



Modified adaptive differential evolution based optimal operation and security of AC-DC microgrid systems

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ABSTRACT

The recent advancement in power electronic systems has enabled the formation of AC-DC microgrids by integration of DC microgrids into conventional AC grid. In this paper, an approach for optimal power flow (OPF) problem formulation in AC-DC microgrid networks is proposed. In the formulated AC-DC microgrid OPF problem, the objective functions considered for minimization are the total cost of generation in both the AC and DC networks and the cost of active power transfer from the AC grid to the DC microgrid. The OPF problem is subject to the limits of voltage magnitudes, power flows, and the AC-DC power electronic converter's limits. This paper also presents an approach to reformulate the nonlinear AC-DC OPF problem as an equivalent traditional AC OPF problem. A modified adaptive differential evolution algorithm is proposed to solve the non-convex AC OPF problem. Simulation studies are performed on an IEEE 30-bus and IEEE 39-bus test system connected to 6-bus and 9-bus DC microgrids under both normal operation and network contingency conditions. The results obtained on the test systems by the proposed approach confirm the validity of the developed approach.

1. Introduction

In the recent past, DC microgrids have received much attention as an excellent means of integrating distributed generation into the electricity grid [1,2]. Usually these autonomous networks are connected as single entities to the public distribution systems. These microgrids consists of different technologies such as photovoltaic systems and wind generators and are operated along with fuel cells, batteries and traditional high-inertia synchronous generators [3]. This increases the reliability due to energy generation in the vicinity of the loads, the utilization of small-scale generators and reduction in power losses overlong power lines. However, the integration of DC microgrids and conventional AC grids makes power network management a challenging task for system planners and operators.

The Optimal power flow (OPF) is an efficient tool for planning and operation of power systems subject to different operational and network constraints. The optimal power flow consists of solving set of equations which characterize the power system. It adjusts the control variables values in order to optimize a specific objective function [4]. The power system state is usually represented by state variables and independent variables. Control variables can be any of the independent variables in the system, and are selected depending on the purpose of the analysis.

Security constrained OPF (SCOPF) is an extended form of OPF,

which also includes security constraints of the power system. Owing to importance of security, especially in the modern power systems, more attention has been paid to SCOPF in recent years. A review of some SCOPF research works can be found in [5–7]. Also, the consideration of voltage stability aspect has become very important in the security analyses of power system planning and operation. The measurement of the severity level of voltage stability issues using different performance indices have been proposed [8]. These indices could be used for on-line or off-line to determine the closeness of the system to the voltage collapse. The minimum singular value has also been used as a static voltage stability index for voltage collapse assessment [9–10]. This index is evaluated using the power flow Jacobian, and tends to zero at the voltage collapse point. The disadvantage of this index is that approximate derivatives are required during the solution process, which may lead to convergence problems.

The voltage stability L-index [11], which is simple to evaluate, can be used to indicate the voltage security and can be easily included while constructing a novel OPF formulation for considering voltage stability margin of the system.

Moreover, the formation of the AC-DC microgrid network by the integration of DC microgrids to an AC grid, and security constraints along with voltage stability indices make the OPF problem as a non-convex optimization problem. The OPF problem consists of the power flow equations of both the traditional AC grid and DC microgrids and is

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subjected to the security constraints and the constraints imposed by the AC-DC converters [12–14]. The quadratic dependency on the bus voltages, and the non-linear power flow equations makes the non-convexity of the formulated problem and causes multiple local optimal solutions for the problem [15].

In the literature, one can find that many mathematical optimization techniques have been applied to solve the OPF problem such as; linear and nonlinear programming methods, quadratic programming and interior point methods [16–19]. The global optimum of all these techniques depends on the initial condition and convexity of the problem. Moreover these assumptions made in these methods can't enable the methods to find the global optimum solution when considering the various types of constraints. Ref. [20] provides a valuable introduction and surveys the classical optimization techniques.

Poor convergence, trapping in local optima and inability to offer great freedom for different objective functions and constraints are some of disadvantages of mathematical programming methods to solve OPF [5,7]. For solving SCOPF, these disadvantages become more highlighted. To remedy these drawbacks, OPF and SCOPF solution approaches based on stochastic search techniques have been presented in recent years.

To overcome the drawbacks of the mathematical programming techniques related to the initial condition and to the form of the specific objective function, new global optimization techniques are developed based on stochastic and heuristic aspects which includes; Genetic algorithm (GA) [21,22], Tabu search (TS) [23], Simulated annealing (SA) [24], Evolutionary programming (EP) [25], Particle swarm optimization (PSO) [26], Differential evolution (DE) [27], Harmony search (HS) [28], Artificial bee colony (ABC) [29], Biogeography based optimization method (BBO) [30,31], A modified Artificial bee (MABCA) [32], Shuffled frog leaping algorithm (SFL) [33], and Gravitational search algorithm (GSA) [34], block-hole-based optimization (BHBO) [35] differential search algorithm (DSA) [36,37] electromagnetism-like mechanism (EM) [38] teaching-learning-based optimization (TLBO) [39] imperialist competitive algorithm (ICA) [40] invasive weed optimization (IWO) [41] and league championship algorithm (LCA) [42] honey bee mating optimization (HBM) [43] and a new mutation based method called MHBMO have been used to solve OPF problems.

All these methods have been applied with great success for solving various problems related to power system operation and control. Ref. [17] provides a significant and valuable introduction and surveys the non-deterministic and hybrid optimization methods that were used for solving the different optimal power flow problems.

In the recent past, Differential Evolution (DE) which is a population-based, direct stochastic search algorithm, is proposed by Storn and Price [44], for optimization problems over a continuous domain. The advantages of DE are: simple to program, few control parameters, high convergence characteristics. The DE has been successfully applied to solve several engineering problems in different areas.

In this paper, the local search ability and the acceleration of the convergence of differential evolution algorithms are enhanced by proposing, a new mutation scheme. The new mutation scheme is formulated using the weighted difference vector which is evaluated from the best and the worst individual at a particular generation [45]. Further, the control parameters are also adapted [46] suitably to achieve a good performance property in the new method called modified adaptive differential evolution (MADE) algorithm. It has been shown that the MADE algorithm results in superior performance quick convergence in comparison with the existing evolutionary methods reported in the literature.

The following are the contributions of this paper:

- In the proposed method, the converter equations are tackled by merging the AC and DC side buses of each converter to form an equivalent AC bus in the system. Since the same operating point is maintained after replacing the DC microgrids with AC grids, one can

easily develop an AC-DC network model as an equivalent AC grid effectively.

- A novel approach is proposed to formulate AC-DC OPF problem as a traditional AC OPF appropriately and is solved by the MADE algorithm.
- Simulations are carried out on an IEEE 30-bus and 39-bus systems connected to a 6-bus and 9-bus DC microgrids to demonstrate the proposed approach performance. It is found that the proposed approach is able to achieve the global optimal solution and computationally feasible for large-scale AC-DC micro-grid networks.
- The rest of this paper is organized as follows. The converter model and AC-DC network are presented in Section 2. The Section 3 presents the approach to address AC-DC OPF problem. The Section 4 presents the OPF problem formulation. Section 5 describes the basic DE and MADE algorithms. Implementation of the proposed algorithm on the AC-DC OPF problem is presented in Section 6. In Section 7, the simulation results are presented. Finally, the conclusions are presented in Section 8.

2. AC-DC microgrid system model

Consider an AC-DC grid consisting of an AC grid connected to a set of DC microgrids denoted by $H = \{1, \dots, |H|\}$. The AC grid is represented by a tuple $\mathcal{C}_{ac}(\mathcal{N}_{ac}, \mathcal{L}_{ac})$, where $\mathcal{N}_{ac} = \{1, \dots, |\mathcal{N}_{ac}|\}$ and $\mathcal{L}_{ac}$ denote the sets of AC grid buses and transmission lines, respectively.

The DC microgrid $h \in H$ is represented by a tuple $\mathcal{O}_{dc}^h(\mathcal{N}_{dc}^h, \mathcal{L}_{dc}^h)$, where $\mathcal{N}_{dc}^h = \{1, \dots, |\mathcal{N}_{dc}^h|\}$ and $\mathcal{L}_{dc}^h$ denote the sets of buses and lines in DC microgrid h , respectively. operates with a power factor angle of $\phi_{r,s}^h$ represents the operating power factor angle of the converter connected between AC bus $r \in \mathcal{N}_{ac}$ and DC bus $s \in \mathcal{N}_{dc}^h$ of microgrid h . The converter converts AC voltage V_r to DC voltage V_s^h based on the following equation [47]

$$V_s^h = k_1 a_{r,s}^h |V_r| \cos(\phi_{r,s}^h) \quad (1)$$

where $k_1 = \frac{3\sqrt{2}}{\pi}$ is a constant and $|\cdot|$ denotes the voltage magnitude. The $a_{r,s}^h$ represents the transformer tap used for controlling the DC voltage level V_s^h .

Since the operating efficiency of the high-power converters is in the high 90% range, the AC-DC converter losses can be neglected for the purpose of simplicity. The active power $P_{r,s}^h$ flows from AC bus $r \in \mathcal{N}_{ac}$ to DC bus $s \in \mathcal{N}_{dc}^h$ in DC microgrid h through the converter. Since the power flow direction is determined by the operating point of the AC grid and the DC microgrid, a four quadrant AC-DC converter, e.g. pulse-width-modulation controlled voltage-source converter is assumed, and it also acts as a controllable reactive power compensator on its AC side. This converter can inject or absorb reactive power $Q_{r,s}^h$ to increase voltage regulation, power factor and stability in the AC grid [47]. The converter power factor is evaluated by using its active and reactive powers and can be represented as

$$\cos(\phi_{r,s}^h) = \frac{P_{r,s}^h}{\sqrt{(P_{r,s}^h)^2 + (Q_{r,s}^h)^2}} \quad (2)$$

Since the current amplitude of a converter would be within a specific upper limit [47] and the changes in the voltage magnitudes are negligible in power grids [48], the upper bound of the current amplitude can be replaced by the maximum apparent power flow $S_{r,s}^{h,\max}$ as the operation constraint. Let $S_{r,s}^{h,\max}$ denote the apparent power flow from AC bus $r \in \mathcal{N}_{ac}$ to DC bus $s \in \mathcal{N}_{dc}^h$ of microgrid h . We have

$$|S_{r,s}^h| = \sqrt{(P_{r,s}^h)^2 + (Q_{r,s}^h)^2} \leq S_{r,s}^{h,\max} \quad (3)$$

Fig. 1 shows an AC grid connecting to a DC microgrid by AC-DC converters between AC bus 2 and DC bus 3 in microgrid $\mathcal{O}_{dc}^1$. The parameter $\phi_{r,s}^h$, $P_{r,s}^h$, $Q_{r,s}^h$ represents the converter variables which are evaluated in the AC-DC OPF. The parameter $a_{r,s}^h$ is known by the system.

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