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System reduction techniques for storage allocation in large power systems

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ABSTRACT

Semi-Definite Relaxation (SDR) techniques for AC optimal power flow (OPF) have recently been proposed as a means of obtaining a provably global optimal solution for many IEEE benchmark power systems. Solving the resulting semi-definite programs (SDP) can, however, be computationally intensive. Therefore new algorithms and techniques that enable more efficient computations are needed to extend the applicability of SDP based AC OPF algorithms to very large power networks. This paper proposes a three-stage algorithm for AC OPF based storage placement in large power systems. The first step involves network reduction whereby a small equivalent system that approximates the original power network is obtained. The AC OPF problem for this equivalent system is then solved by applying an SDR to the non-convex problem. Finally, the results from the reduced system are transferred to the original system using a set of repeating optimizations. The efficacy of the algorithm is tested through case studies using two IEEE benchmark systems and comparing the solutions obtained to those of DC OPF based storage allocation. The simulation results demonstrate that the proposed algorithm produces more accurate results than the DC OPF based algorithm.

1. Introduction

Optimal Power Flow (OPF) plays an important role in power system planning and operations. It is used for determining operating parameters, such as bus voltages as well as real and reactive power flows, such that some objective functions such as total system losses or generation costs are minimized.

The OPF problem is nonlinear and non-convex, thus direct applications of nonlinear optimization methods provide no guarantee that the obtained solution is the global optimum [1,2]. Sub-optimal solutions can lead to higher costs and inefficiency in power system operations. Therefore, there has been great deal of research into different solution techniques that can be used to approximate the globally optimal solution of the OPF problem. Linear approximations, for example, use operational knowledge and mathematical approximations to linearize the OPF problem. The most common linear approximation is the DC OPF, which assumes that the voltage angle differences between adjacent buses in the network are small, the lines are lossless (i.e. their resistances are negligible) and that the voltage magnitudes are constant (usually with a value of 1 p.u.) [3]. Moreover, branch and bound algorithms (B&B) seek the globally optimal solution of the OPF problem by partitioning the search space of the problem [4]. On the other hand, heuristic algorithms, like decomposition techniques use the structure of the problem to subdivide it into some simpler subproblems [5]. Convex relaxations, such as second-order-cone relaxations (SOCR) or semi-definite relaxations (SDR) [6–10] approximate the original OPF problem by relaxing the problem search space to a larger convex space. The resulting relaxation is a convex problem that is known to have a globally optimal solution, under some technical conditions [9]. The SDR and SOCR are exact for a number of different network topologies including all of the IEEE benchmark examples [10–12].

One important challenge to the wide spread application of the SDR approach to solve the OPF problem is that semi-definite programming (SDP) algorithms can be computationally intensive [13]. Thus, solving SDPs for large systems over multiple time steps is likely to require decomposition algorithms or other fast solution methods such as those discussed in e.g. [14].

One important application of OPF which has recently been studied in e.g. [15–18] is OPF-based energy storage scheduling and allocation. Energy storage has received a great deal of attention in the

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recent literature as it can be used to help maintaining the power balance in the face of uncertainty, caused by the addition of renewable energy [16,17].

SDP based approaches have been generalized to study storage dispatch and allocation using an AC OPF formulation [15,19,20]. However, including energy storage in the OPF problem increases the complexity due to the addition of a temporal dimension in the optimization problem.

This paper provides an alternative approach for reducing the computational complexity of an OPF based storage allocation problem. Rather than using a distributed algorithm to solve the OPF with storage problem, as is proposed in [14] for the static OPF problem, we instead propose using a system reduction technique. The storage allocation problem is particularly amenable to system reduction because in many situations there is a small set of candidate buses for locating the energy storage resources. Thus, it is not necessary to consider the rest of the system buses in the allocation problem and a technique that allows merging the rest of the system buses with the candidate buses and evaluating this reduced system may help reduce the computational complexity of the problem.

The proposed procedure involves a three-stage algorithm, where we first reduce the original large system to a smaller equivalent system. In the second stage, this equivalent system is solved using an SDP. Finally, the solution obtained for the equivalent system is transferred to the original system using a set of repeating optimizations for all of the merged buses. In each of these optimizations, one of the merged buses is replaced by its original network and the storage assigned to this merged bus is distributed over the candidate buses of this network.

System reduction techniques have long been used for power system studies [21,22]. Reduction techniques can be divided into static, dynamic, and market based approaches, some important examples of each of these are reviewed and classified in [21]. All techniques require both a partitioning criterion and an algorithm that implements the associated partitioning rules. The admittance and flow capacity of the lines are both evaluated as partitioning criteria in this paper. For both cases we employ a spectral partitioning algorithm, which applies graph theory based techniques to partition the original system into smaller sub-systems, see e.g. [23,24].

The algorithm for storage allocation that is proposed here is validated in two steps. First, we test system reduction methods for each of the two partitioning criteria using the topologies of the IEEE 14 and 30 bus test systems [25] as well as the Polish 3120 bus system [26]. The simulations of both of these IEEE test systems are done over a 24-h period and solved via an SDP, whereas the Polish system is simulated using the MATPOWER toolbox at a small number of time steps, due its large size. For each case, the simulation results show that the equivalent systems accurately reproduce the behavior of their corresponding original systems.

In the second step of the validation process, the proposed three-stage algorithm is applied to solve the storage allocation problem proposed in [20] for the IEEE 14 and 30 bus test networks [25]. The storage allocation problem for both of the IEEE test systems and their corresponding reduced equivalents are solved over a 24-h period using an SDP. The results are then compared to those of a DC OPF based formulation for storage allocation using the full IEEE test systems. The results demonstrate that the proposed approach provides more accurate results but that the computational efficiency of the DC OPF based approach is higher. There is therefore a tradeoff between the accuracy that can be obtained and the computational resources required. Please note that the DC OPF and the method proposed in this paper are both approximated methods for the original problem and used when the original problem cannot be solved due to complexity and intractability. Thus, the solutions provided by both of these methods are also approximations of the globally optimum solution of the problem. In other words, DC OPF uses a linear approximation of AC OPF formulation for solving the OPF for the original system, while the method proposed in this paper uses the SDR techniques to solve an exact AC OPF for the equivalent system. Thus, both methods include approximations and, therefore, their resulting errors as well as their computational complexity reductions are compared in this paper. Future research should also compare the proposed method with other approximations, e.g., heuristic approaches, which are used when exact AC OPF for the original system cannot be solved.

It is important to note that the paper aims to propose an approach to reduce the computational complexity of storage allocation problem in large scale power systems. Thus, the paper does not discuss the accuracy of the SDP relaxation and if the SDP is not exact and other techniques should be used for the storage allocation problem, the method proposed in this paper is still valid and could be used to reduce the computational complexity of the problem.

The main contributions of this paper are as follows. First and foremost, the paper proposes a three-stage algorithm for solving the problem of storage system placement in large power systems based on AC OPF. Secondly, two different similarity indices, i.e., the admittance matrix and the available flow capacity for system lines, are used in the power system reduction stage. Thirdly, the SDR is applied to the non-convex AC OPF problem to obtain the globally optimal solution of the reduced problem. The results are transferred back to the full system via repeating optimizations. Finally, the proposed algorithm is validated through different verifying assessments.

The remainder of the paper is organized as follows. Section 2 reviews the proposed three-stage algorithm for applying the power system reduction techniques to the problem of OPF based storage allocation. The results of the two validation steps described above are discussed in Section 3. Section 4 concludes the paper.

2. The three-stage algorithm

This section details the three-stage algorithm used to solve the OPF based storage allocation problem discussed above.

2.1. Stage 1: Power system reduction

The system reduction comprising the first stage of the three-stage algorithm proposed herein requires a suitable partitioning criterion and an associated algorithm. In what follows, we provide a short description of the criterion and algorithm.

In order to reduce a power system, the system buses should first be partitioned into some groups. Then, the buses located in each group should be aggregated. Thus, the power system reduction consists of two important steps, namely power system partitioning and aggregation [27]. The first step is, however, more important since the buses located in each group can be easily merged once the power system partitioning is done. Thus, this step will be explained in detail.

The start point in partitioning the system is finding a functional relation among the system buses. This relationship can be represented by a so-called similarity matrix which shows the strength of connection between each pair of the system buses. This similarity matrix can be obtained based on static, dynamic, or economic aspects of the power system [21]. Depending on the application, a combination of these aspects may also be used for system partitioning [21]. Thus, it is important to choose the appropriate similarity matrix. In this paper, we select two different similarity