Q_jB\sin\beta)}{(V_i\cos\delta)^2} \tag{26}$$

Where, *A*, *B*, *C* and *D* are the transmission line parameters, *α* and *β* are the phase angle for *A* and *B* parameters, respectively. The ABCD parameter is expressed as follows,

$$\begin{bmatrix} V_i \\ I_i \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix}\begin{bmatrix} V_j \\ I_j \end{bmatrix} \tag{27}$$

1.6 VOLTAGE STABILITY INDEX (VSI)

VSI is formulated by considering line resistance specifically for distribution network due to high R/X ratio

[88]. VSI between sending and receiving bus is given as follows,

$$VSI = 4\left[Q_j X_{ij} + \frac{Q_j R^2}{X_{ij}} \right] \frac{\left[1-\cos 2\phi\right]}{2V_i^2 \sin^2\left(\delta_i - \delta_j - \phi\right)} \quad (28)$$

1.7 VOLTAGE SENSITIVITY INDEX (VSEI)

VSEI proposed by Murthy et al. in [89] using the same concept of power in transmission line between sending and receiving bus. The index is defined as below,

$$VSEI = \frac{4X_{ij}}{V_i^2}\left(\frac{P_j^2}{Q_j} + Q_j \right) \quad (29)$$

1.8 PROPOSED STABILITY INDEX (PSI)

The PSI has been designated by Gupta et al which is also based on the power transmission concept in two bus system [90]. This index is formulated as follows,

$$PSI = \frac{4R}{V_i^2}\left(\frac{Q_j^{\ 2}}{P_j} + P_j \right) \quad (30)$$

1.9 BUS VOLTAGE STABILITY INDICES (BUS VSIs)

Bus VSIs are capable to determine the voltage stability of system buses. However, it cannot be used to identify the weak lines which are prone to voltage instability. Similar as line VSIs, the range of bus VSIs is between 0 to 1. When the value of bus VSIs is closed to 1, it indicates the worst value as the system currently operating at a collapse point and vice versa. The most popular bus VSIs which is commonly used to solve the optimal location and sizing of RPC are briefly reviewed in this section.

2.0 VOLTAGE STABILITY INDEX (SI)

SI_j proposed by Chakravort and Das in [91] is formulated for radial distribution system from a quadratic equation. The index is calculated at all sending end voltages or load buses using the following equation,

$$SI_j = V_i^4 - 4V_i^2\left[R_{ij}P_{Lj} + X_{ij}Q_{Lj}\right] - 4\left[X_{ij}P_{Lj} + R_{ij}Q_{Lj}\right]^2 \quad (31)$$

The indication of bus severity that is prone to voltage collapse is when the value of the SI_j index is minimum. The weakest bus or node is identified as the potential location for RPC or DG installation based on the lowest value of index.

2.1 VOLTAGE STABILITY INDEX (L_{INDEX})

L_{index} proposed by Kessel et al. in [92] is formulated based on the solution of the power flow equation. It is capable to determine vulnerable system states, provide quantitative measurement of the actual power system state, identify the weak bus or area as well as predict the voltage instability under various contingency occasions (line or generator tripping). The index is measured at load bus j that can be expressed as follows,

$$L_{index} = \max_{j\in\alpha_L} L_j = \max_{j\in\alpha_L}\left| 1 - \sum_{i\in\alpha_C} C_{ji}\frac{V_i}{V_j} \right| \quad (32)$$

as follows,

$$C_{ji} = -\left[Y_{LL}\right]^{-1}\left[Y_{LG}\right] \quad (33)$$

And matrices Y_{LL} and Y_{LG} can be determined as follows,

$$\begin{bmatrix} I_L \\ I_G \end{bmatrix} = \begin{bmatrix} Y_{LL} & Y_{LG} \\ Y_{GL} & Y_{GG} \end{bmatrix}\begin{bmatrix} V_L \\ V_G \end{bmatrix} \quad (34)$$

Where I_L and I_G represent currents at load and generator buses while V_L and V_G represents voltage at load and generator buses.

L_{index} is only suitable for systems with constant power type loads. For variation power type load, L_{index} will not provide a reasonable indication and the results may be optimistic or pessimistic.

2.2 BUS VOLTAGE COLLAPSE PREDICTION INDEX ($VCPI_{BUS}$)

$VCPI_{bus}$ derived by Balamourougan et al in [93] is formulated from basic power flow equation. The index capable to estimate the voltage collapse by considering the effects of load at other buses. The system's voltage is stable if the index is 0 while it reaches to collapse point if the index is measured at 1.00.

$$VCPI_{bus} = \left| 1 - \frac{\sum_{\substack{i=1 \\ i\neq j}}^{Nb} V_m^{'}}{V_k} \right| \quad (35)$$

2.3 IMPROVED VOLTAGE STABILITY INDEX (IVSI)

IVSI had been formulated by Yang et. al. in [94] based on the power flow formulas. This index is suitable for both radial and mesh network systems. The index is measured at every bus in the system whereas bus with index closed to 1.0 indicates the system is unstable and voltage collapse may occur.

$$IVSI_T = \sum_{i=1}^{N} \frac{-4\sum_{j=0}^{n}(G_{ij}-B_{ij})(P_i+Q_i)}{\sum_{j=1}^{n}\left|V_j\right|\begin{bmatrix} G_{ij}\left(\cos\delta_{ij}+\sin\delta_{ij}\right) \\ -B_{ij}\left(\left(\cos\delta_{ij}-\sin\delta_{ij}\right)\right)\end{bmatrix}^2} \quad (36)$$

The total voltage stability index ($IVSI_T$) is determined to evaluate the overall stability of the system with the integration of RPC devices. It can be set as the objective function to solve the optimal RPC location problems.

2.4 STABILITY INDEX (SI_{VGE})

SI_{VGE} proposed by Sankar et al [95] is formulated based on the deviation of every bus in a system in which can be obtained by the difference between voltage at slack bus and voltage at that particular bus. The formula of voltage stability index of bus i is depicted in equation below,

$$SI_{VGE}(i) = \frac{1}{\sqrt{l}}\sqrt{\sum_{i=1}^{l}\left(V_{SLACK} - \sum_{i=1}^{N} Z_i\left(\frac{P_i - jQ_i}{V_i}\right)\right)^2} \quad (37)$$

C. VOLTAGE PROFILE

In electric power system, excessively low voltages at bus may lead to an unacceptable service quality and security which may create voltage instability problems [96]. This is because modern electrical equipment only capable to operate within a specific range of voltages and tolerate with fluctuations of voltage in short period of time. Moreover, the tolerable range of voltages are depending on the compliance regulation in different countries. Voltage variations are typically caused by inadequate reactive power supply due to the reactive power supply from generation side does not meet the reactive power demand required by load side. Besides, due to long radial feeders especially at rural areas, transmission of reactive power from supply to end users may be impossible [97]. This significantly leads to high voltage drop at end user bus voltage.

Distribution systems are likely experienced sudden change from low to peak load demand every day. The networks in some industrial area tend to face voltage collapse due to certain critical loading conditions. Therefore, voltage profile management has become essential to guarantee the security of system and reactive power resources are optimally used throughout the entire networks [98]. An appropriate location of RPC plays a significant role in enhancing the voltage profile at bus that helps to avoid voltage collapse in power system [99]. The following indices are typically utilized in literature for solving the optimal location and sizing of RPC optimization problems.

1.0 VOLTAGE DEVIATION INDEX

Voltage deviation is defined as the difference between the nominal voltage and the actual bus voltage [100]. The voltage deviation at every bus must be maintained as small as possible in order to have a good voltage performance within the appropriate operational limits. These can be measured using various voltage deviation indices available in literature as shown in Table 1, where V_i is the actual bus voltage and V_{ref} is the reference voltage which is typically taken as 1.00. The highest value of VDI implies better improvement in voltage profile at every bus. Hence, the location with the highest value of VDI is selected as potential candidate for RPC integration.

2.0 CUMULATIVE VOLTAGE DEVIATION (CVD)

Cumulative voltage deviation (CVD) which also known as aggregate voltage deviation (AVD) or total voltage deviation (TVD) is developed to indicate the voltage profile improvement. The voltage deviation at every bus must be maintained as small as possible in order to have a good voltage performance [101]. The CVD of a network can be obtained as follow,

$$CVD = \begin{cases} 0, & if\, 0.95 \le V_i \le 1.05 \\ \sum_{i=1}^{N} \left| V_{ref} - V_i \right|, & else \end{cases} \quad (47)$$

TABLE I
LIST OF VOLTAGE DEVIATION INDEX

Index	Definition	Equation
VDI_1	Sum of the absolute voltage difference between reference voltage and actual voltage	$\sum_{i=1}^{Nb} \lvert V_{ref} - V_{i(loadbus)} \rvert$ (38)
VDI_2	Sum of the absolute voltage difference between reference voltage (1.0pu) and actual voltage	$\sum_{i=1}^{Nb} \lvert 1 - V_i \rvert$ (39)
VDI_3	Sum of the squared of voltage difference between actual voltage with reference voltage	$\sum_{i=1}^{Nb} \left(V_i - V_{ref}\right)^2$ (40)
VDI_4	Square root of the sum of squared value of absolute voltage difference between reference voltage (1.0pu) and actual voltage	$\left[\sum_{i=1}^{Nb} \lvert 1 - V_i \rvert^2\right]^{1/2}$ (41)
VDI_5	Absolute of the division of voltage difference between reference voltage and actual voltage with reference voltage	$\left\lvert \frac{V_{ref} - V_i}{V_{ref}} \right\rvert$ (42)
VDI_6	Squared of the division of voltage difference between reference voltage and actual voltage with reference voltage	$\left(\frac{V_{ref} - V_i}{V_{ref}} \right)^2$ (43)
VDI_7	Sum of the absolute of division of voltage difference between reference voltage and actual voltage with reference voltage	$\sum_{i=1}^{Nb} \left\lvert \frac{V_{ref} - V_i}{V_{ref}} \right\rvert$ (44)
VDI_8	Sum of the squared of division of voltage difference between reference voltage and actual voltage with reference voltage	$\sum_{i=1}^{Nb} \left(\frac{V_{ref} - V_i}{V_{ref}} \right)^2$ (45)
VDI_9	Square root of the sum of squared of division of voltage difference between reference voltage and actual voltage with reference voltage	$\sqrt{\sum_{i=1}^{Nb} \left(\frac{V_{ref} - V_i}{V_{ref}} \right)^2}$ (46)

The lowest value of CVD indicates enhancement in voltage profile of the power system. Hence, the optimal location of RPC is selected based on the location that provides the minimum value of CVD. The ratio of CVD before and after RPC integration is determined as follows,

$$\Delta CVD_{RPC} = \frac{CVD_{With.RPC}}{CVD_{Without.RPC}} \quad (48)$$

Where $CVD_{With.RPC}$ is the cumulative voltage deviation before RPC integration and $CVD_{Withouy.RPC}$ is the cumulative voltage deviation after RPC integration in power system.

3.0 VOLTAGE PROFILE ENHANCEMENT INDEX (VPEI)

VPEI is developed by [102] to provide a measurement of voltage at every bus. The safest criteria of voltage profile are when the bus voltage is measured far from its corresponding upper or lower limits that are taken as 1.1pu and 0.9pu, respectively. The formulation of proposed index are as follows,

$$VPEI = \frac{VPE_{with.RPC}}{VPE_{wihout.RPC}} \quad (49)$$

VPEI for both cases: with and without RPC can be determined as below,

$$VPE = \frac{1}{N_b}\sum_{i=1}^{Nb}\frac{4(V_i - V_{\min})(V_{\max} - V_i)}{(V_{\max} - V_{\min})^2} \quad (50)$$

Where V_{min} and V_{max} are the lower and upper bounds of the bus voltage magnitude that are required to maintain the system voltage stability.

This index is an indication to the overall performance of voltage profile at bus. The indication can be classified in three categories; (i) if the index measures less than 1.00, it signifies deterioration of voltage profile, (ii) if the index measures greater than 1.00, it indicates improvement in voltage profile and, (iii) if the index is equal to 1.00, it implies that there is no contribution in improving voltage profile. Therefore, higher VPEI value denotes better improvement in voltage profile at every bus.

4.0 VOLTAGE PERFORMANCE INDEX (VPI)

VPI is formulated to determine the severity of contingency occurred in the network through single line outage [103]. The index can be obtained as follows,

$$VPI = \sum_{i=1}^{Nb}\left(\frac{\Delta\left|V_i\right|}{\Delta\left|V_i^{\max}\right|}\right)^{2m} \quad (51)$$

Where, $\Delta\left|V_i\right|$ is the difference between voltage at bus under single line outage and base case scenario, $\Delta\left|V_i^{\max}\right|$ is the permissible limit for bus voltage from shifting in an outage case and m is the exponential value. The typical value taken in literature for $\Delta\left|V_i^{\max}\right|$ is 0.2 pu and m is 2. The highest index indicates the most severe contingencies that should be considered for the placement of RPC.

D. LINE SECURITY

The electrical transmission networks are currently encountering large power flows parallel with the massive growth in electrical power demand and penetration of renewable energy sources at distribution level. This along with other issues contribute to transmission congestion in some part of networks that may lead to unexpected outage. At this point, the systems are operated at unstable or insecure conditions. Hence, power system security is one of the important aspects that has risen much attention in literature. The ability of the system to withstand the impact of sudden changes in power system due to contingencies such as generator or transmission line tripping is known as power system security [104].

In order to mitigate the network congestion, ~~the~~ network expansion is necessary to strengthen~~ing~~ the level of security of power systems. Constructing new transmission lines are rather time consuming and may not be feasible due to environmental, economic and political issues [105]. Therefore, implementing an effective and efficient controls on the existing networks such as generation rescheduling, load shedding and controllable RPC are more preferred. However, generation rescheduling and load shedding are not preferred by both consumers and power producer due to their substantial effect on the existing power transaction contracts [41]. Hence, the implementation of controllable RPC is the best way to maximize power system security and this can be further enhanced with a proper location and sizing of RPC.

The security assessment or also known as contingency assessment is an essential tool in determining the level of severity of every line in power system. The assessment employs various steady state contingencies which associated with all possible events to identify any overloading in line or system collapses incident to come up with the optimal solutions for all given conditions [106]. The aimed of this assessment is mainly to investigate the impact of line or generator tripping on both real and reactive power flow in line and bus voltage magnitudes. Numerous security assessment indices have been proposed in literature to evaluate the performance of power system under various contingency occasions. The following indices are the common security assessment indices for solving the optimal location and sizing of RPC optimization problems.

1.0 REAL POWER PERFORMANCE INDEX

Real power performance index (PI) is defined as an index for quantifying the extent of line overloads [107]. PI contains all line flows which is normalized to indicate the condition of the line itself. If the value of PI index is small, it provides a good measure where all lines are operated within its limits. However, if the value of PI index is high, the networks suffer overloads in a more frequent way. This index provides a good severity indication for overloading line for a given state of power system. Besides, most of the proposed security assessment indices in literature suffer from masking effects due to the utilization of the second order performance in contingency selection algorithm [108]. The masking effect is known as the lack of discrimination in which the index provides the same measurement for case with many small violations or with one huge violation. This is not acceptable as in most of operational standards, a system with one high violation is much more critical compared to a system with many small violations.

$$PI = \sum_{i=1}^{NL}\frac{W_l}{2n}\left(\frac{P_{ij}}{P_L^{\lim}}\right)^{2n} \quad (52)$$

Where :

PI = the active power flow in line ij,

P_{ij}^{lim} = the active power limit at line ij,

NL = the number of lines in the system,

n = specified exponent (n 1 preferred),

W_l = real non-negative weighting coefficient that used to reflect the importance of some lines ($W_l = 1$)

The overall PI can be calculated by summing all PI measured at every line as given in equation (53). The candidate locations of RPC are determined by placing RPC at single location at one time and recorded the overall PI for all cases with different RPC location.

$$Overall_{PI} = \sum_{\forall line} PI \tag{53}$$

2.0 REAL POWER FLOW SENSITIVITY INDEX

Another real power flow sensitivity index proposed in [109] is with respect to the parameter of series compensation which located at line ij. The formulation of this index demonstrates the sum of variation of active power flow in every line with respect to the changes of line reactance in line ij as follow,

$$SI_{ij} = \sum_{m=1}^{NL} \beta_m \left. \frac{\partial P_m}{\partial X_{ij}} \right|_{\Delta X_j \to 0} \tag{54}$$

Where :

$P_m =$ real power flow in line ij,

$X_{ij} =$ the reactance at line ij,

$\beta_m =$ the weighted factor, can be selected higher for congested line,

$NL =$ the number of lines in the system

And,

$$SIn_j = \frac{SI_j - SI_{\min}}{SI_{max} - SI_{\min}} \tag{55}$$

The index is calculated for all cases when the series RPC is placed at a single line at one time. Then the minimum and maximum SI values are identified by sorting the index for all cases in descending order and the normalized real power flow index is obtained as in equation (55). The series RPC must be located in line that has the most positive sensitivity index.

3.0 SEVERITY INDEX

The severity index (SI_L) is another index that can be used to determine the severity of a contingency to line overload as expressed in equation (56) to represent the stress on the power system in post contingency period [110].

$$SI = \sum_{l \in L_0}^{NL} w_l \left(\frac{S_{ij}}{S_{ij}^{\max}} \right)^{2n} \tag{56}$$

Where :

$S_{ij} =$ the actual apparent power flow between buses I and j

$S_{ij}^{\max} =$ the maximum apparent power rating of line connected between buses i and j.

$L_0 =$ the weighting factor to reflect the relative importance of certain lines (typical value 1)

The index will be small when all lines are operated within their thermal limits. If there are overloading in lines, the index will be measured high. Hence, it is a good severity indicator of line overloads for a given power system condition.

4.0 LINE UTILIZATION FACTOR

Line utilization factor (LUF) is commonly used for determining the network congestion. It provides an approximation of proportion of line being used as well as indication of congested line [111]. The LUF of line connected between bus i and j is formulated as follows,

$$LUF_{ij} = \frac{S_{ij}}{S_{ij}^{\max}} \tag{57}$$

Line with LUF greater than 1.00 indicates that this line is overloaded. The candidate location for RPC are determined by calculating the overall LUF in all lines using equation (58) for all given scenarios and ranked in descending order to form a priority list.

$$Overall_{LUF} = \sum_{\forall line} LUF \tag{58}$$

5.0 DISPARITY LINE UTILIZATION FACTOR

Due to the limitation in most of congestion assessment indices as they are not applicable to solve optimal solution for combined series-series controller of RPC, specifically IPFC for instance, hence disparity line utilization factor (DLUF) is proposed in [112]. DLUF provides different lines percentage estimation that are currently used for power flow. DLUF of two set lines; line i-j and line i-k which are connected at bus i and j is determined as follows (by assuming both lines are at the same rating),

$$DLUF_{(ij)-(ik)} = \left| \frac{S_{ij} - S_{ik}}{S^{\max}} \right| \tag{59}$$

The LUF for all lines are initially calculated using equation (57) and arranged in descending order. The priority line with the highest index are classified as the most congested line. Next, DLUF is determined for all lines which are linked to bus where the most congested line was connected and ranked in descending order. The set of lines with the highest index is selected as the most optimal location for combined series-series controller congestion management.

6.0 LINE OVERLOAD SENSITIVITY INDEX (LOSI)

The line overload sensitivity index (LOSI) is developed to determine the optimal location of RPC which aimed to enhance the security of the power system. The index is evaluated in every transmission line under contingencies as follows [113],

$$LOSI_l = \sum_{C=1}^{N_C} \left(\frac{S_l^C}{S_l^{\max}} \right) \tag{60}$$

Where, S_l^C is the apparent power flow in transmission line during contingency, S_l^{max} is the apparent power rating of transmission line l and N_c is the number of considered contingencies. The index in all lines are ranked in descending order and the highest LOSI values are selected at the candidate location of RPC integration.

VI. NOTEWORTHY CONTRIBUTION

In this section, all works related to optimal location and sizing using analytical, metaheuristic and hybrid analytical-metaheuristic approaches presented in past literature are briefly reviewed.

A. POWER LOSS

The author in [114] presents a fast and effective technique for optimal placement and sizing of DSTATCOM using BAT algorithm in the radial distribution networks which aimed to minimize the power loss and enhance ~~the~~ voltage stability. The candidate bus for DSTATCOM was determined using SI and sizing was determined using bio inspired BAT algorithm by considering the feeder load variations from 0.5 (light) to 1.6 (peak) and single and multiple DSTATCOM integrations. The results show that the real and reactive power losses were further reduced and the voltage profile at each bus was slightly enhanced with multiple compared to single DSTATCOM integration. However, the voltage stability indices at bus for multiple DSTATCOM integration were slightly higher compared to single case which clearly shows that the voltage stability of the system was affected with multiple integration of reactive power compensations.

In another work based on the power loss minimization [115], the authors proposed a method of determining the optimal location and size of capacitor using a nature enthused metaheuristic namely, whale optimization algorithm (WOA). The objectives of the optimal sitting of capacitor were mainly set for minimizing power losses, reducing operating cost and enhancing voltage profile. The results obtained were compared with other approaches; Particle Swarm Optimization (PSO), Plant Growth Simulation (PGS), Mixed Integer Non-Linear Programming (MINLP) and Bacterial Foraging Optimization Algorithm (BFOA). The proposed algorithm was observed more effective in reducing ~~the~~ power losses, offering higher net saving and enhancing voltage profile compared to the other four approaches.

In [116], the two stage approach analytical approach was proposed to evaluate the optimal placement of STATCOM that aimed to reduce the system power loss. The optimal location of STATCOM was examined in the first stage using LSF_{bus}. In the second stage, the optimal parameter setting for STATCOM was done using Newton Raphson power flow technique. The study was conducted in IEEE 14 bus test system by evaluating the voltages in the entire network, power flows and power losses before and after STATCOM integration. In [117], various analytical based approaches for selecting the optimal location of FACTS devices were compared. Several sensitivity studies such as LSF_{bus}, LSF_{line} and PI were tested in 5 bus system and IEEE 14 bus system.

In [118], the selection of optimal location for FACTS devices were done to alleviate congestion with power losses reduction, voltage regulation and lower cost of operation. A function of the ratio of total active power loss without and with FACTS devices, the minimum and maximum voltage deviation and cost of FACTS devices were proposed as the weighted mean method to determine the optimal location in IEEE 14 bus system. The load variation in certain buses were tested to examine the impact of congestion networks to the system with some line exceeded its rated limit. TCSC and STATCOM were proposed in this study to relieve the congested network due to load variation. The candidate lines and buses for TCSC and STATCOM were determined using LSF_{line} and the optimal line and bus was proposed using the weighted mean methods. The results show that STATCOM offers more control on reactive power losses compared to TCSC, both devices effectively relieved the network congestion as the loading margin were improved.

In [71], the optimal SC placement was done using the *PLS* for power loss minimization while the optimal location and sizing of SC were obtained using the Plant Growth Simulation Algorithm (PGSA) for voltage profile enhancement and active power loss reduction. The proposed approach was tested on three different radial distribution systems (10, 34 and 85 bus radial distribution networks). Several advantages using PGSA had been highlighted compared to other heuristic based method such as; (i) the algorithm handles the objective function and constraints separately thus prevent any problems on obtaining the barrier factors, (ii) does not require any additional parameters and, (iii) adopt a guiding search direction that capable to dynamically change along with the changes of objective function. Furthermore, this approach offers less number of SC locations with optimal capacity that significantly offers much net annual saving for the initial investment.

An innovative approach utilizing symmetric fuzzy and improved bacterial foraging optimization algorithm (IBFOA) had been proposed by Kishore et al in [73] to determine the optimal location and sizing of capacitors in radial distribution networks. The evaluation of symmetric fuzzy power flow was proposed to maximize the accuracy of the adopted approach in real systems and minimize the computational effort. The candidate nodes for capacitor placement were determined by using load sensitivity factor for power loss reduction and voltage stability index (VSI) on behalf of voltage stability enhancement. Next, the optimal sizing of capacitor at the appropriate location was obtained using IBFOA. Three different types of loading – light (50%), normal (100%) and peak (160%) were tested using three radial distribution networks with and without compensation to evaluate the effectiveness of the optimal bus for capacitor placement.

Devabalji et al [119] introduced a fast and new technique on obtaining the optimal location and sizing of SC bank that aimed to reduce power losses and improve the voltage stability in radial distribution system using hybrid analytical and metaheuristic approaches. The candidate locations for SC had been obtained using two analytical approaches: PLS and SI. Next, the optimal location and sizing of SC were determined using BFOA and the objection function was set to minimize the real power loss by considering load changes from light load (0.5) to peak load (1.6). The proposed techniques had been tested on IEEE 34 bus and IEEE 85 bus radial distribution systems and the effectiveness of proposed algorithm had been compared with several algorithms: PSO, PGS and MINLP algorithms. Similar work using hybrid analytical-metaheuristic approach had been done by Olabode et al in [120] to determine the optimal location and sizing of SC. The potential locations for SC installation were firstly determined using analytical approach, PLS and the optimal location and sizing optimization problems were solved using CSA. A multi-objectives function had been developed to minimize both power loss and voltage deviation. The proposed techniques were validated on IEEE 15 bus RDS and Nigerian 11kV feeder.

Another technique using hybrid analytical – metaheuristic approaches had been done by Abdelaziz et al in [72] to determine the optimal sizing and placement of SC in three different radial distribution networks. The objectives were to minimize the investment cost for new SC injection, reduce the real power losses as well as enhance the voltage profile at all buses. PLS was conducted initially to determine the candidate buses for capacitor placement. Next, FPA was introduced to determine the most optimal location and sizing of capacitors from the selected potential buses. The effectiveness of the proposed method were also compared with other algorithms such as, GA, PGSA, GSA, SA, IP, PSO, discrete PSO, MINLP, DSA, TLBO, Fuzzy GA and DE-PS. Based on the findings, the proposed approach offers the lowest total cost and the highest net saving with the lowest rating. Shuhaib et al in [121] addressed a similar work using the same analytical approach, PLS to identify the candidate location of SC and GSA for solving the SC placement and sizing problems. The optimization technique had been aimed to minimize the real power losses and net saving in RDS. The effectiveness of proposed algorithm had been implemented on several IEEE RDS: 33 bus, 69 bus, 85 bus and 141 bus and the results were compared with other algorithms such as IP, SA and also results obtained from other previous works in literature.

The author of Ela in [122] carried out a similar research using hybrid analytical – metaheuristic approach to solve SC placement and sizing problem. The candidate locations were also determined using PLS to reduce the search space in the proposed optimization algorithm, ACO. The objective function for obtaining the optimal location and sizing was developed to minimize the energy losses and capacitor costs. The implementation of proposed technique had been applied on two IEEE RDS: IEEE 34 bus and IEEE 85 bus with several case studies conducted using fixed SC, switched SC and combination of fixed and switch SC. The results of power flow were obtained using back/forward sweep load flow algorithm. Based on the results, the proposed algorithm provides fast convergence with an efficient and accurate optimal result compared to other methods proposed in literature. Elsheikh et al [123] developed a new algorithm to solve optimal location and sizing of SC in a radial distribution system. A hybrid analytical – metaheuristic approaches had been proposed whereby PLS was used to obtain the optimal location where SC can be placed and the optimal sizing of SC was determined using discrete PSO. The objectives were set to reduce the total annual cost function of SC location and minimize power losses. The proposed method was adopted on three RDS system: IEEE 10 bus, IEEE 15 bus and IEEE 34 bus.

In [124], real and reactive combined power loss sensitivity (CPLS) approach was introduced to obtain the optimal location of capacitors in RDS (IEEE 10, IEEE 34, IEEE 69 and IEEE 85 bus distribution system) to reduce the real and reactive power losses and enhance the voltage profile. The results obtained from the proposed method were then compared with the other two existing methods: PLI and index vector (IV) for comparison. The load growth factor and realistic load model (ZIP load model) were also considered in this study for future planning and expansion for the existing networks. The results obtained are different in all methods whereby the CPLS approach provides the best results in all benchmark test systems in term of the overall cost saving and power loss reduction. The study on optimal location and sizing of capacitor was conducted in [125] using several sensitivity approaches namely CPLS, PLI and IV by considering the cost of energy loss and cost of capacitors. The study was conducted using two unbalanced radial distribution systems; IEEE 13 and 25 bus test systems and the key objectives in determining the capacitor placement are to enhance the voltage, increase the power flow capability and reduce power losses. Based on the findings, the total reduction of real and reactive power loss and total saving for running cost and total cost were higher using CPLS compared to the other two approaches.

Ali et al [126] and Abdelaziz et al [127] carried out another similar research using hybrid analytical – metaheuristic approach. In both studies, the candidate buses for SC installation were firstly determined using PLI. Next, the proposed IHA algorithm was employed in [126] to examine the most optimal location and sizing of SC in which aimed to reduce total cost, minimize ohmic losses and enhance voltage profile. The author in [127] presented the method for optimal allocations and sizing of SC using a new and powerful algorithm, FPA which aimed to diminish the ohmic losses, enhance voltage profile and reduce the total cost of SC installation, operation and reactive power injected. The effectiveness of proposed both techniques were tested in three RDS (IEEE 15 bus, IEEE 69 bus and IEEE 118 bus) and the results were compared with various algorithms to confirm its notability. The optimal placement and sizing of SC in unbalanced RDS to maximize the net saving had been conducted by Subrahmanyam and Radhakrishna in [128]. The optimal location was determined using PLI and the sizing of SC was obtained using variation technique algorithm. The techniques were adopted on two unbalanced RDS namely, 25 bus RDS and IEEE 37 bus RDS.

B. VOLTAGE STABILITY INDICES

The author of [129 – 130] conducted one more similar research by introducing few analytical approaches for determining the UPFCs placement in power system networks using a dynamic voltage stability analysis. The potential locations of UPFCs were determined by adopting few line VSIs such as L_{mn}, LQP and VPCI. The line VSIs were calculated in two different scenarios; by varying the PQ and Q loading in different amount across each of the load buses simultaneously. The VSIs were automatically generated using the proposed design of Proportional-plus-integral (PI) controllers based on the power system variables such as bus magnitude voltages, bus phase angles and branch power lines obtained from power flow results in two different scenarios. Based on the findings, the optimal location of UPFC was proposed at the weakest lines to obtain better improvement not only in voltage stability but also in the voltage profiles of entire network. The effectiveness of proposed approach in both studies were tested on two IEEE benchmark test system: IEEE 14 bus and IEEE 39 bus.

Ahmad et al in [131] proposed a method of UPFC placement by utilizing fuzzy logic and proportional integral (PI) controllers for dynamic voltage stability analysis. Two line VSIs (LQP and VCPI) were adopted in controllers to determine the weakest line for UPFC installation by considering the dynamic load variation. The aimed of this study is to enhance the dynamic voltage stability of the entire network by installing the UPFC at the most optimal location in IEEE 5 bus and IEEE 14 bus test systems. Comparative studies using analytical approach had been conducted by Ismail et al in [132] for solving optimal location of DSTATCOM in distribution network for voltage stability improvement, voltage profile enhancement and power loss reduction. Several line VSIs such as FVSI, VCPI and LCPI, VPI and total power losses were utilized in this work to propose the candidate locations for DSTATCOM in IEEE 30 bus test system with consideration of loading factor. Another analytical approach utilizing FVSI had been adopted in [133] to determine the optimal location of SVC for voltage stability improvement. Contingencies analysis had been conducted in this work to investigate the location of SVC under severe occasions such as line and generator tripping. The proposed techniques had been implemented on IEEE 14 bus test system. Another work on analytical approach had been presented in [134]. The optimal location of UPFC was determined using FVSI and LOSI under several load condition: normal loading, peak loading and light loading. Line with the highest index and bus where this line is connected had been selected as most suitable location for UPFC installation in IEEE 30 bus network. Further analysis had been done with an integration of UPFC at this location to evaluate the impact of UPFC integration on system parameters such as voltage profile, real and reactive power flows and total real power losses under several contingencies occasions such as tripping in line and generator.

In [135], the optimal location of FACT devices was proposed using the two similar behavior of bio-inspired algorithms, namely, PSO and BAT algorithm that aimed to reduce the voltage collapse and real power losses. UPFC and STATCOM were considered in this study since UPFC is one of the most popular FACTS device that is capable to operate under system insecurity while STATCOM is capable to operate under various stress conditions. Three different loading conditions were tested to investigate the voltage stability performance using VCPI index and real power losses' performance for weak bus identification. The optimal location and sizing of UPFC were determined in [136] to improve the voltage stability and bus voltage margin using two swarm intelligent techniques, namely, PSO and Artificial Bee Colony (ABC) Algorithm. The FVSI index was implemented to identify the weakest line and system loading value for optimal location whereas for the optimal sizing of UPFC, it was determined by using the optimization techniques. With the proper location and sizing of the controller, the system stability and voltage profile at each bus were improved as well as the maximum system loadablity was increased.

Author in [137] proposed a technique for location and sizing of combination for series and shunt connected FACTS devices using DE algorithm in improving voltage stability margin, minimizing the real power losses and enhancing voltage profile. The proposed algorithm was implemented in IEEE 30 bus test system under two contingency occasions; critical loading and line outage. The author employed LQP index, total voltage deviation (VDI) and real power loss in lines equation to evaluate the performance of voltage stability, voltage profile and real power losses. Sreedharan et al in [138] presented a novel robust controller GA based for optimal location of STATCOM integration in enhancing power system loading margin. The system stability via several voltage stability indices such as FVSI, L_{mn} and LQP and eigenvalue based small-signal stability assessment were utilized in solving the optimization problems along with the real and reactive power limits, voltage magnitude and phase angle limits, line flow limit and loading factor limit as inequality constraints and the power balance equations as the equality constraints. The proposed scheme was implemented on IEEE 14 bus test system and Indian utility network under normal loading and heavily loading occasions.

Another hybrid analytical and metaheuristic approach had been proposed in [139] for solving optimal TCSC and SVC placement. The proposed approach had adopted several line voltage stability indices (LVSI) such L_{ij}, L_{mn}, LQP and LCPI to identify the critical lines or buses as the potential locations for FACTS devices allocation. This form reduced search space in determining the optimal location, respectively. Next, the optimal location and sizing optimization problem had been done using the proposed LVSI-PSO approach which includes real power losses, voltage profile and L_{ij} in the formulation of objective function. The proposed technique had been tested on modified IEEE 9 bus system which integrated with IEEE 16 bus RDS. The optimal placement and sizing of DG were also included in this work. The impact of loss in transmission lines and load growth occasions on voltage profile were also done to verify the effectiveness of this proposed technique. In [140], a hybrid analytical – metaheuristic approach had been employed in obtaining optimal location and sizing of TCSC, SVC and UPFC. The optimal locations were evaluated using L_{mn} for TCSC placement, PV curves analysis using the continuation power flow (CPF) for SVC placement and real power flow in lines for UPFC placement. Next, the optimal sizing and coordination had been determined using WOA for minimizing operating cost of power system, real power loss cost and FACTS device installation cost under several reactive power loading conditions. Comparative studies were done using other evolutionary algorithms such as PSO and GA to validate the effectiveness of proposed algorithm and were implemented on two IEEE benchmark test systems: IEEE 14 bus and IEEE 30 bus.

Gupta and Kumar in [90] proposed several analytical approaches such as CPLS, FVSI, VSI, VSEI and PSI to determine the optimal location of D-STATCOM in the UK 38 mesh distribution systems (MDS) under both normal and load growth conditions. The load profile for winter and summer seasons and load growth occasions were tested in the benchmark test system. The proposed location obtained by using PSI and CPLS provides better results since when DSTATCOM was integrated at the proposed location, better improvement in voltage profile, lower cost of reactive power and saving the total annual cost were achieved compared to location proposed by other indices.

Similar work done by the same author in [141-143] for determining the optimal location and sizing of D-STATCOM in IEEE 33 bus RDS in which aimed to reduce loss, enhance voltage profile and overall energy saving. In [141], the determination of optimal location for D-STATCOM integration had been selected using two analytical approaches: PSI and PLI and the rating of DSTATCOM that provide minimum power loss had been selected as the optimal sizing. The results were also compared with other several approaches proposed in literature. The same voltage stability index, PSI had been implemented in [142] with various load models such as constant power, constant current, constant impedance, mixture of constant impedance, current and power, air conditioners, battery chargers, compact fluorescent lamps, fluorescent lightings, incandescent lamps, large industrial motors, pumps fan motors, resistance space heaters and industrial motors. Based on the results obtained, constant power types load measured the highest power loss and the lowest bus voltage profile and also required the highest rating of DSTATCOM. The same authors extended their work in [143] using the same approach to solve the optimization problem as well as to analyze the impact of connecting large industrial load model under several loading scenarios: light, medium and high loading into the unbalance radial distribution systems (UBRDS).

Selim et al [144] presented a hybrid analytical and metaheuristic method for solving optimal location and sizing optimization problems for both DG and DSTATCOM in distribution networks. The proposed approaches had adopted VSEI in searching the best location for DG and DSTATCOM integration thus the optimal sizing optimization problems were solved using sine-cosine algorithm. The sizing of both DG and DSTATCOM were determined to minimize the real power losses in the network. The proposed hybrid approach had been established using IEEE 12 bus and IEEE 69 bus RDS. A comparative study was also drawn to validate the effectiveness of the proposed technique with other analytical approaches. Another study using VSEI as analytical approach had been conducted in [145]. The SC placement and sizing in IEEE 9 bus test system had been determined for voltage stability enhancement and real power losses' minimization.

In [146], a new approach using multi-objective particle swarm (MOPSO) for optimal location and sizing of both DG and shunt capacitor bank is proposed. Three objectives were set in solving the optimization problem that aimed to reduce the active power losses, enhance voltage stability for every bus and balance current in the system. The objective function of MOPSO was formulated using the normal real power loss equation, voltage stability index (SI_j) and index of balancing current (SCI). The proposed technique is adopted on IEEE 33 bus radial system and the actual 94 bus Portuguese radial system under consideration of loads uncertainty that are modelled using fuzzy data theory. The results obtained from the proposed approach were also compared using other multi-objective techniques; Strength Pareto Evolutionary Algorithm (SPEA), Non-dominated Sorting Genetic Algorithm (NSGA), Multi-Objective Differential Evolution (MODE) and combination of Imperialist Competitive Algorithm and Genetic Algorithm (ICA/GA).

Moradi et. Al [147] proposed a new combined hybrid metaheuristic – metaheuristic using combined ICA-GA technique for solving optimal location and sizing of both DG and capacitor banks. The five objectives such power loss reduction, DGs and capacitors installation cost minimization, voltage profile improvement, voltage stability enhancement through SI_j and load current balancing were included in the objectives' function. The optimization problem has been solved in twofold. Firstly, the location and sizing of DGs and capacitors were determined using ICA algorithm. The cost value of imperialist and colonies were calculated in each empire. Next, the author utilized crossover and mutation operators in GA to generate a new set of colonies in all search spaces in order to generate better cost than the imperialist. The study has been conducted in two IEEE radial distribution test systems; IEEE 33 and IEEE 69. The proposed technique provides better results, complete searching on solution space and lack of fast convergence in local minima compared to other heuristic approaches; GA, PSO, GA-PSO.

Esmaeilian et al. [148] presented a novel manner in determining the optimal number, location and sizing of DG and capacitors concurrently using multi-objective optimization technique via GA. The formulation of the multi-objective function consists of real power losses, cost of capacitor, cost of DG and SI_j. The proposed technique was implemented in IEEE 33 bus RDS. Similar study had been done by Sajjadi et al in [149] using memetic algorithm (MA) in solving the multi-objective problem. Several objectives had been covered in this study which not only for voltage stability enhancement using SI_j, but also for increasing the cost reduction of purchased active power demand in transmission line and the benefit of cost reduction, energy loss, real power loss and reactive power loss. The study was conducted using IEEE 34 bus radial distribution system under light, medium and peak load occasions. The impotency of voltage stability criteria in the cost function using the weighting factor was also done in this study.

In [150], Abul'Wafa proposed hybrid conventional – metaheuristic approach for solving optimal location problem in radial distribution system for voltage stability improvement. The potential locations of capacitor placement were determined by using analytical approach via SI_j. Next, Fuzzy-Real corded GA based technique was adopted to determine capacitor location and sizing for power loss minimization using PLI, voltage profile enhancement using VDI as well as reduction in cost of capacitor installation and sizing. The proposed technique was implemented in IEEE 33 bus RDS. A hybrid metaheuristic -metaheuristic approach had been proposed by Muthukumar [151] that aimed to trace the optimal location and sizing of SC in IEEE 69 RDS for power loss minimization, voltage profile enhancement and voltage stability improvement under several loading conditions. The formulation of objective function was adopted using combination of several analytical indices such as PI, VDI and SI_j and this is known as Network Performance Improvement Index (NPII). The potential buses for SC placement had been initially determined using PLS and finally, the most optimal location and sizing of SC was determined using hybrid HAS – DE algorithm from the PLS based priority candidates. The comparative studies using normal HSA, DE and hybrid HSA – DE algorithms were also done to validate the performances of proposed technique. Besides, the results obtained were also compared with other techniques from previous works in literature.

In [152], the optimal location and sizing of single and multiple DSTATCOMs in radial distribution networks were determined for power loss minimization and voltage stability improvement. The optimal location of DSTATCOM has been proposed by Yuvaraj et al using SI_j whereas the optimal sizing has been calculated using bio inspired bat algorithm. The effectiveness of the proposed techniques were implemented on two RDS, IEEE 33 bus and IEEE 69 bus with a constant power load model by considering loading factor. The results obtained from proposed algorithm-based optimization were also compared with other heuristic approach. The same authors in [153] proposed a technique to obtain optimal location sizing of DSTATCOM and DG simultaneously in distribution network. The location of DSTATCOM has been determined using SI_j while for DG using LSF. Next, the nature-inspired cuckoo search algorithm (CSA) has been adopted for solving optimal sizing of both DSTATCOM and DG to minimize the real power losses, enhance voltage profile as well as reduce total operating cost. Various scenarios have been considered in this work to validate the performance of the proposed technique by considering a single DSTATCOM integration, a single DG integration, both DSTATCOM and DG integration and lastly, multiple DSTATCOM and DG integration. The proposed technique was tested on IEEE 12 bus, IEEE 34 bus and IEEE 69 bus RDS to validate the feasibility and the results were also compared using other heuristic techniques.

Yuvaraj et al [154] have extended their previous work in [151] by proposing multi-objective function for CSA utilizing the fast and efficient Backward/Forward Sweep (BFS) algorithm for solving load flow calculations. The multi-objective function consisted of minimizing the system total power loss and enhancing the bus voltages via cumulative voltage deviation (CVD). The proposed method has been tested on IEEE 30 bus and IEEE 136 bus RDS. Similar work had been conducted by Devabalaji et al in [155]. The candidate buses were selected using SI_j index and the optimal location and sizing of shunt capacitor in RDS test systems (IEEE 34 bus and IEEE 69 bus) were obtained using CSA under consideration of various load factors. The effectiveness of proposed approach had been also compared with other heuristic approaches such as GA, PSO, DSA and TLBO. In [156], the formulation of multi-objective function for solving optimal placement of DSTATCOM using non-dominated sorting genetic algorithm II (NGSA-II) includes minimizing voltage stability metrics using SI_j, reducing total voltage deviation and reducing total real power losses. The solutions obtained in NSGA-II are produced in a cluster of solutions called Pareto front. Hence, in the second stage, the best compromise solution was obtained using parent front technique utilizing the fuzzy decision-making engine (FDM). The proposed approach was implemented on IEEE 33 bus RDS and Portuguese 94 bus real RDS.

Author in [157] proposed two stage approach using PLS in identifying the potential buses for SC placement and ABC based algorithm for ascertaining the final optimal sizing and location for SC integration. The formulation of objective function for ABC algorithm was set to maximize the peak real power loss reduction, reduce capacitor costs and enhance voltage stability via SI_j and was tested on two IEEE standard RDS: IEEE 34 and 94 bus test systems. The results obtained from proposed algorithm were also compared with other different heuristic approaches: GA, PSO, HAS, PGSA and EA. In a different publication [158], the same author had extended the work in [157] to determine the optimal location and sizing of fixed and switched SC using the same techniques by taking daily load variations into consideration. The proposed approach had been tested on small and large scale IEEE RDS: IEEE 34 and IEEE 118 bus test systems. Comprehensive comparisons using other evolutionary approaches such as HAS, GA, PSO, PGSA, EA and CSA had been also demonstrated to verify the validity of robustness and usefulness of the proposed technique.

In [159], the authors have developed multi-objective function to determine the optimal location and sizing of RPCs using GA. The objectives were to enhance the voltage stability as well as minimize the power losses and generation cost. L-index was used to evaluate the voltage stability at each bus. A comparative study was conducted to evaluate the performance of several type of RPC controllers such as series controller (TCSC), shunt controller (SVC) and series-shunt controller (UPFC) in solving the optimal RPC placement and setting problems. The effectiveness of the proposed technique was tested on IEEE 14 bus and IEEE 57 bus test systems. Based on the results obtained from the benchmark test system, the reduction of real power losses and improvement of voltage stability are the highest when UPFC is installed, followed by TCSC and SVC. Author in [160] proposed a novel technique using hybrid PSO-GSA technique in determining the location and sizing of FACTS devices in transmission system for voltage stability improvement. The GSA's agents are most likely to move away from the best position due to the gravitational constant that is varied according to the variation of solution. Due to this limitation, the author adopts PSO technique in optimizing the GSA's gravitational constant. A single multi-objective was formulated with two objectives using L-index for voltage stability enhancement and the normal real power loss equation for power loss minimization. The effectiveness of proposed technique was implementedin obtaining the optimal location and sizing of IPFC and UPFC in IEEE 30 bus test system.

Nascimento et al in [161] proposed a method to determine the TCSC and SVC location using an adaptive evolutionary algorithm (EA) for improving voltage profile, increasing voltage collage margin and reducing reactive power flow losses via three indicators; voltage deviation, reactive power losses and $L_{index.}$ The proposed technique was implemented in IEEE 14 and IEEE 57 test systems and compared to other two heuristic optimization methods: PSO and SA. Based on findings, the proposed adaptive EA provides better results compared to PSO and SA. Ranganathan et al [162] adapted a new strategy using self-adaptive firefly algorithm (SAFA) to determine the appropriate type, location, sizing and parameter of mutli-type FACTS devices such as SVC, TCSC and UPFC in standard IEEE 30 and IEEE 57 bus test systems. The comparative studies using single and multi-objective function which aimed to reduce real power losses, enhance voltage profile and reduce cost had been done in this work and the effectiveness of the proposed technique had been compared with other heuristic approach: honey bee algorithm (HBA) and BFA.

In [95], hybrid analytical – metaheuristic technique had been adopted for solving the optimization problems. In the first stage, the optimal location of UPFC was determined using CSA for minimizing the real power loss. Next, in the second stage, the optimal capacity of UPFC was obtained using EP that aimed to enhance the voltage stability via SI_{VGE} and reduce real power loss. The proposed techniques had been tested on IEEE 30 bus system. The same index, SI_{VGE} was adopted by Kumar et al in [163-164] as a dynamic stability constraint together with other control variables such as power balance condition, power loss, UPFC cost, real and reactive power flow equations. The proposed techniques were implemented in two separate algorithms for solving the optimal location and optimal sizing of UPFC. In [163], the best position of UPFC was determined using FA and the optimized capacity was obtained using CSA. The comparative analysis between other combined algorithms such GSA-BAT, BAT-FA and CSA techniques was drawn to highlight the effectiveness of the proposed approach. The work is extended in [164] by the same author using other combined algorithms considering generator tripping occasions. The best location of UPFC was determined using modified salp swarm optimization algorithm (MSSA) while for optimal rating of UPFC was obtained using moth-flame optimization algorithm (MFO). The proposed technique had been compared with other techniques such as GSA-BAT, MFO-FF, SSO-FF, BAT-FF and CSA-FF and the novelty of this proposed approach had been exemplified in improving searching ability, random reduction and reduced complexity. The proposed techniques for both studies were implemented on IEEE 14 and IEEE 30 bus test systems.

The optimal location of STATCOM and TCSC had been done in [165] by identifying the weak bus through $VCPI_{bus}$. The proposed location for STATCOM and TCSC had been conducted in IEEE 14 bus test system. Kishore and Mohan in [166] had proposed several analytical approaches for optimally locating UPFC in IEEE 14 bus system with load growth occasions. The location of UPFC was evaluated using LUF and L_{mn} to identify the most congested network that is classified as the most optimal location. Next, another two indices, PI and $VCPI_{bus}$ were computed without and with UPFC placement to validate the ability in congestion alleviation and voltage stability improvement, respectively. In [167], Yang et al presents an optimal setting of RPC devices using a hybrid differential evolution (HDE) for enhancing voltage stability and reducing line losses. The proposed technique has been employed to determine tap setting of on load tap changing transformer (OLTC), excitation settings of synchronous condensers (SCs) and the location and sizing of SVCs. A comparative study between the new proposed index, IVSI and other two indices, VSI and Lmn was done to examine the capability of the indices in predicting the voltage collapse in power system. Three candidate buses for RPC were initially determined using IVSI and the optimal location and sizing were then solved using the proposed technique.

C. VOLTAGE PROFILE

Dutta et al in [167] presents a method of solving optimal location problem using chemical reaction optimization (CRO) algorithm for voltage profile enhancement, power loss reduction and voltage stability improvement in a power system. The proposed approach had been adopted for searching optimal location of STATCOM in two standard IEEE benchmark test system, IEEE 30 bus and IEEE 57 bus. The results were also compared with other heuristic approaches, PSO and DE to validate the effectiveness of the proposed technique. The author has extended this work in [168] by solving the optimal location and parameter setting optimization problem for UPFC in both single and multi-objective functions. Minimizing total generation cost and UPFC installation cost, enhancing voltage profile as well as reducing system power losses were formulated as the objective function and the optimal solutions were obtained using hybrid CRO-DE. The efficiency of proposed algorithm had been adopted on two IEEE standard systems, IEEE 14 bus and IEEE 30 bus test systems and the results had been compared with several evolutionary algorithms such as IPSO, PSO, GA, IA and IGA.

In [169], the optimal location and controller parameters of UPFC had been determined using new θ hybrid particle swarm optimization based co-evolutionary cultural algorithm (θ-CPCE). The multi objective function proposed by the author was aimed to minimize the real power losses, voltage deviation and damping ratio of electromechanical modes. The proposed technique was implemented on IEEE 39 bus test system. The comparative studies using other algorithm such as PSO and GA had been done to highlight the effective performance of the proposed approach. Phadke et al [170] introduced fuzzy based GA (fuzzy-GA) technique in determining the optimal location and sizing of STATCOM. The applicability of the proposed technique had been implemented on two IEEE benchmark test system, IEEE 14 and IEEE 57 bus. The formulation of the multi-objective function was set to maximize the distance to saddle node bifurcation, minimize bus voltage deviation and minimize the capacity of the controller with a consideration of loading factor. El-Fergany in [171] proposed CSA in solving the static shunt capacitors allocation and sizing problems in radial distribution systems. The potential locations had been initially obtained using analytical approach through PLI and next, the most optimal location and sizing were found using the proposed algorithm. Three objectives that aimed to reduce real power losses, minimize overall operating cost and enhance voltage profile were adopted in the objective function. The proposed approach had been tested on two IEEE RDS: 69 and 118 test systems with different load levels and compared with other heuristic approaches: DE, PSO and DE-PSO to validate the effectiveness and performance.

Author in [172] has presented WOA for solving optimal location of shunt (SVC) and series (TCSC) compensation in minimizing real power losses, bus voltage deviation and total operating cost. The potential locations were determined initially using analytical approaches. For TCSC, the candidate locations were identified from the power flow results whereby the candidate lines are determined based on the following criterion; carried high reactive power flow, located at load bus only and connected to end point bus (weak bus). The candidate locations for shunt compensation via SVC were determined using VCPI whereby buses approaching to instability point are classified as weak buses and these buses are highlighted as the candidate locations for SVC. The optimal location of series and shunt compensation was then obtained by using WOA. Comparative analysis had been done using GWO, DE, SPSP, APSO and EPSO algorithms to validate the results obtained by WOA. The proposed technique had been implemented on IEEE 30 and IEEE 57 bus test systems. In [173], a study on optimal location of SVC had been done using analytical approach via VD_2, VPI and real power losses. The SVC placement was determined based on the lowest value of voltage deviation and total real power losses. The technique had been tested on IEEE 30 bus with two contingencies occasions; single line outage and load growth.

Musa et al in [174] had adopted BFA in solving optimal DSTATCOM allocation in two RDS: IEEE 33 bus and 50 bus canteen feeder. The proposed algorithm had been set to minimize the voltage deviation and reduce power loss under several loading conditions to establish the most appropriate location and sizing of DSTATCOM in two test systems. In [175], the optimal location and sizing of UPFC has been solved using CSO technique by considering line outage occasion. The objectives were aimed to enhance the voltage profile and maximize the loading parameter with a minimum UPFC rating. The (N-1) contingency analysis was by removing one particular transmission line at one time to identify the most critical line that provide the highest rate of deterioration of voltages. The candidate lines were identified using VD2 initially and nest, the most optimal location and sizing for both single and multiple UPFC was obtained using CSO. The proposed technique has been implemented on two IEEE test system, IEEE 3 bus and IEEE 14 bus system.

The allocation of DSTATCOM with high photovoltaic (PV) penetration was examined in [176] to reduce the investment cost and improve the overall system's performance in term of real power loss reduction and voltage deviation minimization. The candidate locations were determined initially using LSF and most optimal bus for DSTATCOM location was evaluated using multi-objective differential evolution grey wolf optimization (MODEGWO). The results obtained from proposed algorithm were compared to other optimization techniques, GWO and NGSA-II and tested on IEEE 33 bus RDS. Arya et al in [177] proposes GSA for solving optimal location and sizing of DSTATCOM in two IEEE RDS, IEEE 33 and IEEE 69 bus. The multi-objective function was formulated to find the accurate placing and capacity for reducing power losses, minimizing the voltage deviation and maximizing the annual energy saving. The effectiveness and performance of the proposed algorithm was also compared with both heuristic algorithms; immune algorithm (IA) and BAT and analytical approaches; VSI and PLI.

In [178], a hybrid approach had been proposed using both analytical and metaheuristic method for solving optimal location and sizing of SC and DG. Two analytical approaches had been adopted in this study initially to determine the optimal placement for SC installation via PLI and for DG via IV. Next, Gbest-guided Artificial Bee Colony (GABC) had been proposed to solve the sizing problem that aimed to minimize the real power losses. Voltage deviation, VSI and total annual cost saving were evaluated to validate the improvement of the overall system before and after SC and DG integrations. The proposed method had been implemented on IEEE 33 bus RDS and standard 85 bus RDS by adopting single and multiple SC and DG integration and comparative studies using several heuristic techniques, IMDE, FGA, BPSO, BFOA and MOPSO were also done to validate the effectiveness of proposed technique.

The author in [179] investigates the optimal location and parameter setting of UPFC using hybrid approach. The candidate lines were determined initially using analytical approach, VD and line utilization factor (LUF) with contingency analysis through single line outage contingencies (N-1). The overloaded lines and buses with voltage limit violations for every line outage occasion were ranked and the severe lines are identified according to the most severity contingency scenarios. Next, the optimal location and parameter setting of UPFC were determined using DE technique which aimed to eliminate or minimize the overloaded lines and bus voltage limit violations. The results obtained from DE were also compared with PSO to verify the performance of proposed technique. The same method had been implemented in [180] using different optimization techniques, Artificial Algae Algorithm (AAA) and the results were also compared with DE and PSO. Both studies had been implemented in IEEE 14 and IEEE 30 bus test systems to validate the performance of proposed approaches. The work in [179 – 180] had been extended in [181] using optimization techniques for optimal location, number, type and sizing of multi type-FACTS devices (TCSC, SVC, TCSC-SVC and UPFC). The formulation of objective function consists of minimizing the cost of FACTS devices, voltage deviation and line loading and had been analyzed using PSO, weight improved PSO (WIPSO) and biogeography optimization (BBO) with load growth occasions. The works had been done using several standard IEEE test systems: IEEE 14, IEEE 30 and IEEE 57.

Sirjani et al in [182] proposes method for optimal location and sizing of shunt RPC using hybrid technique. The potential candidate buses for SC, SVC and STATCOM were determined using modal analysis where buses with large participation factors in the critical mode which is prone to voltage instability are identified as the most critical buses in the power system. The sizing of shunt RPC was done using heuristic optimization technique through novel global harmony search algorithm (NGHSA) and the objectives were aimed to reduce the real power losses, minimize voltage deviation, maximize the voltage stability margin and reduce the cost of shunt controllers. The effectiveness of proposed approach has been compared with other heuristic techniques, HSA and IHSA and has been implemented on IEEE 57 bus test system.

Yuvaraj and Ravi in [183] had suggested a hybrid analytical – metaheuristic approach for identifying optimal location and sizing of single and multiple DSTATCOMs in IEEE 33 bus RDS for power loss reduction, voltage deviation minimization and voltage stability improvement. The optimal location for single and multiple DSTATCOM integrations were obtained using voltage stability factor (VSF) while the optimal sizing of DSTATCOMs were obtained using BAT algorithm. The performance of system under light, normal and peak loading conditions were determined using proposed algorithm to determine the real and reactive power losses, optimal sizing, total CVD and total annual cost saving. The results obtained from proposed technique were also compared with other several analytical approaches (PSI, VSI and LSF) and evolutionary algorithms (BFOA and IA). The authors had extended their work in [101] using the same objectives implemented in a multi-objectives function for solving optimal location and sizing of DSTATCOM and DG simultaneously. The work had been done using a new metaheuristic optimization tool, Lightning Search Algorithm (LSA) and tested on two IEEE standard RDS: IEEE 33 and IEEE 69 bus test systems with the same loading occasions. The comparative studies had been done to validate the results obtained from the proposed algorithms with other approaches in literature.

Sannigrahi et al in [184] proposes rooted tree optimization (RTO) algorithm in solving the optimization problems in distribution system. Three proposed objectives such as voltage profile enhancement through voltage profile enhancement index (VPEI), power loss reduction through index of loss reduction (ILR) and pollutant gases emission diminution through index of pollution reduction (IPR) were formulated to determine the optimal location and sizing of

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DSTATCOM and DG in IEEE 33 bus RDS. In [185], voltage stability studies via SI_{bus} had been done initially to identify the unhealthy buses that will be the candidate locations for DSTATCOM and DG integration. Next, the location and sizing of DSTATCOM and DG were determined using three proposed algorithms, PSO, rapid PSO (RPSO) and linearly decreasing inertia weight PSO (LPSO) and the objectives were aimed to improve voltage profile via VPEI, maximize the benefit cost ratio and enhance the emission cost benefit. The comparative studies between the proposed algorithms and several different evolutionary algorithms, RGCA, DE, IPSO-SR had been done to validate the effectiveness and the work had been tested on IEEE 33 and IEEE 69 bus RDS systems.

Authors in [186] presented PSO – time varying acceleration coefficients (PSO-TVAC) for solving optimal location and sizing of STATCOM in IEEE 30 bus system. The severity of contingency through single line outage had been analysed using VPI from the perspective of voltage violation limit at buses. Next, the optimal solution for location and sizing were obtained using PSO – time varying acceleration coefficients (PSO-TVAC) with consideration of several most severe line outage scenarios. The optimal solutions were aimed to minimizing the voltage deviation at bus with the minimum rating of STATCOM. Similar studies had been carried out by Dixit et al using GA to obtain optimal location and sizing for SVC in [187] and STATCOM in [188]. The implementation of GA had been done by performing single line outage study at the selected most severe lines obtained via VPI. The objectives of proposed algorithm in both studies were to minimize real power losses, reduce voltage deviation as well as minimize the rating of RPC. The proposed technique was employed on IEEE 30 bus test system. In a different publication [189], a similar study had been conducted using GA for optimal location and sizing of SVC which also for minimizing power loss and enhance voltage profile by considering several line outages at the most severe contingencies.

D. LINE SEVERITY INDEX

In [190], the placement of IPFC was evaluated using composite severity index (CSI) which is formulated with a combination of PI and L_{mn} for contingency management. The study was aimed to provide an exact measure of overloading in lines and voltage instability. The optimal location of IPFC had been tested and implemented on IEEE 30 and Indian utility 62 bus test network. The systems were further investigated under highly stressful condition where all loads are set up to the critical value to determine the effectiveness of IPFC in managing the contingency condition. The location of IPFC was proposed to be located at whichever line that experienced the maximum risk of severity due to overloading and voltage violations in order to reduce the real power losses, enhance voltage profile, reduce security margin and reduce capacity of IPFC. The same author had extended their work in [190] by proposing the probability of severity-based placement strategy for IPFC using the same analytical approach, CSI in [191]. Based on the results, IPFC was placed at line that has the highest probability of severity under various outages. The multi objective function had been set to reduce real power losses, security margin, voltage deviation and sizing of the installed IPFC using DE and the results obtained from proposed algorithm were compared to GA. Rao et al in [192] proposed an approach for optimal allocation of FACTs devices in power system which aimed to reduce the real power losses and overloading in the networks. A generalized approach for any type of FACT devices placement using PI and LSF indices were proposed with a fixed parameter setting. This generalized approach was fully developed based on mathematical model of FACTS devices in which the control parameters of FACT devices itself were determined and next, the PI and LSF were obtained with the integration of FACT devices in every line. Three type of FACTS devices that capable to control both real and reactive power: UPFC, IPFC and OUPFC were considered in this study. The proposed approach was tested in IEEE 5 and IEEE 14 bus system.

Samimi and Naderi in [109] proposed an analytical approach using several sensitivity indices such as LSF_{bus}, LSF_{line} and SI_j to optimally locate TCSC in IEEE 14 bus test system. The study had been extended in [193] by Samimi and Golkar using hybrid analytical – metaheuristic approach for TCSC and STATCOM integration to alleviate the congested network and enhance voltage stability, respectively. A new combination voltage – loss sensitivity index (VLSI) that formulated based on combination of VSI and LSF_{bus} had been introduced by the authors. Several sensitivity approaches such as LSF_{bus}, LSF_{line}, SI_j, VSI and VLSI were conducted to examine the optimal location of TCSC and STATCOM in IEEE 14 bus test system. The optimal rating for TCSC and STATCOM were then obtained using GA. Another work using the same index, SI_j was proposed in [194] to optimally locate FACTS devices in the network by considering several variations in power system variables such as line variation, load variation and generation variation. The approach had been demonstrated on three IEEE benchmark test systems: IEEE 24 bus, IEEE 30 bus and IEEE 39 bus. The work had been aimed to improve the total transmission capacity of the network as well as to increase the flexibility of power flow.

The study on optimal number, location and parameter setting of multiple TCSCs had been done in [195] using NGSA-II. The multi-objectives had been set to reduce the installation cost of TCSCs as well as reduce the real power losses. Next, the contingency analysis had been performed to validate the impact of TCSCs integration under load growth and line outage occasions via SI_L. The overloading lines had been eliminated with the optimized TCSCs that significantly improved the system loadability and security of power system. The proposed technique had been implemented on

IEEE 30 bus test system. Another metaheuristic approach had been adopted in [196] to determine the optimal location and parameter setting of UPFC in the network using DE. The severities of contingencies for single line outage were determined initially to identify the most critical contingency occasions. Next, the optimal location and parameter setting of UPFC was proposed to alleviate the overloaded lines and bus voltage limit violations under the most critical contingency occasions. The objection function had formulated to enhance the system security level through a combination of two indices, SI_L and VD. The effectiveness of proposed approach had been implemented on two IEEE test systems; IEE 14 bus and IEEE 30 bus and the results obtained using DE had been also compared using other algorithms; GA and PSO. The work had extended by Kang et al in [41] to determine the optimal location and setting for TCSC and SVC. The candidate locations of TCSC and SVC were initially obtained using min cut algorithm (MCA) and tangent vector technique (TVT) to reduce the search space. Next, CSA had been employed to obtain the optimal location and setting of TCSC and SVC simultaneously. The proposed technique had been tested on IEEE 6 bus and modified IEEE 14 bus systems and the results obtained through CSA had been compared with other algorithm, PSO to validate the effectiveness of the proposed approach. It had been observed that with the proper location and setting for TCSC and SVC, the power system security can be further improved under both normal and single line contingency occasions.

Mishra in [197-198] introduced a combination of two separate indices, LUF and FVSI to indicate the overloading line and bus voltage violations. The combination of these two indices is known as composite severity index (CSI). The most severe lines in which corresponding to every line outage had been determined and lines which are connected between load buses had been highlighted as the priority list for IPFC placement. The proposed analytical approach had been implemented on IEEE 14 bus and IEEE 30 bus test systems in [197]. In [198], the proposed work had been adopted on IEEE 30 and Indian Utility 62 bus systems. The comparative analysis was done to validate the performance of the benchmark test system with and without optimal IPFC implementation under both normal and load growth occasions. Similar study had been conducted by the same author in [199]. The proposed approach in [197-198] may be very cumbersome for large and complex network. Hence, the author had introduced rapid contingency ranking technique for selecting few important buses to ease the procedure of identifying the most severe lines through CSI. In [200], the author has been further developed four combination of composite indices which are formulated by combining one index from line severity index and voltage stability, LUF – FVSI, LUF – Lmn, PI – FVSI and PI – Lmn to determine the optimal IPFC placement. The proposed technique had been tested on IEEE 57 bus test system.

The same author introduced DLUF in [201] to determine the optimal location of IPFC. DLUF in each line where it is connected to line with the highest congested had been calculated and ranked in descending order. The pair of lines with the highest value of DLUF were considered as the most optimal location of IPFC integration for alleviating the network congestion. The proposed analytical approach had been adopted on two IEEE test systems, IEEE 14 bus and IEEE 30 bus under several loading condition. This work had been extended in [202-203] using the same approach, DLUF to determine optimal location of IPFC. Next, the optimal sizing of IPFC had been determined using FA in [202] and CSA in [203] and the multi-objective function had been formulated aimed to reduce real power losses, minimize the voltage deviation and minimize the security margin with the minimum capacity of IPFC. The proposed hybrid analytical – metaheuristic approach had been adopted on IEEE 30 bus test system under several loading condition in both studies and the results had been also compared using GA to indicate the effectiveness of the proposed algorithm in [199].

In [204], the best location of TCSC were obtained analytically via LOSI. The optimal location of TCSC had been determined under several occasions such as base case loading, 5% loading increment from the base values and 5% loading decrement from the base value and the most optimal

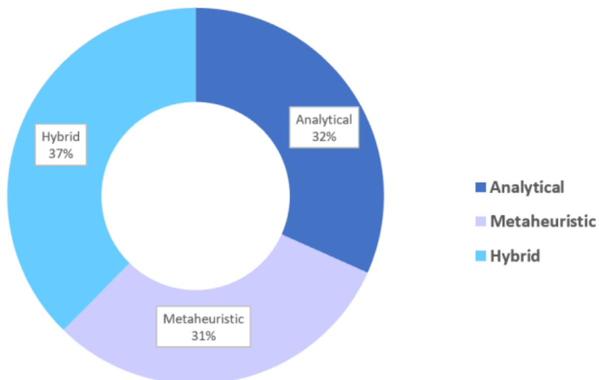

FIGURE 5. The applied techniques for solving optimal location and sizing of RPC in percentage

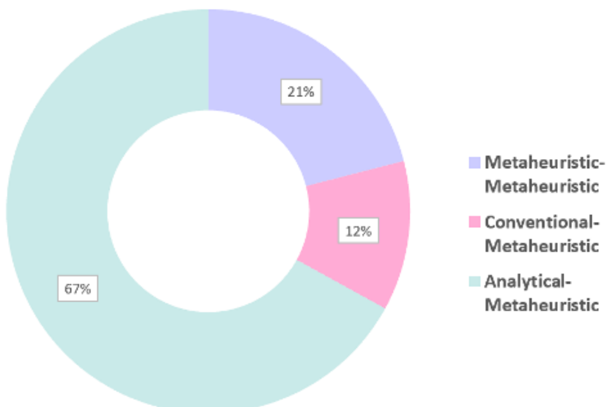

FIGURE 6. The applied hybrid-based techniques for solving optimal location and sizing of RPC in percentage

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placement has been proposed by taking the average of all occasions in each line. The proposed technique has been adopted in two IEEE networks, IEEE 30 bus and IEEE 118 bus test systems. In [205], the severity analysis had been conducted using LCPI to determine the most critical lines and generator shift factor (GSF) to determine the most critical generators. Various contingency scenarios had been conducted to analyze the security of the system under normal condition, line outage, generator outage and both line and generator outage. Next, the optimal location of UPFC has been obtained using analytical technique as done in [204] via LOSI analysis and had been implemented in IEEE 30 bus test system.

Jordehi in [206] proposed metaheuristic approach using enhanced PSO to determine the optimal location of distributed TCSC under several line outage occasions. The formulation of multi-objective function consisted of minimizing overloading in lines, voltage deviations at buses and real power losses. The proposed techniques had been adopted in two IEEE test systems, IEEE 14 bus and IEEE 18 bus. The results obtained from the proposed algorithm had been compared with other optimization algorithms such as GA, GSA, galaxy based search algorithm (GBSA), invasive weed optimization (IW)), asexual reproduction optimization (ARO), threshold acceptance (TA), pattern search and NLP to validate the effectiveness of proposed enhanced PSO in minimizing the amount of overloaded lines, voltage deviation and power losses. The same study had been conducted by the same author in [207] using BSOA to allocate the optimal location of TCSC and SVC in IEEE 57 bus system. The same multi-objective function as proposed in [207] had been adopted in this study. The effectiveness of proposed algorithm had been compared using PSO, GA, DE, SA, hybrid GA pattern search (GA-PS), backtracking search algorithm (BSA), GSA and ARO.

VII. TAXONOMY OF THE REVIEWED WORK

Table II summarizes 101 recent research articles from year 2010 until 2020, that were reviewed based on the optimization type, objective functions, constraints, implementation method, type of indices implemented, utilized RPC, adopted benchmark test systems and case studies involved. In most studies, hybrid-based approaches appeared as the most preferred method for solving optimal location and sizing problem due to effectiveness and efficiency of this approach compared to other approaches as shown in Fig. 5. Hybrid analytical-metaheuristic based approaches are the most preferred techniques for hybrid-based approach, followed by hybrid metaheuristic-metaheuristic based approaches and hybrid conventional-metaheuristic based approaches as illustrated in Fig. 6.

FIGURE 7. The applied algorithms for solving optimal location and sizing of RPC

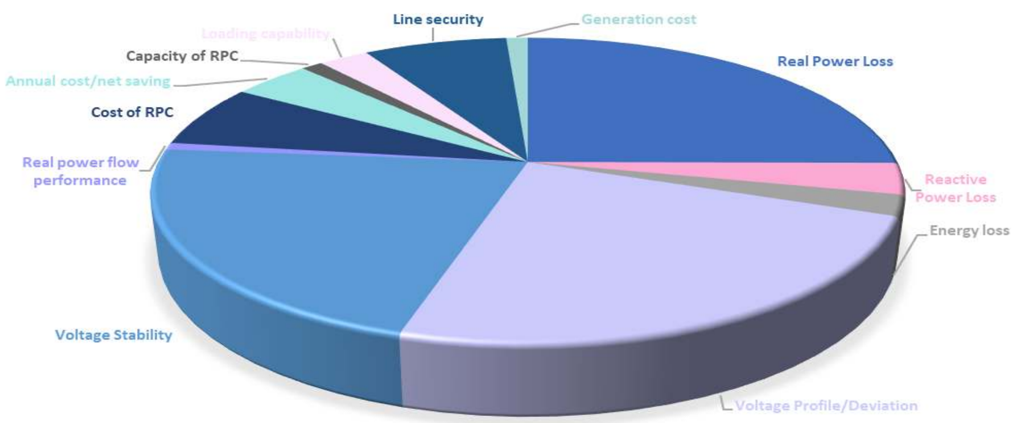

FIGURE 8. The list of objective functions adopted in the reviewed work in percentage

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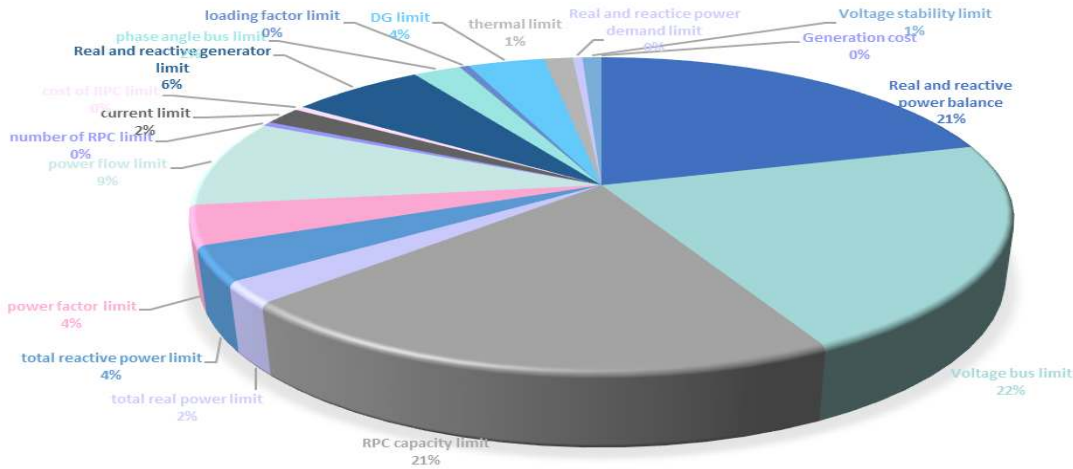

FIGURE 9. The applied equality and inequality constraints for solving optimal location and sizing of RPC

FIGURE 10. The list of available indices for solving optimal location and sizing of RPC

According to Fig. 7, GA, PSO and CSA are among the top preferences in solving optimal location and sizing problems due to their simplicity, efficiency and effectiveness in solving the optimization problem in rather large system. Fig. 8 highlights the typical objective functions that have been done in most of reviewed research articles which can be narrowed down into four main objectives based on the popularity, as shown in Fig. 11. Voltage stability enhancement is one of the most important criteria for selecting optimal location and sizing of RPC, followed by voltage profile improvement, power loss reduction and line loadability enhancement. Next, voltage bus limit, real and reactive power balance and RPC capacity limit are typical constraints that had been set in most research works when solving the optimal location and sizing of RPC as shown in Fig. 9. The common indices that were implemented in most analytical, metaheuristic and hybrid-based approaches are highlighted in Fig. 10, where VD and S_{ij} are among the popular index that had been used to determine the candidate locations for RPC.

Most of studies prefer shunt RPC such as STATCOM and SC and shunt-series RPC such as UPFC compared to series RPC as indicated in Fig. 12. According to Fig. 13, IEEE 30 and IEEE 14 bus test systems are the two most preferred transmission system whereas IEEE 33 and IEEE 69 bus test systems are the two most ideal radial distribution system in the most part of studies. Most of the optimal location and sizing studies have been conducted on transmission system compared to distribution system as shown in Fig. 14. Voltage stability, voltage profile and line loadability are the three important aspects that must be taken into consideration in determining the optimal location and sizing of RPC in transmission system. This is because both security and stability assessments are very essential since the current operation of transmission networks is closed to their physical limits. Power loss has always been a main issue in distribution system since the total power losses in power system occurred mostly at distribution level. This is clearly shown in Fig. 15, where most of the studies done in transmission system have been considering voltage stability, voltage profile and line loadability enhancements whereby study on power loss reduction is mostly done for distribution system.

Various case studies have been implemented in most research works. Load growth, line outage and comparative studies using several evolutionary algorithms are among the most common case studies that had been considered to determine the optimal location and sizing of RPC in power system as illustrated in Figure 13. Load growth and line outage are the essential studies that need to be considered in searching the optimal location and sizing to ensure the effectiveness of RPC integration in the network. The comparative studies using other evolutionary algorithms are also necessary to validate the effectiveness and efficiency of proposed algorithm.

VIII. KEY FINDINGS AND RECOMMENDATIONS FOR FUTURE WORKS

Based on this reviewed work, several recommendations for future works in solving optimal location and sizing of RPCs optimization problems are proposed as follows:

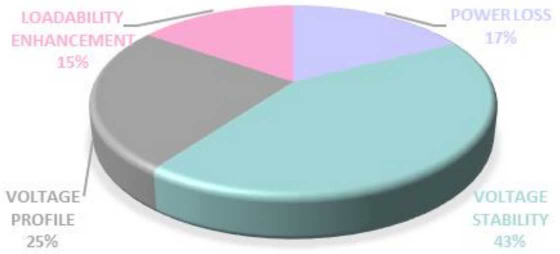

FIGURE 11. The four common objectives adopted in the reviewed work in percentage

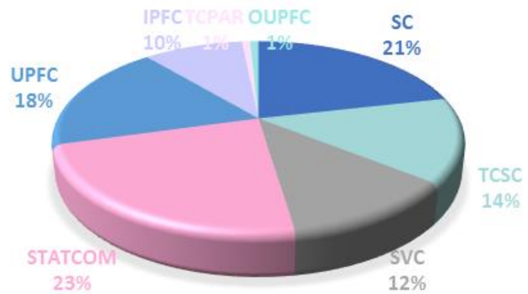

FIGURE 12. The list of RPC applied in most research work in percentage

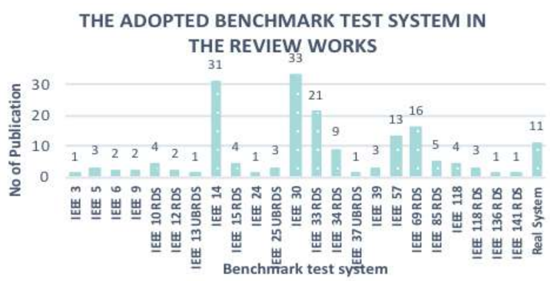

FIGURE 13. The adopted benchmark test system for solving optimal location and sizing

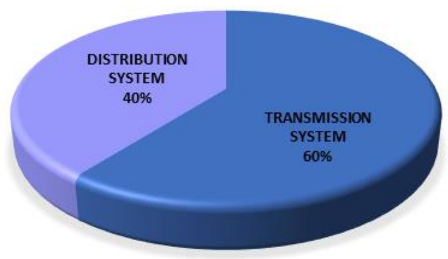

FIGURE 14. The percentage of adopted test system highlighted in two categories

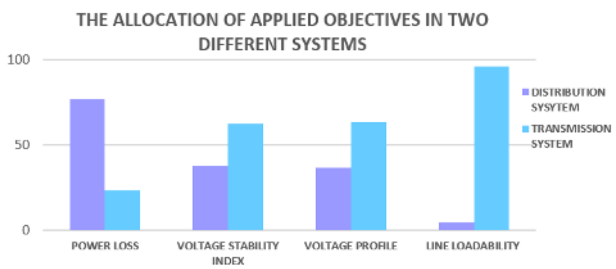

FIGURE 15. The percentage of allocation of applied objectives in categorized in two different systems

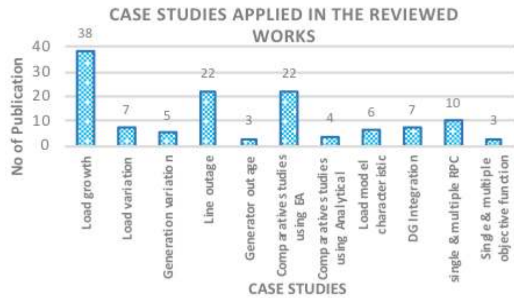

FIGURE 16. The applied case studies for solving optimal location and sizing

- In most works done using metaheuristic approaches, perform the comparative studies to validate the effectiveness of proposed algorithm with other algorithms. However, there are still few studies that covered on validating the efficiency of the proposed algorithm in term of computation time, number of iterations, and convergence rate. Hence, there is a need for a comparative study using several metaheuristic approaches to validate effectiveness and efficiency of the algorithm.
- The validation on effectiveness and efficiency of proposed algorithm had been done only on metaheuristic optimization techniques. None of the recent studies had covered on validating the performance of the hybrid-based approaches in term of comparing the effectiveness and efficiency of different hybrid-based approaches; combined analytical-metaheuristic, conventional-metaheuristic and metaheuristic-metaheuristic. This is recommended for future research.
- The combination of hybrid-based analytical-metaheuristic approaches or also known as two-stage approaches are preferred in most studies. However, no comparative studies were conducted to examine the effectiveness and efficiency between the existing two-stage approaches that should be considered for future research.
- Most of studies conducted using analytical-metaheuristic approaches in literature only performed the comparative studies on various metaheuristic techniques to validate the effectiveness of the proposed algorithm. None of these works had compared the effectiveness of the proposed index with other various indices available in literature. Various aspects such as type of FACTS controllers that can be series, shunt or combined series-shunt controller, the characteristic of benchmark IEEE test system or real test system and analysis of various contingency based simulation scenario such as load variation and single or multiple line outage or generator tripping should be considered in selecting an ideal and effective index. Therefore, the comparative studies among the indices should be validated as a recommendation for future work.

- The consideration on DG integration in determining the optimal location and sizing of RPCs are still low. All possible and potential impacts with the high penetration of multi-microgrid systems that consist of variety renewable energy resources must be very much considered in selecting proper location for RPCs integration. This should be considered in future research so that the results are more practical for real networks.
- Most of works in literature considered the impact of having single or multiple line(s) outage in the network toward the stability and security of power system. The consideration on the protection aspect especially on short circuit current level for solving optimal location and sizing of FACTS devices are still quite low in literature that could be considered in future research.

IX. CONCLUSION

This work presents a comprehensive review on optimal location and sizing of RPC using hybrid-based approaches for power loss reduction, voltage stability improvement, voltage profile enhancement and loadability enhancement. The available RPCs technologies, impact of RPCs integration in transmission and distribution system and the available optimal location and sizing of RPCs techniques had been discussed in this work. The available techniques proposed in literature for solving an optimal allocation of RPC problems are categorized in fourfold; (i) analytical, (ii) conventional optimization, (iii) metaheuristic optimization and (iv) hybrid-based approaches where the hybrid-based techniques can be a combination of analytical-metaheuristic approaches or traditional-metaheuristic approaches or metaheuristic-metaheuristic approaches. Among all these available techniques, the hybrid analytical-metaheuristic based approaches or also known as two-stage approach are the common technique for solving the optimal location and sizing optimization problems as the structure of algorithms is simple and requires less computational time. In this technique, the candidate locations of RPCs are initially pre-determined using analytical techniques and lastly, the optimal location and sizing is obtained using metaheuristic algorithm. In some works, the optimal location and sizing of RPCs are determined separately whereas the best location is obtained using analytical approach and the best sizing is determined using metaheuristic technique.

Various type of indices adopted in analytical approach proposed in literature had been discussed in detail based on four categories: power loss, voltage stability, voltage profile and line severity. Next, the review works related to the application of proposed indices for optimal location and sizing of RPCs have been summarized and tabulated based on the implementation of objectives, equality and inequality constraints, method, type of RPC, benchmark test systems and case studies involved. Lastly, the key findings and recommendations for future works related to this work had been proposed.

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