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Robust model predictive control based voltage regulation method for a distribution system with renewable energy sources and energy storage systems

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ABSTRACT

With the integration of high penetration renewable energy sources (RESs) in distribution networks, the uncertainty of RES outputs brings a great challenge for the voltage regulation of distribution systems. This paper proposes a method based on robust model predictive control (RMPC) for voltage regulation by optimally coordinating the reactive power outputs of the RESs, energy storage systems and on-load tap changers (OLTCs). By considering the prediction error of the RES active outputs, the voltage regulation problem is formulated as a multitime period robust optimization model to obtain the optimal control actions in the prediction horizon. The control actions for the first time period are applied to the distribution network. Since the RMPC-based optimization model is nonlinear, it is linearized and transformed into a quadratic programming model that can be solved effectively by commercial software. The effectiveness of the proposed method is demonstrated in a real Finnish distribution network model.

1. Introduction

With the increasing demand for energy and the growing environmental pressure around the world, large amounts of renewable energy sources (RESs), such as photovoltaic (PV) and wind power, have been integrated into distribution networks. The high-level penetration of RESs in the distribution network entails bidirectional power flow and causes voltage rise problems on the feeders. In addition, due to the uncertainty of RES output and the low X/R ratio of the distribution networks, the node voltages in the distribution network fluctuate frequently and significantly. Voltage regulation becomes a key issue for the operation of a distribution network with RESs. The conventional voltage regulation methods [1], which rely on on-load tap changers (OLTCs) and VAR compensation devices such as voltage regulators (VRs) and switched capacitor banks (CBs), cannot control the voltage profile efficiently because the devices have a slow response, discrete actions and independent control mechanisms [2]. Consequently, more advanced methods are needed to control the voltage.

Because the voltage regulation problem results from the integration of RESs, some local control methods have been proposed to keep the bus voltage in the acceptable range by controlling the output power of the RESs. The curtailment of active power based on PV power forecasts is proposed to circumvent imminent violations of the upper voltage limit [3]. Since the curtailment of active power wastes a significant amount of energy, the reactive power capacity of RESs is utilized to improve the voltage profile. In [4,5,6], the reactive capability of PV inverters is employed to mitigate sudden voltage drops by absorbing or supplying reactive power. In addition to controlling the reactive power of RESs, reference [7] employs energy storage systems (ESSs) to store excessive power and solve local voltage problems. In [8], DGs and EESs are combined to address problems in local voltage fluctuations.

The local control methods may result in competition among the control devices and may interface with the OLTCs and VRs [9]. In addition to local control methods, the coordination of available reactive power control equipment in a distribution network is widely used for voltage regulation in the current research. In [9], a constrained nonlinear optimization model is established to coordinate various reactive power sources, including the reactive power of PVs, OLTCs and VRs, while satisfying the voltage limits of the feeders and minimizing the number of tap operations. In [10], an OLTC and a static VAR

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compensator (SVC) are coordinated to optimize the voltage profile with a mixed-integer nonlinear programming model, which is solved by a two-stage strategy to accelerate the calculation speed. A voltage regulation method is proposed with the coordination of vehicle-to-grid (V2G) electric vehicles (EVs) in [11]. An OPF-based model [12] and convex quadratic optimization model [13] are presented to optimize the reactive power of distributed energy resources (DERs) for the regulation of bus voltages. The soft open point (SOP) combined with multiple regulation devices is employed as a continuous reactive power source to minimize the operation costs and eliminate the voltage violations in [14]. A multistage reactive power optimization scheme is proposed to regulate the voltage by coordinating OLTC, capacitor banks, and multiple distributed energy resources in [15]. In addition to the above centralized methods, distributed control schemes have also been studied in many papers. A multiagent-based scheme is developed to optimally dispatch the reactive power of DGs [16]. A coordination of distributed and localized control strategies for distributed ESSs is presented to regulate the feeder voltage and effectively utilize the storage capacity [17]. A coordinated control strategy, including local droop-based control and distributed control, is proposed to optimize the charge/discharge of BESs for voltage regulation [18]. A decentralized-distributed hybrid voltage control was proposed in [19] by coordinating inverters and OLTCs.

The aforementioned coordinated methods assume the output power of the RESs are deterministic, neglecting the uncertainty of RES outputs. Several methods have been proposed to cope with the uncertainty of RES outputs by taking into account the prediction error. In [20], the prediction error was considered to generate the day-ahead voltage references for PVs and operation of OLTCs. In [21], model predictive control was employed to optimally coordinate the reactive power of RESs, ESSs and an OLTC for voltage regulation. In [22] and [23], MPC-based voltage optimization scheme and two-stage stochastic programing model were proposed, which considers the uncertainty of the model prediction errors that are modelled as a beta distribution function to generate typical scenarios of RES outputs.

In [20,21], the uncertainty of RES outputs was handled by regenerating the optimal reference based on the short-term updated forecast data. However, the methods cannot avoid the impact of forecast errors on voltage regulation. For the scenario-based methods in [22,23], it is difficult to obtain the distribution function of uncertainty parameters. Moreover, a large number of scenarios are needed to have a good approximation of the uncertainty, which lead to a heavy computational burden. Beside the scenario-based method, the robust optimization-based method is a popular approach to address uncertainty issues because the bounded intervals of the uncertainty parameters are much easier to obtain [24,25]. Additionally, the robust optimization-based method has a lower computational burden than the scenario-based method.

This paper proposes a voltage regulation method based on robust model predictive control (RMPC) to optimally coordinate RESs, ESS, and OLTC considering the uncertainty of RES outputs. The uncertainty of RES outputs is described as predefined uncertainty sets. The reactive power of RESs, charging/discharging power of ESSs and control actions of OLTC in a finite time horizon are optimally coordinated. Compared with current works, the main contribution of the proposed method can be summarized as follows:

(1) The voltage regulation model based on RMPC is formulated to coordinate the voltage regulation capacities of the RES, ESS and OLTC considering the uncertainty of the RES outputs.
(2) The coupling relationship between the active and reactive power of wind farms is formulated in the voltage regulation model to constrain the reactive power of wind farms.
(3) The reactive power constraint in the RMPC-based voltage regulation model is linearized using Taylor series expansion for efficient computation.

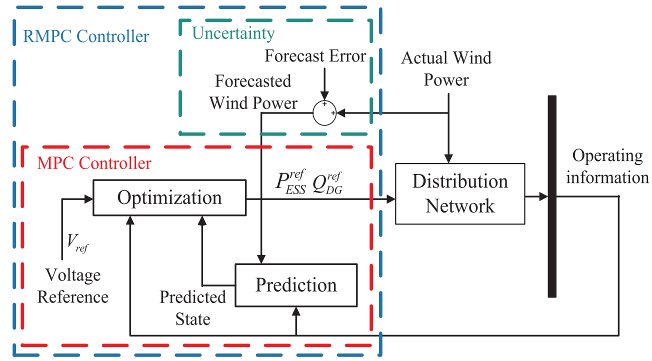

Fig. 1. The structure of voltage control for distribution networks.

(4) The RMPC-based voltage regulation model is transformed to a quadratic programming problem using the strong duality theory, which can be efficiently solved by commercial solvers.

The rest of this paper is organized as follows. Section II briefly introduces the structure of the voltage regulation scheme based on the RMPC method. Section III presents the voltage control model based on RMPC, including the objective function, prediction model and constraints. In section IV, the solution process of the nonlinear model is proposed. Section V discusses the simulation results followed by the conclusions.

2. RMPC-Based voltage regulation

The structure of the proposed RMPC-based voltage control scheme for the distribution network is shown in Fig. 1. A large number of RESs are integrated into the distribution system, which results in the frequent and significant fluctuations of the node voltages. Meanwhile, various controllable resources, including the ESS and OLTC, as well as the RESs, can be coordinated to optimize the distribution of reactive power and the regular voltage by system operators. The data acquisition system in the distribution system collects the operating information, including 1) the node voltage, 2) the power injection of RES units, 3) the charging/discharging power of the ESS units and their SoC information, and 4) the tap position and time-to-act of the OLTC. With the advance of smart grid technologies, the advanced metering infrastructure (AMI) has been widely deployed to collect real-time data in the distribution systems to the control center [26]. The power forecasting system, such as very short-term wind power prediction [27], can forecast the power outputs of the RES units in the next time intervals. The power regulation of RESs has been widely implemented to participate in distribution network operation [28].

The real-time measured operating information and the forecasted information for the RES units are the input information for voltage regulation. The operating information and the forecasted information are first sent to the prediction module as the input to the prediction model of various controllable resources. Next, the predicted state and the operating information are integrated to formulate the optimization model for voltage regulation. The solution of the optimal model can generate the control references of the controllable resources. Finally, the control references are sent to each unit.

The optimization model in this paper is built based on RMPC. RMPC is a feedback control strategy that calculates the optimal control actions for the next several time periods, considering the forecast errors of the RESs, and then implements the control actions for the first time period. Compared with the traditional MPC, the control actions of the RMPC model can maintain the security of the distribution system within the bounded uncertainties of the RES units. Compared with the scenario-based MPC method, the RMPC-based model has a lower computational burden.