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An unequivocal normalization-based paradigm to solve dynamic economic and emission active-reactive OPF (optimal power flow)☆

Mahdi Pourakbari-Kasmaei*, Marcos J. Rider, José R.S. Mantovani

Department of Electrical Engineering, State University of Sao Paulo (UNESP), Ilha Solteira, Brazil

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This paper presents a straightforward compromising methodology of dynamic economic and emission AROPF (active-reactive optimal power flow). AROPF considering environmental effects is a highly nonlinear problem, and the dynamic consideration of such problems makes it even more complicated and extra-high nonlinear; find an appropriate compromising solution for such problems is considered as a complicated task. In one hand the traditional compromising methodologies cannot find an acceptable compromise point for large-scale systems, and on the other hand metaheuristic methods are time consuming. In this paper an UNBP (unequivocal normalization-based paradigm) is proposed, while instead of maximum output-based pollution control cost, an adaptive pollution control cost is used to consider the system topology in dynamic scheduling and under various system conditions such as normal, outage, and critical conditions. By using a normalization process and adaptive pollution control cost, a uniform compromising procedure is obtained. Three case studies such as 14-bus, 30-bus, and 118-bus IEEE test systems are conducted and results are compared to those reported in literature. Results confirm the potential, effectiveness, and superiority of the proposed UNBP compared to traditional and heuristic-based multi-objective optimization techniques.

1. Introduction

OPF (optimal power flow) is an extension of the conventional ELD (economic load dispatch). The ELD does not consider all the network and operating constraints and in order to have a proper power system, the consideration of some constraints such as active and reactive power balance, power flow limit, and also active and reactive power generation limits are unavoidably essential; then using a reliable and precise model to satisfy these constraints has always been a momentous issue. The idea of using a unified model to consider the aforementioned concerns was introduced by Carpentier in 1962 [1] with aiming to determine the power flow solution, optimizing an economic-oriented, security-oriented, or power quality-oriented problem. As the cost of power generation in fossil fuel-based power plants is exorbitant, the economic-oriented tools such as ELD and OPF, which can saves a considerable amount of money via an optimal solution, are considered as the kernel of a power system [2,3].

On the other hand, harmful environmental impacts of generating electricity are inseparable parts of each technology used in this regard. Among these technologies, the fossil-fuel-based power generating station, which releases sulfur oxides (SO_X), nitrogen oxides (NO_X), and carbon dioxide (CO_2) into atmosphere, is considered as the most environmentally harmful technology. These days, there is a growing concern for harmful environmental impacts [4,5]; that can affect human health. Air pollution, in particular, can cause a variety of environmental effects such as acid rain, eutrophication, haze, effects on wildlife, ozone depletion, crop, forest damage, and global climate change [6]. Since 1990, the CAAA (clean air act amendments), the utilities have to modify their design or operational strategies to deplete the pollution and atmospheric emissions [7,8]. From the operational standpoint, finding a proper compromise between operating cost and emission, which have conflicted objectives, is one of the most challenging problems for power systems.

Moreover, the reactive power has a key role on power systems to improve the transfer of Alternating Current power over transmission lines, and also it has a significant effect on power system reliability and efficiency of the power systems [9]. In addition, it has a close relationship with active power generation as the generation and transfer of reactive power yields to active power loss and therefore consumes energy. Then in order to consider its profound

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* Corresponding author. Avenida Brasil, 56, Bairro: Centro, 15385-000 Ilha Solteira, SP, Brazil.

E-mail address: mahdi.pourakbari@ieee.org (M. Pourakbari-Kasmaei).

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effect, using an AROPF (active-reactive optimal power flow) is taken into account and in this regard the capability curve as a nonlinear constraint is considered [10], [11]. For a synchronous generator operating at rated voltage, the capability curves give the maximum active and reactive power loadings that can be supplied with constant and maximum armature current, without armature heating limit or the field heating limit [12]. The conventional OPF problem is considered as a very large, non-linear mathematical programming problem; consequently the AROPF is a highly nonlinear problem in power system.

In DOPF (dynamic optimal power flow) problem, the ramping constraints couple the scheduling hour. A traditional approach for OPF with N units and T scheduling hour would require solving an optimization problem of size $N \times T$ and it is considerably a more complex problem than to solve the OPF of the N units system for T times [13], [14]. Moreover, the DEEOPF (dynamic economic and emission OPF) handles two conflicting objective functions of total cost and emission minimization in order to determine a compromise between costs and emissions. This, as a result, makes the problem an even more complex one. In this paper, the dynamic economic and emission compromise via an AROPF is taken into consideration. As the proposed methodology is so fast, it is applicable to real-time problems.

There are a lot of methodologies to find a solution for OPF problem where some of them are analytical, and the others are heuristic-based search methods. In Ref. [15], to consider the effects of power wheeling in a power system, a linear programming-based OPF (LP-based OPF) has been presented. In Ref. [16], the authors have presented a fast and efficient successive linear programming method to solve the environmental constrained OPF. A semismooth Newton-type algorithm that is a useful method to reduce the dual variables has been proposed in Ref. [17]. In Ref. [18], the application of a nonlinear programming-based OPF to allocate VAr support has been presented. In Ref. [19], W. Yan et al. have presented a decomposed predictor-corrector interior point method to solve reactive OPF. The heuristic-based algorithm is widely used in the OPF-based problems. A TLBO (teaching–learning-based optimization) technique has been presented in Ref. [20]. TLBO is a robust method that can provide effective and high-quality solutions. In Ref. [21], a multi-hive bee foraging algorithm has been proposed to solve the multi-objectives OPF problem where in this paper three objectives such as cost, emission, and loss have been considered. In Ref. [22], to find the optimal choice and allocation of FACT devices, a genetic-based OPF has been presented such that the rate and type of FACT devices can be optimized simultaneously. In Ref. [23] the authors have been applied an evolutionary programming to allocate the FACTS devices in order to maximize the TTC (total transfer capability) of power transmission; in this regard, a multi-objective OPF with FACT devices that includes TTC and penalty functions has been used. A MSFLA (modified shuffle frog leaping algorithm) to solve the multi-objective OPF problem has been proposed in Ref. [24] where two conflicting objectives of cost and emission have been considered. Moreover, some works have considered the combination of two or more techniques in order to modify the drawbacks of the aforementioned methods. In Ref. [25], a combination of evolutionary algorithm and classic deterministic method to solve the transient-constrained OPF has been proposed. A genetic evolving ant direction differential evolution was presented in Ref. [26] to solve the OPF problems with non-smooth cost function while an innovative statistical analysis was considered. In Ref. [27] a sequential quadratic programming combined by a differential evolution algorithm, which has the potential to solve the problem with more non-convexity, was proposed. Also in the literature, there are numerous methods that can be harnessed in order to make a compromise between emissions and costs, such as conventional, heuristic and hybrid methods. In Ref. [28] an analytical solution which has a superiority in CPU time than the classical method has been applied to joint economic and emission dispatch problem. In Ref. [29] a hybrid method of PSO (particle swarm optimization) and evolutionary programming has been proposed and results show its high quality performance. A hybrid PSO and gravitational search has been proposed in Ref. [30] to solve economic and emission dispatch by considering practical constraints such as ramp-rate, valve-point, and prohibited operating zones. The conventional methods mentioned in the literature mostly use a constant pollution control cost and usually these methods cannot make a good compromise. The metaheuristic methods are time consuming and are not good for such real-time problems [31], [32]. Several methods have been used to solve DOPF, e.g. a Benders decomposition method to solve DOPF has been proposed in Ref. [33] that is a useful method for a deregulated power market. In Ref. [34] a modified HBMO (honey bee mating optimization) technique has been proposed; modification on mutation of this technique overcomes the main drawback of HBMO, probability of trapping in local minimum. An enhanced charged system search algorithm has been proposed. In Ref. [35] to solve the reserve constrained DOPF considering valve-point, prohibited operating zones, and multi-fuel constraints, an enhanced charged system search algorithm has been proposed. In Ref. [36] a reduced gradient method, which is a successful methods for solving the OPF problem, has been used to solve the multi-stage dynamic optimal power flow considering wind power integrated system. In Ref. [14] a predictor–corrector interior point has been used to solve dynamic OPF problems where in order to avoid unnecessary computation, an inequality iteration strategy was introduced.

This paper aims at contributing to: 1) introducing an APCC (adaptive pollution control cost) for compromising problem regarding to [5] and 2) the presentation of a paradigm based on a normalization theory in order to find an acceptable compromise between costs and emissions via a dynamic active-reactive optimal power flow. Moreover, in power systems, unexpected generator outages or transmission line failures and the unanticipated spikes in the demand, yields inevitable fluctuations in the voltage and frequency [37]. Then, in order to show the effectiveness of the proposed methodology, three case studies of 14-bus, 30-bus, and 118-bus IEEE test systems under various system conditions such as normal, outage, and critical conditions are conducted.

The rest of this paper is organized as follows. Section 2 contains the proposed compromising strategy of UNBP (unequivocal normalization-based paradigm) methodology and its application to the dynamic economic and emission AROPF problem. In order to show the performance of the UNBP method, case studies and results are in Section 3. Section 4, contains the concluding remarks.

2. Problem formulation

The objective of a dynamic economic and emission AROPF problem is to derive the optimal output of generators. These involve assessing the operating costs and how much corresponding emissions would be produced in order to make an acceptable compromise during the scheduling time horizon while satisfying network and operating constraints. The role of a good compromising strategy as incontrovertible would then be the result.

2.1. Compromising strategy

From an engineering standpoint, compromise is an agreement between two different objectives. While each objective accepts less than what they want, the situations are changed slightly so that they can exist together. In power systems, finding an acceptable