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A Comprehensive Review of Optimization Techniques Applied for Placement and Sizing of Custom Power Devices in Distribution Networks

***Abstract**. Custom power devices (CPD) are used to protect conventional and sensitive loads against power quality disturbances such as voltage sag/swell and harmonic distortion in power systems. The proper placement of CPDs has an important effect on the quality of improvement and ensures that the total costs are minimal in accordance with maximum efficiency. This paper presents a survey of the literature in the last decade that have focused on the various optimization techniques applied to determine optimal placement and size of CPD.*

***Streszczenie.** W artykule przedstawiono przegląd literatury z ostatniej dekady z zagadnienia metod optymalizacji rozmieszczenia i rozmiaru urządzeń energoelektronicznych o regulowanej mocy (ang. Custom Power Device) pracujących jako filtry, do poprawy jakości energii w systemach energetycznych. (**Kompleksowy przegląd technik optymalizacji rozmieszenia i rozmiaru filtrów mocy w sieciach przesyłowych**)*

Keywords: custom power device, heuristic optimization, optimum location, power quality.
Słowa kluczowe: Aktywny filtr mocy, optymalizacja heurystyczna, lokalizacja optimum, jakość energii

Introduction

In the current deregulated electricity market, electrical energy is considered as the basic right of every individual that should be available at all times [1]. Therefore, the produced electricity should be considered as a certain kind of product with predetermined characteristics, which needs to be continuously analysed, predicted, and enhanced to ensure its quality, reliability, and availability (QRA) [2, 3]. Consequently, any deviation from the predesigned characteristics can cause power quality problems and failure of equipment on the customer side [4]. Among the power quality disturbances, voltage sags and harmonic distortions are the most important power quality issues that can affect all customers in the distribution systems [5]. For example, voltage decreases to 80% of nominal voltage with occasional tens of millisecond duration, which can cause an interruption in processing plants, resulting in hours of downtime [6-9]. The increasing tendency to use power electronic-based controllers at the generation, transmission, and distribution systems can also have direct or indirect effects on the system modelling, simulation, and monitoring tools [10, 11]. In addition, as the concern for power quality grows, other related concerns such as reliability and availability of power also increase due to the presence of short-duration power quality events, growing demand, uncertain markets, and changing environmental regulations [12]. Hence, the best solution to improve QRA and protect sensitive loads from power quality events is to feed these loads with proper types of state-of-the-art power electronic-based devices called custom power devices (CPD) [13-15]. The required CPDs to improve QRA can be installed for an individual customer or a group of customers that need enhanced power quality levels rather than the standard ones [16, 17].

Technically, the mitigation option, location, and sizing of the required CPDs should be determined based on the economic feasibility according to the required QRA, which is a major concern in the selection process and needs to be optimized [18]. Compared with the extensive research on the optimal location and size of the Flexible Alternating Current Transmission System (FACTS) devices in power transmission systems, few reports can be found in the literature regarding the placement issues of CPDs to improve QRA in distribution systems. Studying the relevant applied heuristic optimization techniques to solve the optimal placement of the FACTS devices can be very helpful due to similarity in the structure and characteristics of the CPDs and FACTS devices. For instance, optimal placement and sizing of Static VAR Compensator (SVC) can be done using Improved Harmony Search Algorithm [19], and a hybrid Bee Colony Optimization and Harmony Search algorithms [20], and the optimal placement of Unified Power Flow Controller can be solved using Shuffled Frog Leaping Algorithm [21].

Considering both the CPDs and FACTS devices, different formulations and methodologies based on heuristic, artificial intelligence or hybrid techniques have been proposed to solve the difficult combinatorial optimum location problem [22, 23]. The objective functions of these proposed methodologies were mostly formulated based on the cost considerations, while some limits such as bus voltage and harmonic distortion levels are considered as the constraints to control variables [24-28].

In this paper, a comprehensive literature survey on the optimization techniques that solve the optimal CPD placement problem and that have been proposed recently by various researchers is presented. This survey covers most of the applied heuristic and hybrid optimization techniques such as genetic algorithm (GA) and simulated annealing (SA) to solve power system optimization problems.

Optimal CPD Placement and Sizing Formulation

Due to the recent advances in power electronic technology, CPDs have been developed to enhance the quality, reliability, and availability of the delivered power [29, 30]. Many types of CPDs are connected in shunt or series or a combination of both in distribution systems such as Dynamic Voltage Restore (DVR), Distribution STATic COMpensator (D-STATCOM), and Unified Power Quality Conditioner [31-33]. Generally, locating the CPDs for power quality improvement can be categorized as either “central improvement” or “distributed improvement” [34]. In the central improvement schemes the CPDs are installed at the point of common coupling to support all customers supplied from the feeder, while in the distributed improvement schemes the CPDs are installed at the individual buses to improve power quality for specific customers. Nonetheless, power quality improvement using a single CPD in the central improvement configuration is not reasonable and economical. Therefore, distributed improvement configuration is preferred by most system planners [35].

The ultimate goal in radial distribution systems is to determine the optimal location and size of the CPDs to maximize the power quality improvement while minimizing the total cost. Therefore, the best types of CPDs and their locations in an entire radial distribution system must be determined to minimize the costs incurred due to low power quality and CPD installation. The general multi-objective combinatorial function, C, to solve this problem can be formed as [28]

(1) $$\text{Minimize } C = F(C_{LPQ}, C_{CPD}, C_{UTI}, P_{UTI}) \quad \text{Subject to } F_f \leq F_{f\text{-}limit}$$

where C_{LPQ} is the attributed cost of low power quality posed to customers, C_{CPD} is the cost of CPDs including investment, operation, and maintenance costs, C_{UTI} is the penalty cost posed to utility due to the lack of the regulatory targets, P_{UTI} is the utility revenue due to installation of CPDs, and Ff is the optimization constraint. All costs are in dollars per year.

The constraints of the optimization model must be well defined to control variables based on real applications [36, 37]. The general constraints that are usually applied to locate CPDs are defined as follows:

i) Bus Voltage Limits

The bus voltage magnitudes must be kept within acceptable operating limits throughout the optimization process as

(2) $$V_{\min} \leq |V_i| \leq V_{\max}$$

where V_{min} is the lower bound of the bus voltage limits, V_{max} is the upper bound of the bus voltage limits, and Vi is the rms value of the bus voltage. In the case of CPDs, these limits are set based on the voltage sag considerations. Therefore, the voltage limits for sensitive loads should be within 80% to 90% while these limits should be kept at a desired level for overall system bus voltages [38].

ii) Frequency of Voltage Sag

This limit should be set to mitigate voltage sag in the distribution system based on yearly voltage sag frequency assessment as

(3) $$VS_i \leq VS_{i-Limit}$$

where V_{Si} is the voltage sag frequency in the bus, while *i* and $V_{Si\text{-}Limit}$ is the maximum acceptable value of the voltage sag frequency for the same bus. This assessment can be done using the statistical measurement method or analytical modelling method [39].

iii) CPD Rating Limits

The pre-specified maximum power rating of individual CPDs should not be exceeded as

(4) $$S_{CPD} \leq S_{CPD-\max}$$

where $S_{CPD\text{-max}}$ is the maximum acceptable size of CPDs.

iv) Total Harmonic Distortion (THD) Limits

The harmonic distortion at bus i should be compensated to meet the allowable harmonic distortion level as

(5) $$THD_i \leq THD_{\max}$$

where THD_{max} is the maximum allowable harmonic distortion level at each bus.

After determining the suitable objective function and constraints, the stopping criterion should be defined based on the improvement of the QRA level, which is mostly limited by predetermined constraints. Therefore, if all the solutions at the given level do not fulfil the predefined constraints, the procedure should be iterated until the goal solutions are reached [40].

CPD Placement Using Heuristic Optimization Techniques

Generally, optimization techniques are needed to determine the optimum location, type, and parameters of each CPD. The objective function has to be multi-objective, nonlinear, non-continuous, and non-differentiable due to the combination of different devices with different characteristics [41]. In other words, this kind of problem can be classified as a non-deterministic polynomial problem, and its problem size may increase exponentially, which would make it very difficult to solve [42]. In recent years, several heuristic optimization techniques have been applied to solve these kinds of multi-objective combinatorial optimization problems in power systems [43-45]. These heuristic algorithms search for the solutions within a subspace of the total search space to find the optimum solution within a reasonable computation time [46, 47]. The most important advantage of heuristic algorithms is that their solutions are not limited by restrictive assumptions about the search space, and these algorithms can also find a near global optimum solution [48, 49]. Therefore, many researchers have concentrated on various types of heuristic optimization techniques to determine the optimal location and size of FACTS and CPDs in transmission and distribution systems. Figure 1 shows the number of indexed research papers related to optimal placement of CPD to improve power quality, especially voltage sag mitigation in distribution systems. This section presents a review of heuristic optimization techniques that have been applied to solve optimal CPD placement problems for the improvement of QRA.

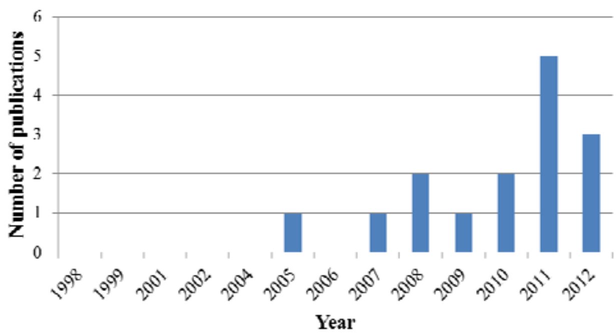

Fig. 1. The number of indexed papers in field of optimal placement of CPDs

Genetic Algorithm

GA can be classified as a kind of evolutionary algorithm that is able to obtain the solutions of optimization problems using methods that are derived from natural evolution, such as inheritance, mutation, selection, and crossover [50]. The GA searches for optimal solutions using the principles of evolution based on a certain string that is judged and propagated to form the next generation [51]. The algorithm is designed to survive the “fitter” strings and propagate them into the later generations [52]. The major advantage of the GA is the ability of its algorithm to search and find a global solution within the optimization process [53]. Moreover, the GA has the ability to find the global solution among a wide variety of functions including differentiable or non-differentiable, linear or nonlinear, continuous or discrete, and analytical or procedural functions [54, 55].

In 2007, a GA-based optimal placement approach was proposed to reduce voltage sag cost in the distribution system using power electronic controllers including SVC, STATIC COMpensator (STATCOM), and DVR [56]. In the proposed method, the sag performance is measured using the evaluation of network annual losses due to voltage sags, with and without the SVC, STATCOM, and DVR. The multi-objective function is formed to minimize the Pay-Back Year and Net Present Values of the system. The stopping criterion for the GA is set for the time that the best solution remains unchanged within a certain number of iterations. Otherwise, the GA stops when a certain number of generations are reached.

Another GA-based optimization approach was proposed by Zhang to optimally select and allocate CPDs in a distribution network to minimize the number of voltage sags [57]. In this method, the numbers of sags in different magnitude ranges are considered variables to form the objective function and niching type of GA (NGA), which is applied to find the optimal solutions. The advantage of using NGA over simple GA is that NGA has the ability to search a wider space by “maintaining genes” diversity in the population, which increases the possibility of convergence to the global optima. Nonetheless, NGA requires another method to determine the distance between two individuals, which can dramatically increase the computation time.

Particle Swarm Optimization

Particle swarm optimization (PSO) was first introduced by Kennedy and Eberhart [58]. The technique is based on the simulating social behaviour among individuals (particles) “flying” through a multidimensional search space, in which each particle represents a single intersection of all of the search dimensions [59]. In this approach, the particles evaluate their positions relative to a goal (fitness) at every iteration, and the particles in a local neighbourhood share memories of their “best” positions and use those memories to adjust their own velocities and subsequent positions [60, 61]. The PSO algorithm has the benefits of parallel calculation and robustness, and it can find the global optimal solution with a higher possibility and efficiency than other optimization methods. In addition, unlike the GA, PSO has no evolution operators such as crossover and mutation, which make it fast converging and easy to implement [62]. PSO is widely applied to solve the optimal placement of FACTS devices [25] and Distributed Generations [63] to improve power quality in transmission and distribution systems, but its effectiveness for optimal placement of CPDs has not been investigated.

Simulated Annealing

SA is a powerful optimization approach inspired from the resemblance between the minimization process and crystallization in a physical system. The SA algorithm begins with a feasible solution point, and the solution is then perturbed to obtain new feasible solutions that are either accepted or discarded, depending on a probabilistic acceptance criterion [64]. SA can provide a good approximation of the global optimum for functions within a large (and even discrete) search space [65]. In addition, for some problems and under specific circumstances, SA can provide a more efficient solution than the exhaustive enumeration-based method, which means that the goal is set to find a reasonably global solution within a specific time duration rather than the best possible solution [66].

A SA-based method has been presented to determine the optimal size and location of DVR in power distribution system [38]. The method consists of a multi-objective function with cost and voltage limit considerations to maximize the sensitive loads and overall system voltages. In this method, the sensitive load voltage limits are set within 80% to 90% of the nominal voltage, while overall system voltage limits are considered to be over 60% of the nominal voltage for all buses. In addition, the goal attainment method [67] is applied to convert the multi-objective function to a single function for simplification of the optimization problem. Finally, SA is applied to solve the DVR optimal placement problem and mitigate voltage sag.

Gravitational Search Algorithm

Gravitational search algorithm (GSA) is an optimization algorithm inspired by the law of gravity [68]. In GSA, agents are modelled as objects with characteristics that can be quantified by their masses. All these objects attract each other, and their interactions can be measured by the Newtonian laws of gravity. This force causes a global movement of all objects toward the objects with heavier masses. Therefore, each mass presents a solution, and the global solution can be attained by accurately adapting the gravitational and inertia masses [69].

In 2012, a method was proposed to enhance reliability and mitigate voltage sag propagation in power distribution systems by optimal placement of D-STATCOM using GSA [70]. In this method, the objective function is formed based on the fault rate of system buses and distribution transformer, where the nominal bus voltages, the current flow of the lines, and the system line loss are considered as the system operation constraints. Then, a binary version of gravitational search algorithm (BGSA) is applied as a heuristic computational optimization tool to solve the optimization problem.

Other Optimization Techniques

Dynamic Programming Technique

Dynamic programming (DP) is a very powerful method that is able to solve complex problems by dividing them into a collection of sub-problems and undertaking them one by one from the smallest one to calculate the larger ones until the whole problem is solved [71, 72]. In other words, to solve a given problem, the DP algorithm attempts to find a solution for different parts of the predetermined problem called sub-problems. Then by combining the found solutions for the sub-problems, a global solution can be determined. The DP technique can drastically reduce the computational burden. Nonetheless, this method may lead to very similar results with other heuristic techniques but with fewer computation time [73].

In 2008, an approach was proposed to optimally allocate DVR in distribution networks to minimize the number of voltage sags using the bottom-up approach and DP technique [28]. First the voltage sag frequency of each bus is estimated to accurately model the performance of the DVRs to mitigate voltage sag. In the next step, the objective function is formed using the total cost relevant to the voltage sag including the cost of each event, the cost of the mitigation devices, and the cost of penalties due to the lack of regulatory targets. Finally, the optimization problem of the location and size of the mitigation device is solved using the bottom-up approach according to the DP paradigm. The stopping criterion is set based on the enhancement of the power quality level and voltage sag mitigation.

Artificial Neural Network

Artificial neural networks (ANN) are computational techniques whose conception has been motivated from the current knowledge of biological neural networks [74]. The ANN approach is different mainly because of the instantaneous use of a large number of relatively simple processors and learning ability by example. These days, ANN models are effective tools for the identification and control of complex systems that cannot be easily solved in many research fields such as medicine, engineering, and economics [75]. The ANN has some countable advantages including the learning and control ability, adaptation to the data, appropriateness, and robustness. Nonetheless, the

ANN has some disadvantages such as large dimensionality, choice of the optimal configuration, and difficulty to select among various training methods.

In 2011, an ANN-based optimization approach was proposed to optimally locate the D-STATCOM in distribution systems to mitigate voltage sag [76]. The feed forward type of neural network is trained by post-fault voltage magnitude of three phases at different buses and different fault types to solve the optimization problem. In addition, the normal p.u. voltages of the different buses are considered as the output target data. After network training, some data are used to test the performances of the network and provide information about the most insecure bus of the system based on the highest deviation of the bus voltage from the target voltages. The bus with the highest deviation from the target is considered as the optimal location of D-STATCOM to mitigate the voltage sag problem.

Hybrid Optimization Techniques

Two or more optimization techniques should be combined to improve the performance of the optimization process to create a hybrid optimization system. During the last decade, hybrid systems have been applied in engineering applications.

In 2011, a stochastic-based assessment using the weighted sampling method and GA was proposed to optimize the cost of placing series compensation devices including DVR and a new type of CPD named Thyristor Voltage Regulator for voltage sag mitigation in distribution systems [34]. Due to the sensitivity of the GA results to parameters that govern the crossover and mutation process, the weighted sampling method is applied to simplify the problem using the probability densities of voltage sags, which are obtained from power quality surveys. After simplification of the problem, the GA as a global-search tool is applied to achieve reliable and fast convergence to determine the optimization solution.

Conclusion

This paper presents a survey of the work published on the application of different optimization techniques to solve the optimal placement and sizing problem of the CPDs in power distribution systems. This paper also considers a list of related published references as essential research guidelines in the field of optimal CPD placement and sizing to improve power quality. In addition, various kinds of single and hybrid optimization techniques that were used to address the problem are summarized and classified.

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