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Dynamic Reconfiguration of Electrical Power Distribution Systems with Distributed Generation and Storage ⋆

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Abstract: In this paper we present a nonlinear model predictive control strategy for dynamic reconfiguration of electrical power distribution systems with distributed generation and storage. Even though power distribution systems are physically built as interconnected meshed networks, as a rule, they operate in a radial topology. The network topology can be modified by changing status of the line switches (opened/closed). The goal of the proposed control strategy is to find the optimal radial network topology and the optimal power references for the controllable generators and energy storage units that will minimize cumulative active power losses while satisfying operating constraints. By utilizing recent results on convex relaxation of the power flow constraints, the proposed dynamic reconfiguration algorithm can be formulated as a mixed-integer second order cone program. Furthermore, if polyhedral approximations of second order cones are used then the underlying optimization problem can be solved as a mixed-integer linear program. Performance of the algorithm is illustrated on a small simulation case study based on actual meteorological and consumption data.

Keywords: model predictive control, dynamic reconfiguration, power distribution system, optimal power flow, convex relaxation, mixed-integer programming, conic programming

1. INTRODUCTION

Reliable and efficient functioning of electrical power distribution systems, which comprise numerous interacting components (e.g. distributed energy sources, storage units, distribution network, and large and small consumers), is becoming increasingly important due to the growing penetration of distributed intermittent energy sources in power distribution systems. The dynamic interaction of locally managed components gives rise to complex dynamic behavior of the overall system and can lead to large-scale disruptions, i.e. black-outs in the electric grid. Hence, to achieve optimal operation of the power system, the operator (controller) must take this dynamic behavior into account. Moreover, power distribution systems are built as interconnected meshed networks but they, as a rule, operate in a radial topology. Since the topology of the network can be modified by changing the opened/closed status of line switches, the optimal management of the overall system has to find the optimal configuration of the network.

The Optimal Power Flow (OPF) problem has been recognized as the fundamental problem in power system operation since the first formulation by Carpentier (1962). Since then the OPF has been studied extensively and a great number of methodologies and algorithms have been developed to solve the problem (Dommel and Tinney (1968); Frank et al. (2012)).

Distribution System Reconfiguration (DSR) problem extends the OPF problem with binary variables modeling the switching actions in the network and aims to find the network topology that will ensure the minimal power losses in the network. The DSR problem can generally be modeled as a Mixed-Integer Nonlinear Program (MINLP). Historically, most of the methods for network reconfiguration relied on heuristics (Merlin and Back (1975)) and artificial intelligence techniques (Ramos et al. (2005); Carreno et al. (2008)). Although these algorithms are generally easy to implement and sometimes very fast on practical networks, global solution optimality is not guaranteed and cannot be formally verified.

Global deterministic optimization methods for solving both the OPF and the DSR problem have attracted a great deal of attention recently. This development has been mostly due to the convex relaxation of the non-convex network constraints that was first proposed by Jabr (2006). In the work by Jabr et al. (2012), the DSR problem is formulated as a Mixed-Integer Second Order Cone Program (MISOCP). A linear model of the network where loads are represented as constant current sources in parallel with constant impedance is proposed in work by Ahmadi and Marti (2015). The optimization problem they consider is formulated as a Mixed-Integer Quadratic Program (MIQP).

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The conventional OPF and DSR problem formulations are essentially static optimization problems, i.e. a steady-state operation of the power network is assumed. In order to take into account the dynamics in the power network, we propose a closed-loop Nonlinear Model Predictive Control (NMPC) strategy based on the MISOCP formulation of the DSR problem by Jabr et al. (2012). The MISOCP formulation can be reduced to the Mixed-Integer Linear Programming (MILP) formulation using the polyhedral approximation of the second order cone introduced by Ben-Tal and Nemirovski (2001). For simplicity, in this paper we model only battery storage dynamics, although any other component with (piecewise) linear dynamics can be modeled in a similar manner. In work by Gayme and Topcu (2013), the Semidefinite Programming (SDP) formulation of the OPF problem has been extended with storage dynamics, but they do not consider the network reconfiguration and they implement the control action in an open-loop manner. Jabr (2014) investigated the open-loop DSR formulation but dynamics of various components was not taken into account.

We pay special attention to the problem of ensuring the radiality of the network. Note that the constraints used by Jabr (2014) are necessary but generally not sufficient to ensure the radial topology of the network (cf. Lavorato et al. (2012); Ahmadi and Marti (2015)). For a special case when the power distribution system can be represented with a planar graph, we use a formulation of the radiality constraint based on the idea by Williams (2002).

The rest of this paper is organized as follows. The control problem considered herein is introduced in Section 2. In Section 3 a mixed-integer formulation of the control problem is derived. A closed-loop NMPC algorithm is described in Section 4. Finally, a simple simulation case study is used to verify the performance of the proposed algorithm in Section 5. Concluding remarks are given in Section 6.

2. PROBLEM SETUP

Consider a power network represented by the graph $G = (\mathcal{V}, \mathcal{E})$, where $\mathcal{V} := \{1, 2, \ldots, n\}$ is the set of nodes, and $\mathcal{E} \subseteq \mathcal{V} \times \mathcal{V}$ is the set of flow lines (i, j), where $i, j \in \mathcal{V}$ and $i \neq j$. Let $N(i)$ denote a set of all nodes adjacent to node i, i.e. $N(i) := \{j \mid (i, j) \in \mathcal{E}\}$. Node n is designated as the root of the network and represents the substation node, e.g. the node that connects the distribution network to the rest of the power system. Let $\widetilde{\mathcal{V}} := \{1, 2, \ldots, n-1\}$ denote all nodes except the substation node n. Each node, except the substation node, may have photovoltaic (PV) generation, battery storage, and loads connected to them. It is assumed that all lines are equipped with switches and can participate in the reconfiguration of the network topology. In the following, to simplify notation, we associate with each line $(i, j) \in \mathcal{E}$ a unique index $\ell \in \{1, 2, \ldots, m\}$, where m is the total number of lines. We define the following variables and parameters of the system model:

- $\mathcal{G} \subseteq \widetilde{\mathcal{V}}$, the set of nodes with PV generation.
- $\mathcal{B} \subseteq \widetilde{\mathcal{V}}$, the set of nodes with battery storage.
- $\mathcal{D} \subseteq \widetilde{\mathcal{V}}$, the set of nodes with loads.
- P_t^{S} and Q_t^{S}, the active and reactive power of the substation connected to node n at time instant t.
- $P_{i,t}^{\mathrm{D}}$ and $Q_{i,t}^{\mathrm{D}}$, the active and reactive power of the load connected to node $i \in \mathcal{D}$ at time instant t.
- $P_{i,t}^{\mathrm{PV}}$ and $Q_{i,t}^{\mathrm{PV}}$, the active and reactive power of the PV generator connected to node $i \in \mathcal{G}$ at time instant t.
- $x_{i,t}^{\mathrm{BAT}}$, the amount of battery storage connected to node $i \in \mathcal{B}$ at time instant t.
- $P_{i,t}^{\mathrm{BAT}}$, the rate of charge/discharge of battery storage connected to node $i \in \mathcal{B}$ at time instant t.
- $Q_{i,t}^{\mathrm{BAT}}$, the reactive power of the battery storage connected to node $i \in \mathcal{B}$ at time instant t.
- $V_{i,t}$, the voltage magnitude at node $i \in \mathcal{V}$ at time instant t.
- $\theta_{i,t}$, voltage angle at node $i \in \mathcal{V}$ at time instant t.
- $\theta_{ij,t}$, voltage angle difference between nodes $i \in \mathcal{V}$ and $j \in \mathcal{V}$, $(i, j) \in \mathcal{E}$, at time instant t, $\theta_{ij,t} = \theta_{i,t} - \theta_{j,t}$.
- $P_{ij,t}$ and $Q_{ij,t}$, the active and reactive power transferred from node $i \in \mathcal{V}$ to the rest of the network through line $(i, j) \in \mathcal{E}$ at time instant t.
- $\delta_{ij,t}$, the switching status of line $(i, j) \in \mathcal{E}$ at time instant t, i.e. $\delta_{ij,t} = 1$ means the line is switched on and $\delta_{ij,t} = 0$ means the line is switched off. Note that each $\delta_{ij,t}$ can be also denoted by $\delta_{\ell,t}$.

The circuit model of the power network can be derived by replacing every transmission line and transformer with their equivalent Π-models (Kundur (2004)). In this circuit model, for each line $(i, j) \in \mathcal{E}$, let $z_{ij} \in \mathbb{C}$ denote its impedance (with $r_{ij} = \Re\{z_{ij}\}$ and $x_{ij} = \Im\{z_{ij}\}$), and $y_{ij} = z_{ij}^{-1}$ its admittance (with $g_{ij} = \Re\{y_{ij}\}$ and $b_{ij} = \Im\{y_{ij}\}$).

For every node $i \in \widetilde{\mathcal{V}}$ of the network, the following constraints on active and reactive power injection ($P_{i,t}^{\mathrm{I}}$ and $Q_{i,t}^{\mathrm{I}}$, respectively) must be ensured at every time instant t:

$$P_{i,t}^{\mathrm{I}} = P_{i,t}^{\mathrm{PV}} + P_{i,t}^{\mathrm{BAT}} - P_{i,t}^{\mathrm{D}} = \sum_{j \in N(i)} \delta_{ij,t} P_{ij,t}, \ \forall i \in \widetilde{\mathcal{V}}, \quad \text{(1a)}$$

$$Q_{i,t}^{\mathrm{I}} = Q_{i,t}^{\mathrm{PV}} + Q_{i,t}^{\mathrm{BAT}} - Q_{i,t}^{\mathrm{D}} = \sum_{j \in N(i)} \delta_{ij,t} Q_{ij,t}, \ \forall i \in \widetilde{\mathcal{V}}, \quad \text{(1b)}$$

where $P_{ij,t}$ and $Q_{ij,t}$ are computed as follows:

$$P_{ij,t} = g_{ij} V_{i,t}^2 - V_{i,t} V_{j,t} \left(g_{ij} \cos\theta_{ij,t} + b_{ij,t} \sin\theta_{ij,t} \right), \quad \text{(2a)}$$

$$Q_{ij,t} = V_{i,t} V_{j,t} \left(b_{ij} \cos\theta_{ij,t} - g_{ij} \sin\theta_{ij,t} \right) - b_{ij} V_{i,t}^2. \quad \text{(2b)}$$

Substation located at node n connects the power distribution network to the rest of the power system. It is assumed that the substation provides the balance of active and reactive power in the distribution network:

$$P_{n,t}^{\mathrm{I}} = P_t^{\mathrm{S}} = \sum_{j \in N(n)} \delta_{nj,t} P_{nj,t}, \quad \text{(3a)}$$

$$Q_{n,t}^{\mathrm{I}} = Q_t^{\mathrm{S}} = \sum_{j \in N(n)} \delta_{nj,t} Q_{nj,t}, \quad \text{(3b)}$$

where $P_{nj,t}$ and $Q_{nj,t}$ are computed as in (2).

The voltage magnitude at node $i \in \mathcal{V}$ lies within predefined lower and upper bounds $\underline{V}$ and $\overline{V}$, respectively:

$$\underline{V} \leq V_{i,t} \leq \overline{V}, \ \forall i \in \mathcal{V}. \quad \text{(4)}$$