Review of Non-Traditional Optimization Methods for Allocation of Distributed Generation and Energy Storage in Distribution System

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Abstract: The integration of distributed energy sources transforms passive distributed grid, in which the energy flows only in one direction (from the source to the consumer), in an active one, in which energy flows in both directions. To maximize positive impacts, which distributed generation (DG) can provide to the distribution network, it is necessary to determine the optimal allocation of distributed generation. The optimal allocation can be determined by using the optimization method. There are two main categories: exact methods (traditional) and heuristic (non-traditional) methods. Exact methods search for global optimum while heuristic methods achieve satisfactory solutions with greater computation speed. This paper gives a brief review of non-traditional methods used for determining optimal location and optimal power of DG with the aim to reduce real power losses and to improve voltage characteristics. Also, there is a review of the application of those methods in determining the optimal power, optimal location and optimal cycle of charging/discharging of electrical energy storage systems.

Keywords: active distribution grid; distributed generation; genetic algorithm; optimization of the distribution grid

1 INTRODUCTION

The increasing integration of renewable energy into the distribution grid makes distribution grid more complex [1]. This high level of penetration, which is expected to be even higher in the future, requires study of its impact on the power system [2]. DG can have positive effects on the network voltage, but if the demand is less than supply, there may be an increase in voltage in parts of the network. Also, DG can increase active power losses with a two-direction flow of energy. Power quality can also be affected due to a variable and unpredictable production, which can lead to the emergence of voltage fluctuation [3].

The technologies of the wind power plants (WPPs) and photovoltaic power plants (PVs) are continually increasing their share in the production of electric energy. Europe almost doubled the share of renewables – from 258 465 MW in 2007 to 486 693 MW in 2016, while in Croatia it increased from 2097 MW to 2740 MW in the same period [4].

However, production from some renewable energy sources (WPP, PV) is variable and unpredictable, so they have an impact on voltage fluctuations, which could exert a detrimental influence on the voltage quality in the power distribution network. Electric energy storage (EES) can be used to solve the problem of variability of renewables in the way to store the produced energy or to deliver stored energy to the grid [5].

This paper provides an overview of the non-traditional methods used to determine the optimal location and power of the DG as well as optimal location, power and the charge/discharge cycles of the EES. The most commonly used traditional methods are Gradient Search, Linear Programming, Sequential Quadratic Programming, Nonlinear Programming and Dynamic Programming. Non-Traditional methods that authors use are Genetic Algorithm, Tabu Search, Particle Swarm Optimization, Ant Colony Optimization, Artificial Bee Colony, frog jumping methods, Evolutionary Programming Simulated Annealing and Bat Algorithm [6, 7].

This paper consists of five chapters. After the introductory chapter, the second chapter provides an overview of the influence of distributed energy sources on the distribution grid. The third chapter provides an overview of the methods used to determine the optimal power and location of the DG and optimal cycle of charging/discharging of EES. The fourth chapter presents summary of the survey and possible future trends, and this paper ends with a conclusion in the fifth chapter.

2 INFLUENCE OF DISTRIBUTED ENERGY SOURCES ON DISTRIBUTION GRID

Conventional distribution grid is designed for the transmission of electricity taken from the transmission network to the medium and small consumers, [8, 9].

By increasing the number of distributed sources, distribution network becomes active, and there is a possibility of changing the direction of power flow from the low voltage network to the high voltage network.

Apart from the above mentioned, adverse impacts of DG integration in power distribution network, usually observed is the impact on voltage conditions and on power quality.

2.1 Impact of DG on Voltage

Although the integration of DG in the distribution network achieved a reduction of voltage drop, if demand is low and the production of distributed resources is significant, an increase in voltage can occur in some parts of the network. The approximate value of the voltage in the weak grid with DG [10] is:

$$\Delta V = \frac{P \cdot R + X \cdot Q}{V} \tag{1}$$

where P is active power output of the generator, Q is reactive power output of the generator, R is resistance of the circuit, X is inductive reactance of the circuit, and V is nominal voltage of the circuit.

According to [8]:

$$P = P_G - P_L \tag{2}$$

$$Q = (Q_C - Q_L \pm Q_G) \qquad (3)$$

where P_G is generator active power, P_L is active power of load, Q_G is generator reactive power, Q_L is load reactive power, Q_C is capacitors reactive power.

If Eqs. (2) and (3) are put to (1) the approximate value of the voltage in the weak grid with DG is:

$$\Delta V = \frac{R(P_G - P_L) + X(\pm Q_C - Q_L \pm Q_G)}{V} \qquad (4)$$

According to EN 50160 standards [11], the voltage must be within the range ± 10% of nominal voltage. This requirement must be met with the integration of DG in the electricity distribution network.

2.2 The Impact of DG on the Losses in the Network

Integration of DG in power grid has a positive influence on the reduction of active power losses up to certain strength of DG. When the border of the optimum power of DG for integration into the network is crossed, with each additional increase of DG power, active power losses are also increasing. According to [3] this loss can be more than five times higher than without DG connected. Accordingly, it is not enough just to find the most favourable location of DG but is necessary to determine the optimal size of DG.

$$\text{DGpen} = \frac{\text{capacity factor} \cdot \text{DG installed capacity}}{\text{feeder capacity}} \qquad (5)$$

where DG pen is "The ratio of the amount of DG energy injected into the network to the feeder capacity", "Capacity factor – the ratio of the energy produced,

during the period of time considered, to the energy that could have been produced if DG had operated at continuous full power during the same time period", "DG installed capacity – the total maximum output of each DG unit. The DG installed capacity in the network is the sum of the individual DG installed capacities" [3].

2.3 Impact of DG on the Power Quality

When the power quality is in focus, then the interaction between users (a way how the current of devices affects the power system) and grid (a way how grid voltage affects devices) is considered. Integration of DG has a local effect on the quality of electricity, but by integration into a larger extent, this impact becomes global. Variable production of distributed generation can lead to voltage fluctuations. For example, if several wind farms are connected to the network, the short-term voltage flicker is calculated using the following equation:

$$P_{st} = \sqrt{\sum_{i=1}^{N} P_{st,i}} \qquad (6)$$

where $P_{st.i}$ is the contribution of each individual turbine.

Very short variations (changes) of voltage induced integration of wind power plants:

$$VSV_V = R \times VSV_p + X \times VSV_q \qquad (7)$$

where $VSVp$ stands for variation in active power, $VSVq$ stands for variation in reactive power, R is resistance (p.u.) and X is reactance (p.u.) [12].
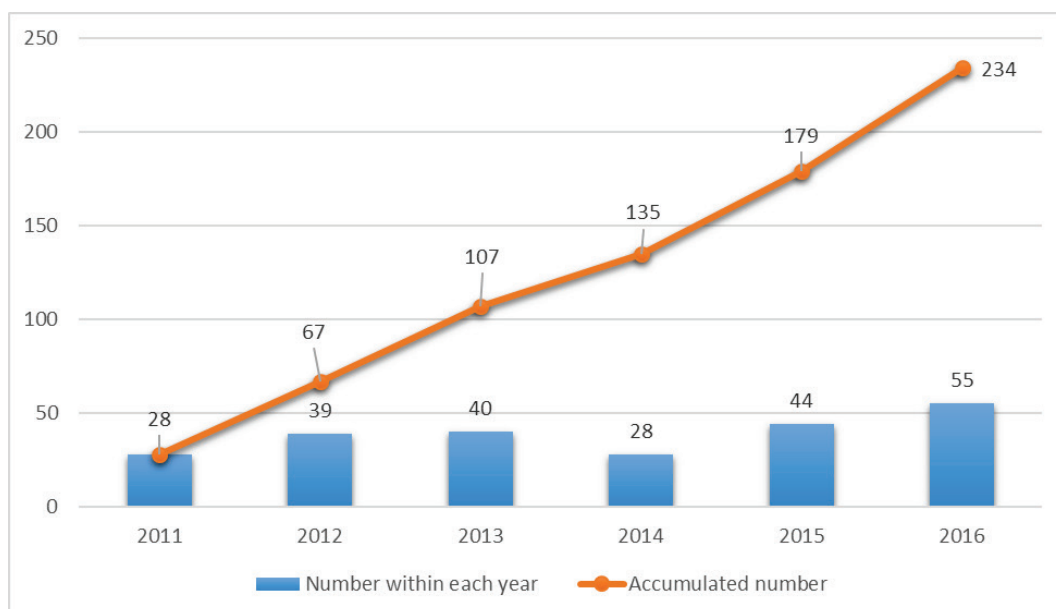

Figure 1 The number of published articles in each year (bar chart), as well as the total number of published articles (line chart)

Hariri et al. [13] simulated the integration of distributed sources (DS) and their impact on the quality of electricity in RSCAD/RTDS simulation software. They used wind power plant of 2 MW and two photovoltaic power, 25,2 MW, and 0,35 MW. The first simulation was

without DS, in the second simulation photovoltaic power plant was connected, and in the third simulation photovoltaic power plant 0,35 MW was disconnected, and wind farm was connected.

The simulation results showed the appearance of harmonics in both cases with the integration of DS, but total harmonic distortion did not exceed the limit of 5% which is prescribed by the IEEE 1547 standard [14].

Voltage fluctuation was recorded in both scenarios of DG integration. In the third simulation with wind power plants, in some moments, fluctuations have exceeded the allowable limit of ±5% set by ANSI standard [15].

3 REVIEW OF METHODS FOR OPTIMAL ALLOCATION OF DG AND EES
3.1 Method of the Survey

Due to the increasing introduction of renewable energy sources into the power grid, the research area of the optimal location of distributed energy sources has received significant attention from 2011 to 2016. Fig. 1 shows the number of published articles in each year (bar chart), as well as the total number of published articles (line chart). Of the 234 most related published articles, 45,3% (106) were conference publications and 54,7% (128) were journals and magazines publications. IEEE Xplore Digital Library database and ScienceDirect databases were analysed in detail and searched.

3.2 Non-traditional Methods for Determining Optimal Location and Optimal Power of DG

Traditional mathematical optimization methods such as dynamic programming, linear programming and nonlinear programming intended to search for the global optimum, fail to solve today's problems of optimization within a reasonable time. The solution to this issue is to use the well-known non-traditional optimization methods to obtain a satisfactory solution within a reasonable time. Non-traditional methods are genetic algorithms, artificial immune algorithm, particle swarm optimization, ant colonies optimization and frog jumping methods [16], [17].

Mitra et al. [18] presented a method based on dynamic programming to determine optimal places, the power, and the energy mix. Authors applied the method to the system of 6 buses.

Kotb et al. [19] used a genetic algorithm to determine the optimal power and the place of distributed sources. The proposed algorithm was simulated in Matlab software. The authors concluded that the addition of distributed sources to the distribution network reduced losses of the active and reactive power and improved the characteristics of voltage. Also, the authors concluded that the genetic algorithm was faster, easier and gave more accurate solutions than traditional methods.

In the literature [20-25], the authors investigated the problem of deployment of distributed electricity sources to reduce active power losses and improve voltage characteristics. Lalitha et al. [20] used the fuzzy artificial immune system to determine the location of distributed sources, to improve the characteristics of voltage and reduce active power losses. First, the analytical methods were used to find the best place for the integration of distributed sources and then the clonal selection algorithm determined the optimal power of distributed generation, to minimize active power losses and improve voltage

characteristics. Successful testing of the IEEE 33 bus test system showed significantly better solutions and determining the effectiveness of mentioned computer system when compared to other approaches.

In [21] authors determined the optimal location of a distributed generator, using a genetic algorithm, then used a real-coded genetic algorithm to determine the optimal power of distributed generators. By testing it on the IEEE 33 bus test system, the authors showed that the method drastically reduced overall system power losses and significantly improved the characteristics of voltage.

In [22] authors used a simple method to accommodate a unit of distributed source, then used the Particle swarm optimization for determining the optimal power of distributed sources to reduce losses of the active power and improve the characteristics of voltage in the radial distribution network. The success of the method was confirmed by testing on the IEEE 33 bus test system. In [23], authors used the artificial bee colonies algorithm to determine the optimal power of distributed sources in the radial distribution network. By testing on the IEEE 33 bus test system authors concluded that the artificial bee colonies algorithm is simpler than the Genetic Algorithm and Particle Swarm Optimization and has a shorter computation time. The simulation results also showed a reduction of active power losses and improved voltage characteristics.

In [24] authors used fuzzy logic to determine the optimal location of distributed sources to reduce losses of the active power and maintain the voltage within the allowable limits. Artificial bee colonies algorithm was used to determine the optimal power of distributed generation; the method was successfully tested on IEEE 33 bus test system.

Ramudu et al. [25] proposed an algorithm to determine the optimal location of a distributed generation. The algorithm was created in the Matlab simulation environment. Artificial bee colonies algorithm was used to determine the optimal power of distributed generation in the radial distribution network. The method was successfully tested on a simulation of the current medium voltage system (20 kV) of the southern province of Khorasan in Iran.

El-Ella et al. [26] used a genetic algorithm to determine the capacity of distributed generation and simulated annealing algorithm for the expansion of the distribution network.

Shi et al. [27] used a genetic algorithm with built-elitism (elitism provides a copy of at least one of the best solutions from the previous population in the new population) and particle swarm algorithm for determining the capacity and place of distributed generation. The authors concluded that these algorithms surpass the use of the genetic algorithm in [26].

Buayai [28] used non-dominated sorting genetic algorithm II to determine the size and place of distributed generation, then used the fuzzy method of decision-making to achieve the most optimal solutions. The method was tested on IEEE 33 bus test system.

Coelli et al. [29] proposed multiobjective function optimization for planning and management of distributed energy resources; they solved them by the genetic algorithm and Multi-Objective Programming. The used

algorithm may well determine where and how many of distributed generation must be installed in the network.

Amanifar et al. [30] used Particle swarm optimization integrated with harmonic power flow algorithm to determine the optimal strength and position of distributed generation. Particle swarm optimization was successfully tested on the IEEE 33 bus test system.

Jayavarma et al. [31] proposed a new algorithm using the Particle swarm optimization to determine the optimal location of photovoltaic systems with the aim of reducing active power losses and improving voltage characteristics. The algorithm was successfully tested on a modified IEEE 14 bus test system.

Bhumkittipich et al. [32] used the Particle swarm optimization method to determine the place of distributed generation within the distribution network with the aim of active power losses reduction.

Vallem et al. [33] used simulated annealing to determine the size and place of distributed generation in the microgrid.

Marghaki et al. [34] used bee algorithm for allocation of distributed resources to reduce power losses and improve the voltage profile. The proposed intelligent system was successfully tested on the 26 bus test system.

Vallem et al. [35] applied the method of simulated annealing to accommodate distributed generation, which takes into account the costs of implementation and cost savings from the use of Combined Heat and Power facilities. The method was tested on the six bus test system.

Carpinelli et al. [36] used a genetic algorithm to determine the optimal location and size of distributed energy sources, EES and capacitor banks. After determining the optimal size and location, they used a sequential quadratic programming algorithm for the optimal cycle of charging/discharging and for scheduling of active power that distributed sources, and capacitor banks should produce. A hybrid method with the goal to reduce the total cost of the distribution system was successfully tested on the medium-voltage three-phase network with 18 buses.

Kanwar et al. [37] proposed an improved bat algorithm for optimal allocation of DGs and network reconfiguration with the aim to minimize energy losses and to improve voltage profile in the radial distribution grid where customers load patterns were considered. The results obtained by testing on the IEEE 33 bus test system showed a significant reduction in power losses and an increase in the minimal node voltage.

3.3 Arrangement of the Electrical Energy Storage in the Distribution Network

Technologies for electrical energy storage play a significant role in the power system. They can store electricity in periods without peak loads and use it during periods of peak loads, provide sustainability and supply during the blackout, maintain and improve the quality of electricity. They are the solution for the problem of variable and unpredictable production from distributed energy sources [38]. There are many shapes of electrical energy storages in a power system. Continuous development of technology makes that number even

higher. According to [39] EES can be classified into mechanical (pumped storage power plants, compressed air, and flywheels), thermal chemical (fuel cells), electrochemical (secondary battery), chemical (hydrogen), electrical (double-layer capacitor and superconducting magnetic warehouses) and thermal storage systems (tank sensible heat).

There are two basic categories of EES by the size. The first type is small plants up to 10 MW (the most used batteries), the second type includes large plants, which are greater than 10 MW (pumped storage hydropower plant, make up 99% of the EES for storing energy installed worldwide).

The old and the most used EES is the pumped storage power plants, which use pumping water from the lower reservoir in the upper reservoir when supply exceeds demand (at low loads). When supply is less than demand (during the peak load), the water from the upper reservoir is released through turbines to produced electrical energy. Because of the possibility of storage, significant amounts of energy and rapid reaction, pumped storage power plants could reduce the uncertainty of wind generation [40], [41].

Ferrier et al. [42] gave a comparison of the technology to store electricity, their characteristics and qualitative methodology for the selection of appropriate technology for EES.
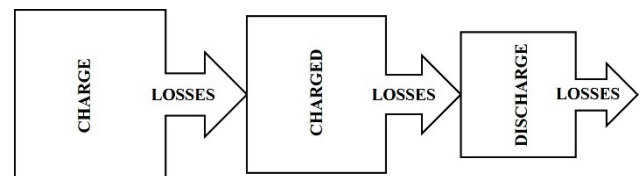

Figure 2 EES operation conditions in power systems

Chen et al. [43] provided an overview of the technology systems for electrical energy storing. According to [44] EES may be located in one of the three operating conditions within the power system, Fig. 2. which are charging, charged, and discharge.

In all operating conditions the next two Eqs. (8), and (9) must be met:

$$N_{gen} - L_1 + P_s = 0 \qquad (8)$$
$$Q_{gen} + Q_1 + Q_s = 0 \qquad (9)$$

where: N_{gen} is active power generated by the supply side of the power system, Q_{gen} is reactive power generated by the supply side of the power system, L_1 is active power consumed by demand side of the power system, Q_1 is reactive power consumed by demand side of the power system, P_s is active power from EES, and Q_s is reactive power from EES.

The equation of energy balance:

$$E_{gen} - \delta E_s - E_1 = 0 \qquad (10)$$

where: E_{gen} is generated energy, δE_s is losses in the EES, and E_1 is energy consumed by the power system.

Table 1 Summary of the methods for determination of the optimal location and size of DGs in distribution network

Method	Application		Key idea	Comparison to other methods		Reference
	Optimal location	Optimal size		Compared to	Advantage	
Genetic algorithm (GA)	✓	✓	Power losses reduction and voltage profile improvement	Traditional method - TM	Faster, easier and gives more accurate solutions	[19, 21, 26, 36]
Algorithm with elitism strategy (EGA)	✓	✓	Solve the size and location of multi DG	GA PSO	Outperformed the original GA and a bit better than PSO	[27]
Particle swarm optimization (PSO)	✓	-	Placement of Solar PV with minimum active power losses	TM	Easy to implement	[31]
	✓	✓	Minimizing the total real power loss		Fast and accurate in determining the sizes and locations	[32]
	✓	✓	Minimize the total cost of the system		Effectiveness to search optimum point and the size of DGs	[30]
Non-dominated Sorting Genetic Algorithm II (NSGAII)	✓	✓	Determine the optimal locations and sizes of DG	X	Improvement of steady state system performance	[28]
Artificial Bee Colony algorithm (ABC)	✓	✓	Minimize total system real power loss	Grid search method	Close agreement with grid search method	[34, 55]
Simulated annealing (SA)	✓	-	Optimal location and sizes of DG units in a microgrid	X	The proper selection of parameters could assure global optimum	[35]
Improved Bat Algorithm (IBA)	✓	-	Minimize energy losses and to improve voltage profile	X	Significant reduction in power losses and an increase in the minimal node voltage	[37]
Analytical Method AM +Clonal Selection Method CSA	✓ (AM)	✓ (CSA)	Power losses reduction and improvement of the voltage profile	GA PSO	Less computation time	[20]
GA+Real-coded Genetic Algorithm RCGA	✓ (GA)	✓ (RCGA)	Power losses reduction and improvement of the voltage profile	AM	Overall system power losses reduction and improvement of the characteristics of voltage	[21]
Single DG Placement SDGP+PSO	✓ (SDGP)	✓ (PSO)	Power losses reduction and improvement of the voltage profile	AM	Improved convergence characteristics and less computation time	[22]
SDGP+ABC	✓ (SDGP)	✓ (ABC)	Power losses reduction and improvement of the voltage profile	GA PSO	Shorter computation time	[23]
Fuzzy Logic FL+ABC	✓ (FL)	✓ (ABC)	Power losses reduction and improvement of the voltage profile	PSO	Shorter computation time	[24]
FL			Energy management of the EES, balancing EES in microgrid, reducing fluctuations in RES production		simplicity compression of complex algorithms	[49, 50], [51, 53]
Matrix real-coded genetic algorithm (MRCGA)			Deployment and economic value of EES		microgrids with high integration of photovoltaic systems and EES	[52]

According to [45], EES degrades with use during each process of charging and discharging.

The service lifetime of the energy storage is also affected by way of discharge. Discharge may be shallow (the stored energy is less discharged), less harmful to the containers, and deep (discharge of the majority or the entire stored energy) of greater harm.

During charge and discharge cycles of EES, the losses appear in the process of storage of electricity, as well as in the process of electric power delivery from the EES.

According to [46], the efficiency of the cycle can be expressed as:

$$\eta_e = \frac{\eta_{in}}{\frac{1}{\eta_{out}} + \frac{T}{\tau_s} \cdot \frac{E_s}{E_{out}}} \tag{11}$$

$$\tau_S = \frac{E_s}{P_{idl}} \tag{12}$$

where: T is cyclic period, η_{in} is conversion efficiency from commercial AC side to storage system side, η_{out} is conversion efficiency from storage system side to AC

side, P_{idl} is loss power load, and E_s is stored energy. To improve the impact of EES in the active electricity distribution networks, it is necessary to determine the optimal location, power and develop a system for management of energy storing.

Oudalov et al. [47] used dynamic programming to manage EES to reduce peak loads.

Nick et al. [48] propose an algorithm for the optimal accommodation of the EES, to support voltage control of the active distribution power networks. The proposed algorithm was implemented in MATLAB programming environment and successfully tested on the IEEE 13 bus test system. To improve the methods, they introduce sensitivity analysis of optimal accommodation to the maximum number of nodes to accommodate the EES. The authors conclude that with the introduction of the proposed sensitivity analysis, this method can investigate seasonal load changes and variable production of distributed sources.

Fuzzy logic was proposed for the energy management of the EES due to the simplicity compression of complex algorithms [49].

Diaz et al. [50] used fuzzy logic to achieve the balance between multiple EES to store the energy of DC microgrid which was located in the island mode.

Diaz et al. [51] adapted and applied fuzzy implementation system [50] and used it on the AC microgrids. Simulation of a microgrid in MATLAB / Simulink showed that the application of the proposed algorithm of fuzzy logic is applicable achieving a balance of electricity storage of distributed energy storage in AC microgrids.

Chen et al. [52] used matrix real-coded genetic algorithm for deployment and economic value of EES. The proposed method can be used for commissioning of microgrids with high integration of photovoltaic systems and EES.

Li et al. [53] used fuzzy logic based on wave transformation to reduce fluctuations in production in microgrids with wind power, photovoltaic and EES. Simulation implemented in MATLAB / Simulink software demonstrates the ability to manage EES.

4 DISCUSSION AND FUTURE TRENDS
4.1 Summary Overview of the Methods

Tab. 1 presents summary of the above mentioned methods for determination of the optimal location and size of DGs in distribution network. Last two rows show the most common used methods for allocation of EES. For every method (or hybrid method), application, key idea, comparison to other methods and related literature are given.

4.2 Future Trends

A genetic algorithm is the most used non-traditional method for determination of the optimal location and size of DGs in distribution network [19, 21, 26, 27, 28, 36]. Also, the researchers added elitism or used it in combination with other algorithms [27]. Artificial bee colony algorithm was superior to the genetic algorithm to determine the optimal power DG [23].

Considering that certain methods for optimization are more appropriate for determining optimal location, [21, 24, 25, 31, 36] and other methods for determining the optimal size of DG, the researchers used a combination of methods for optimization to achieve better results, [20, 21, 22, 24÷30] and [36]. For example, a mix of the fuzzy logic to determine the optimal location and the artificial bee colonies algorithm to determine the optimum power were used in [24]. A hybrid method of genetic algorithm and sequential quadratic programming with the aim of reducing the total cost of the distribution system has proved successful in [36]. In this article, a genetic algorithm is used to determine the optimal location and size of the EES, a sequential quadratic programming for optimum charge/discharge cycles.

Fuzzy logic has been used successfully to EES due to the simplicity compression of complex algorithms [49, 50, 51, 53]. Vukobratovic at al [54] discuss voltage and power losses control using DG using computational intelligence. Authors [55] analyse active power losses minimization in electric power network using chaotic artificial bee colony algorithm.

Thus, the future trends in determining optimal location and size of DGs and EES are combination of non-traditional methods. In this way, every problem can be solved by the most appropriate method.

5 CONCLUSION

The impact of the optimal size and location of DG to reduce power losses and to improve the voltage characteristics is an increasingly important subject in recent scientific researches. To maximize positive impacts, which distributed generation (DG) can provide to the distribution network, it is necessary to determine the optimal allocation of distributed generation. Non-traditional optimization methods applied to the above mentioned problem are reviewed in this paper. Metaheuristic Optimization methods give good results in the optimization of complex power systems within a reasonable computational time.

Some renewable energy sources such as WPPs and PVs, due to their variability in production, have to be used during periods when they are available. Otherwise, produced energy must be stored using electrical energy storage. Thus, a review of the application of those methods in determining the optimal power, optimal location and optimal cycle of charging/discharging of electrical energy storage systems is presented in this paper.

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