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IFAC-PapersOnLine 49-22 (2016) 085–090

Exploitation of uncertain weather forecast data in power network management ⋆

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Abstract: In power network management, the heat capacity of transmission lines originally arises from the line temperature constraint. The line temperatures are affected not only by the Joule heat but also by the thermal environment. This motivates us to exploit weather forecast data to improve the power management performance. The goal of this paper is to propose a stochastic model predictive control scheme for this purpose. In particular, we compensate for the probabilistic uncertainty by means of chance constraint optimization. The effectiveness of the proposed control scheme is examined through numerical simulation of power grids under the area dependent uncertainty and transmission line failure.

Keywords: Stochastic model predictive control, Applications, Electric power systems, Electrical network, Parallel circuit transmission lines

1. INTRODUCTION

Recent power grids are going green and smart (Amin and Wollenberg (2005); Farhangi (2010); Chakrabortty and Ilic (2012)). Several renewable energies are now available in practice and a variety of current sensor and network technologies serve the real time monitoring, automatic operating technology of the power flow. Furthermore, the prediction techniques of climates, demands of the power have been developed and the accuracy of the prediction has been improved.

However, it is still difficult to predict the amount of the renewables, the demands, and the climates with high accuracy. These large prediction errors can make the grid fragile; for example, too much power transmittance can damage the transmission lines and electric facilities, which causes blackout, breaking of wire, and other serious accidents. Therefore, it is necessary to handle the power generation with taking into account the prediction errors.

To avoid such a situation, the power generators conventionally had to transmit the power under the allowable current. This approach only considers the steady state of the heat dynamics of the transmission lines, and therefore is conservative. As this conservative method tends to cost the fuel, other approaches to protect the transmission lines have recently been proposed (Banakar et al. (2005); Olsen et al. (2013); Sugihara et al. (2015); Alguacil et al. (2005); Almassalkhi and Hiskens (2015a,b); Adrees and Milanovic (2016)). In particular, since the damage of the transmission lines is mainly caused by their Joule heat, the heat of the transmission lines has directly been considered (Banakar et al. (2005); Sugihara et al. (2015); Almassalkhi and Hiskens (2015a,b)).

Almassalkhi and Hiskens (2015a) proposed a model predictive control (MPC) scheme to manipulate a given power grid with storages and renewables in a deterministic manner. However, as mentioned above, it is preferable to consider the randomness due to the prediction errors directly and we should clarify how the randomness affects the temperature of the transmission lines.

In this paper, we consider an optimization problem to minimize the generation cost by the stochastic MPC for a given power grid with transmission line temperature fluctuation. Transmission lines are usually outside and exchange the heat energy with the environment whose temperature is predicted with errors. Since the temperature around each transmission line depends on the area and the prediction accuracy and the power generation cost of each generator is usually different, we examine how the difference of prediction errors affects the total generation cost numerically. Furthermore, we investigate a power system that consists of parallel circuit transmission lines and one of its transmission lines is broken. For simplicity, we only consider parallel single-circuit lines in this paper. Since transmission lines are necessary to be a carrier of power supply even if some of them are accidentally broken, parallel transmission lines are used to assure reliability in general. If one of the parallel lines is broken, the electric current of the other line doubles and increases the line temperature drastically. We examine single circuit fault on the parallel-single circuit lines while the proposed stochastic MPC scheme is being applied and check how it works well.

⋆ This work was supported by CREST, JST.

10.1016/j.ifacol.2016.10.377

The remainder of this paper is organized as follows. The model of the power grid and the dynamics of the transmission lines are introduced in Section 2. We also set an optimization problem of power generation scheduling in the section and give a relaxation to a quadratic programming problem in Section 3. The numerical results is shown in Section 4 and we summarizes the paper in Section 5.

Throughout this paper, we use following notations: $\mathbb{R}$ and $\mathbb{C}$ are real numbers and complex numbers, respectively, and $j := \sqrt{-1}$. E_n denotes n-dimensional identity matrix. $\otimes$ denotes the Kronecker product and I^* implies complex conjugate of $I \in \mathbb{C}$.

2. MODEL

2.1 Power grid and line temperatures

In this paper, we consider the network model that consists of middle transmission lines and the electrical property of each line is described by the Π model (Kundur (1994)). Let $\mathcal{G} := (\mathcal{V}, \mathcal{E})$ be an undirected and connected graph representing the network of a given power grid, where $\mathcal{V} := \{1, \ldots, n\}$ is a set of all nodes and $\mathcal{E}$ is a set of edges. We assume that all edges have same admittance $g(j\omega)$. Each node represents a consumer or a generator in the grid, and each edge represents the corresponding transmission line. We sort the nodes so that $\{1, \ldots, n_g\}$ are the generators.

Assume that all transmission lines have same mechanical and electrical properties in this paper. Let $\dot{Y}' \in \mathbb{C}^{n\times n}$ [S] be the node-admittance matrix of $\mathcal{G}$ defined by

$$\dot{Y}' := g(j\omega)L + H(j\omega),$$

where $L \in \mathbb{R}^{n\times n}$ is the graph Laplacian of $\mathcal{G}$, $g(j\omega) \in \mathbb{C}$ [S] is a admittance of transmission line, $H(j\omega) \in \mathbb{C}^{n\times n}$ [S] is a diagonal matrix which reflects small load of the corresponding node, and $\omega \in \mathbb{R}$ is a fixed angular velocity. For given node-admittance matrices $\dot{Y}_1, \dot{Y}_2 \in \mathbb{C}^{n\times n}$ of $\mathcal{G}_1$ and $\mathcal{G}_2$, respectively, the admittance matrix $\dot{Y}_{\text{par}} \in \mathbb{C}^{2n\times 2n}$ of parallel single-circuit lines are modeled as

$$\dot{Y}_{\text{par}} := \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} \otimes \dot{Y}_1 + \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} \otimes \dot{Y}_2, \tag{1}$$

Then the reduced node-admittance matrix $\dot{Y} \in \mathbb{C}^{n\times n}$ is

$$\dot{Y} := ([1\ \ 0] \otimes E_n)\, \dot{Y}_{\text{par}} \left(\begin{bmatrix} 1 \\ 0 \end{bmatrix} \otimes E_n \right). \tag{2}$$

Then, describing the voltage in phasor representation of node k by $\dot{V}_k$ [V], the current $\dot{I}_k$ [A] at the node k is calculated by the Kirchhoff's law; $\dot{I}_k := \sum_{l=1}^{n} \dot{Y}_{kl}\dot{V}_l$. The active and reactive powers of node k are described as P_k [W] and Q_k [var], respectively, and they should satisfy the following power flow equations:

$$P_k := \mathrm{Re}\left(\dot{V}_k \dot{I}_k^*\right) = V_k \sum_{l=1}^{n} V_l Y_{kl} \cos(\theta_l - \theta_k - \phi_{lk}), \tag{3}$$

$$Q_k := \mathrm{Im}\left(\dot{V}_k \dot{I}_k^*\right) = V_k \sum_{l=1}^{n} V_l Y_{kl} \sin(\theta_l - \theta_k - \phi_{lk}), \tag{4}$$

where $\dot{V}_k = V_k e^{j\theta_k}$ and $\dot{Y}_{kl} = Y_{kl} e^{j\phi_{kl}}$, and since the voltage V_{kl} of each node usually fluctuates small, assume that every V_{kl}, $(k,l) \in \mathcal{E}$ is a given constant. Furthermore, since we only use the difference of the phases $\{\theta_k\}$, we assume that $\theta_1 = 0$, i.e., node 1 is the reference node. We use the active powers of generators as control inputs,

$$u := \left(P_1,\ P_2,\ \cdots,\ P_{n_g} \right). \tag{5}$$

The rest of active powers are consumers' demands, which are assumed to be given *a priori*.

The dynamics of the line temperatures is driven by the power flow fluctuations and meteorological conditions. Each line temperature $\tilde{T}_{kl}$ [°C] at the line $(k,l) \in \mathcal{E}$ is described by the line heat balance equation (Banakar et al. (2005)). Since the absorption of heat solar radiation and the dissipation heat are small enough in our setting, we consider the following simplified dynamics; for each $(k,l) \in \mathcal{E}$,

$$\frac{d\tilde{T}_{kl}(t)}{dt} = \frac{R_{ac}(\tilde{T}_{kl}(t)) I_{kl}(t)^2}{C} + \lambda (T_{kl}^{out}(t) - \tilde{T}_{kl}(t)), \tag{6}$$

where C is the thermal line capacitance, $I_{kl}(t)$ is the line current at time t, $R_{ac}(\tilde{T}_{kl})$ is the line resistance, λ is the thermal diffusivity of the transmission line, and $T_{kl}^{out}(t)$ denotes the outside temperature of the environment surrounding the transmission line at time t. In what follows, we assume that the outside temperature T_{kl}^{out} can be decomposed to predicted one and its error;

$$T_{kl}^{out}(t) = T_{kl}^{pre}(t) + \sigma_{kl} w_{kl}(t), \tag{7}$$

where σ_{kl} is the amplitude of the prediction error and $w_{kl}(t)$ is a stationary standard white Gaussian noise (formally, derivative of the standard Wiener process).

2.2 Problem formulation

Let us consider a power generation scheduling problem associated with the above power grid. A naive scheduling problem is minimization of the cost of power generation satisfying consumers' demand and sustainable manipulation. In order to avoid desynchronization and overheating of the transmission lines, we impose the following mathematical constraints, respectively;

$$|\theta_k - \theta_l| < \frac{\pi}{6}, \quad \hat{T}_{kl}(t) \le T_{\max}, \tag{8}$$

where $T_{\max} > 0$ is the upper bound of the admissible temperature of the transmission lines. Then, we consider an optimization problem with chance constraints. We set the objective function as

$$J(u_{[t_0, t_0+\tau]}) := \int_{t_0}^{t_0+\tau} u^\top(t) S u(t) dt, \tag{9}$$

where $S = \mathrm{diag}(s_1, \ldots, s_{n_g})$ and $s_i > 0$ is the cost for the generator i. The line temperatures should be lower than $T_{\max}$ with high probability, which is prespecified by a given number $p \in [0, 1)$. Finally, we end up with the following chance constrained optimization problem.