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Optimum placement of active power conditioner in distribution systems using improved discrete firefly algorithm for power quality enhancement

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ABSTRACT

This paper presents an improved solution for optimal placement and sizing of active power conditioner (APC) to enhance power quality in distribution systems using the improved discrete firefly algorithm (IDFA). A multi-objective optimization problem is formulated to improve voltage profile, minimize voltage total harmonic distortion and minimize total investment cost. The performance of the proposed algorithm is validated on the IEEE 16- and 69-bus test systems using the Matlab software. The obtained results are compared with the conventional discrete firefly algorithm, genetic algorithm and discrete particle swarm optimization. The comparison of results showed that the proposed IDFA is the most effective method among others in determining optimum location and size of APC in distribution systems.

Introduction

Over the past few decades, the occurrence of power quality disturbances such as harmonic distortion and voltage sag in distribution systems is increasing and is becoming of great concern. These disturbances may cause interruption in processing plants, resulting in hours of downtime and high turnover losses for utilities and customers. Therefore, the delivered power should be constantly monitored and improved to ensure that power quality is within pre-specified baseline [1,2]. The traditional solutions for power quality improvement are by applying passive harmonic filters and zig-zag reactors, nonetheless the best and most effective solution to mitigate power quality disturbances and protect sensitive equipment is to install proper types of custom power devices (CPDs) such as active power conditioner (APC), dynamic voltage restorer, static compensator and unified power quality conditioner [3]. The placement and sizing of the CPDs should be determined based on economic feasibility, in which optimization is usually considered in the procedure.

In the last two decades, various types of population based optimization algorithms such as bee colony-based approach [4], particle swarm optimization algorithm [5,6], cuckoo search algorithm [7,8], firefly algorithm [9,10] have been widely developed and applied in many industrial applications such as structural designs, milling operations and power systems [11]. In addition, hybrid evolutionary optimization algorithms such as hybrid Taguchi-differential evolution algorithm [12], hybrid differential evolution algorithm [13], hybrid immune algorithm [14], hybrid immune-hill climbing optimization approach [15], hybrid artificial bee colony algorithm [16] can be applied to increase the convergence speed and robustness in finding the global minimum [17].

From power systems point of view, many heuristic optimization techniques have been applied to address the optimal placement and sizing problems of CPDs by introducing different objective functions and constraints to minimize cost and disturbances such as voltage sag and harmonic distortion. A fuzzy system was applied to optimally locate APCs by minimizing harmonic distortion in active power systems [18]. Genetic Algorithm (GA) was applied to optimally place a dynamic voltage restorer and thyristor voltage regulator by minimizing the imposed costs due to the occurrence of voltage sags [19]. Genetic Algorithm was also used to solve the optimal placement problem of several types of flexible alternating current transmission system for improving the overall network sag performance of a power system [20]. An improvement to the conventional GA was then developed using the niching genetic algorithm which has the capability of exploring a wider search space to decrease the probability of convergence in local optima [21]. A solution to the problem of optimal placement of D-STATCOM

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was suggested by using the binary gravitational search algorithm to improve reliability of distribution systems [22]. The optimal placement and sizing of unified power quality conditioner for improving voltage and current profiles and reducing power was considered by using differential evolution algorithm [23].

In addition to the CPDs, many research works have also focused on the optimal placement of other devices such as capacitor banks and distributed generations (DG) for improving power quality by applying heuristic optimization techniques such as particle swarm optimization (PSO) [24,25], GA [26,27], combined GA and neural network [28], combined GA and PSO [29], sensitivity-based heuristic solution [30] and shuffled frog leaping algorithm [31]. Due to the discrete nature of the optimal placement and sizing problem of DG and CPD, discrete optimization techniques such as discrete nonlinear programming [32], GA [33] and discrete PSO (DPSO) [34,35] are also applied for minimizing harmonic distortion and improving system reliability.

In this paper, a new heuristic optimization technique is proposed using the improved discrete firefly algorithm (IDFA) for determining the optimal size and location of APCs. A multi-objective problem is formulated by minimizing the average voltage total harmonic distortion (THD_V), voltage deviation, and total investment cost including installation and incremental costs to improve overall power quality of the system. The voltage limits, APC capacity limits, power flow limits and THD_V for each individual bus are considered as constraints in the optimization problem. The performance of the proposed IDFA is then evaluated on the radial IEEE 16- and 69-bus test systems. To evaluate the effectiveness of the proposed IDFA, the results are also compared with the obtained results using other optimization techniques such as the conventional Discrete Firefly Algorithm (DFA), GA and DPSO.

Modeling of active power conditioner

APC is a parallel multi-function compensating device, which, depending on the available controller design, is able to mitigate voltage sag and harmonic distortion, performs power factor correction, and improves the overall power quality. The voltage–source converter is the main part of the APC, which converts the dc-link voltage into three-phase ac voltages with controllable amplitude, frequency and phase. Considering the steady-state APC losses such as transformer and inverter losses, an accurate load flow model of the APC should be obtained. Fig. 1 shows the schematic diagram of an APC and its Thevenin equivalent circuit with respect to bus N. From the figure, the injected current I_{APC} at bus N in fundamental and harmonic frequencies can be expressed as

$$I^h_{\text{APC}} = I^h_L - I^h_S = I^h_L - \frac{(V^h_S - V^h_N)}{Z^h_S} = \frac{(I^h_{\text{con}} Z^h_{\text{APC}} - V^h_N)}{Z^h_{\text{APC}}} \tag{1}$$

where, I_{APC} is the injected current by APC with phase angle δ_i; I_{con} is the Norton current with phase angle δ_{con}; I_S is the utility side current with phase angle θ_i; V_S is the utility side voltage with phase angle θ_v; V_N is the voltage at bus N with phase angle $\theta_{v\text{-}N}$; I_L is the load side current with phase angle λ_i; Z_S is the utility impedance; Z_{APC} is APC Norton impedance ($1/Y_{\text{APC}}$); h is harmonic orders, like $1, 2, 3, \ldots, H$.

Eq. (1) shows that the injected APC current I^h_{APC} can correct voltage sag, voltage variation and harmonic distortion at bus N by adjusting the voltage drop across the impedance Z_{APC} in the fundamental and harmonic frequencies.

To compute the bus voltage variations in fundamental and harmonic frequencies in the presence of APC, it is assumed that APC is added to the system as a PQ bus (the bus with the specified real power $|P|$ and reactive power $|Q|$) with impedance Z^h_{APC} between the existing bus N and the newly added virtual bus K in a M-bus system. Therefore, the new impedance matrix of the system should be modified based on Z^h_{APC} as [36]

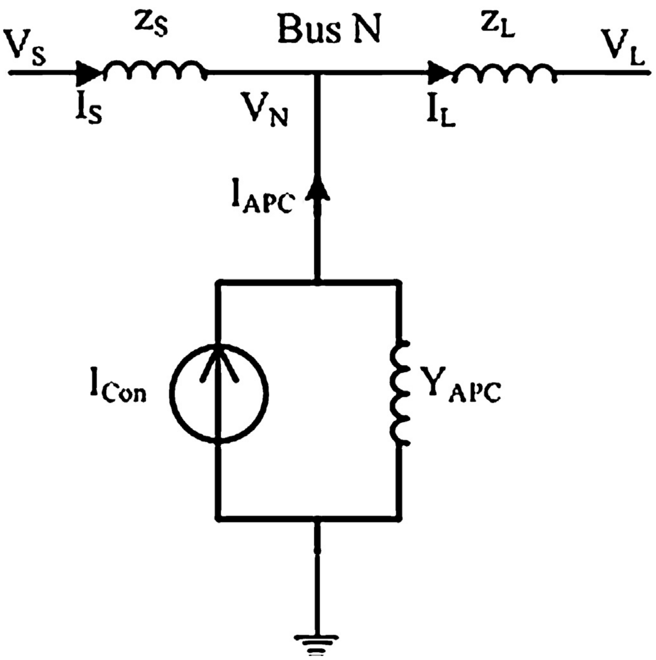

Fig. 1. APC single line Norton equivalent circuit.

$$Z^h_{\text{bus-new}} = \left[\begin{array}{ccccc} & & & & Z^h_{1N} \\ & & & & Z^h_{2N} \\ & & Z^h_{\text{old}} & & \vdots \\ & & & & Z^h_{MN} \\ Z^h_{N1} & Z^h_{N2} & \cdots & Z^h_{NM} & Z^h_{NN} + Z^h_{\text{APC}} \end{array}\right] \tag{2}$$

The new column accounts for the increase of all bus voltages due to Z^h_{APC}. Considering virtual bus K is short circuited to the reference node, the virtual bus K can be eliminated using the Kron reduction method on (2) as

$$Z^h_{hi\text{-new}} = Z^h_{hi} - \frac{Z^h_{h(M+1)} Z^h_{(M+1)i}}{Z^h_{NN} + Z^h_{\text{APC}}} \tag{3}$$

Hence, the bus voltages calculated at the fundamental and harmonic frequencies due to the presence of APC can be obtained using the modified impedance matrix (2) and (3) as

$$I^k_i = I^{\text{rel}}_i(V^k_i) + jI^{\text{Img}}_i(V^k_i) = \left(\frac{P_i + jQ_i}{V^k_i}\right)^* \tag{4}$$

$$V^h = Z^h I^h \tag{5}$$

where, $V_i{}^k$, $I_i{}^k$, I^{rel}_i and I^{Img}_i are the node voltage at the kth iteration, equivalent current injection at the kth iteration, and the real and imaginary parts of the equivalent current injection at the kth iteration, respectively. In addition, [V], [Z] and [I] are the bus voltage vector, system impedance matrix, and nodal injected current vector in fundamental and harmonic frequency.

Eqs. (4) and (5) can be solved using the backward/forward sweep method [37,38]. Note that the values of P and Q in (4) are positive for conventional PQ (load) buses and negative for bus with APC. The bus voltage at bus i in the fundamental and harmonic frequencies, and the voltage THD can be changed by altering the rating of the installed APC during the optimization process.