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Comparative study of MPC based coordinated voltage control in LV distribution systems with photovoltaics and battery storage ☆

Pavan Balram *, Le Anh Tuan, Ola Carlson

Chalmers University of Technology, Göteborg 41296, Sweden

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ABSTRACT

This paper compares traditional local voltage control strategy with coordinated, optimization-based ones in low voltage (LV) distribution systems with photovoltaics and battery energy storage systems. Optimization-based strategies are formulated within a model predictive control (MPC) framework. Three strategies based on MPC are proposed and implemented, namely, centralized, decentralized and distributed MPC. The formulated strategies for voltage control are compared in a case study using a modified CIGRÉ European 3-area low-voltage network. Results indicate that decentralized MPC gives a better voltage profile in the network when compared to local voltage control strategy, since the latter inherently fails to maintain voltages of buses in the network not connected to photovoltaics or battery storage system within limits. Centralized MPC strategy is able to provide the optimal voltage profile across the network but utilizes 13% higher reactive power from the control devices to achieve this when compared to decentralized MPC. The latter performs well as long as the reactive power reserves within an area is sufficient but faces drawbacks similar to that of local voltage control strategy when the reactive reserves are completely exhausted. Distributed MPC utilizes 1.3% higher amount of reactive power reserves compared to centralized MPC in order to provide a network voltage profile similar to that of the latter while also yielding architectural advantages of decentralized MPC.

1. Introduction

1.1. Background

Renewable energy-based generation is increasingly being integrated into the distribution systems and higher penetration of DGs is expected in the future [1–4]. This could bring about new challenges to the DSO when it comes to performing voltage control [5] in such LV active distribution systems since they were traditionally not designed to host local generation [6,7]. Currently, voltage monitoring at the LV network is not common in distribution systems. This makes the DSO unaware of voltage variation occurring at the customers' side. With large PV penetration, this factor coupled with the variable nature of PV generation based on the time of day, season and cloud effect could pose limitations in effectively regulating LV bus voltages using traditional methods involving tap-changing transformers and capacitors banks at MV substations.

1.2. MPC-based voltage control

Through grid codes for distribution systems, requirements could be imposed that DGs, such as PV and BESS connecting to distribution system, be able to provide local voltage support [8,9]. With very high penetration of PVs and the possible increase in voltage measurements and communication in future distribution systems [10], coordinating the voltage regulation operation over the entire LV distribution system by utilizing an optimization-based strategy might become a feasible option. This type of coordinated control could be achieved using just one central controller regulating all the devices or through many decentralized controllers, each

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Abbreviations: LV, Low Voltage; MV, Medium Voltage; DG, Distributed Generator; DSO, Distribution System Operator; PV, Photovoltaic; PI, Proportional-Integral; PCC, Point of Common Coupling; BESS, Battery Energy Storage System; MPC, Model Predictive Control; MPPT, Maximum Power Point Tracking; LVC, Local Voltage Control; PDVC, Predictive Decentralized Voltage Control; PCVC, Predictive Centralized Voltage Control; P-PDiVC, Parallel Predictive Distributed Voltage Control.

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* Corresponding author.
E-mail address: pavan.balram@chalmers.se (P. Balram).

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controlling few devices at a time [11–14]. An additional possibility is to use communication links to exchange information so that a distributed controller in one area has knowledge on the actions to be taken by other distributed controllers before it could make its own decision. By utilizing MPC [15], the effectiveness of distributed controllers could be enhanced, since prediction of possible future actions is implicitly obtained. In order to decide on the most suitable control strategy for a distribution system, it is necessary to understand the advantages and disadvantages of utilizing these strategies.

Automating the coordination with the help of optimization-based control strategies could offer a greater advantage because the number of DGs could potentially be extremely large to determine the ideal setpoint for each device. With automation, it would be possible to readily define a new objective and augment the model to include control variables into the optimization problem if new DGs are connected. But challenges remains even within an optimization-based coordinated control strategy [16]. The optimizer could be a single, central optimizer that handles the overall objective function of the system and determines optimal set-point changes to all the control devices or it could be multiple, decentralized optimizers controlling only a few devices in an area [6]. Either way, a shift from a local, equipment-level to an additional central, system-level control structure is visible. Now, a central controller would give the optimal performance for a defined objective taking into consideration all interactions that occur within the system. But it could have multiple drawbacks, the biggest being decreased reliability in case of controller malfunction, increasing processing times with very large number of control variables and great complexity in practical implementation [17]. With decentralized strategy, each optimizer handles a limited number of control devices in an area but has no knowledge about its interactions with other optimizers. The major advantage of decentralized control is that it could be much more practically implementable and maintainable when compared to the central control strategy. However, as it loses information about interactions with other areas, it is unable to perform well when control variables are at their limits. In between these two lies the distributed control strategy that maintains the decentralized control architecture and offers performance similar to that of central controller since it also takes interactions between the optimizers into consideration.

Local control strategies to regulate power output from PVs have been investigated in [18–22]. In [23] local control strategies already available commercially along with other advanced LVC techniques yet to be made available commercially for PV connected to LV distribution systems have been compared. In [24], a central MPC-based controller is used to regulate active and reactive power response from PVs to maintain bus voltages in MV distribution system within acceptable limits. In [25], centralized, decentralized and distributed MPC strategies to regulate active power of a BESS for power market participation have been studied. However, research work on a distributed MPC-based strategy for coordinated voltage control in distribution system and also, its comparison with local, centralized and decentralized MPC-based control strategies has not been carried out so far.

1.3. Paper contribution

In this paper, a mathematical formulation of centralized, decentralized and distributed MPC based strategies for voltage control in LV power systems have been proposed and their performance have been compared to the traditional local voltage control strategy. Models of PV and BESS active/reactive power controllers have been utilized and time domain simulations have been carried out to observe dynamic responses of the investigated optimization-based controllers to sudden voltage variations in the modified CIGRÉ European LV distribution system. The main contributions of this paper can be summarized as follows:

- Local voltage control strategy has been compared with three coordinated MPC-based optimization strategies for LV distribution systems with BESS and large amounts of PV namely- centralized, decentralized and distributed control strategies.
- A novel formulation of coordinated voltage control problem for LV distribution systems based on iterative cooperative distributed MPC has been proposed and implemented in the case study. Architecturally, the distributed optimizers exchange information simultaneously at every time step and hence, the term *parallel* has been preferred instead of iterative in this paper. Henceforth, it is referred to as P-PDiVC.
- The mathematical formulation for PDVC and P-PDiVC strategies can be readily derived from the mathematical model of PCVC as will be described in Sections 3.2 and 3.3.
- The optimization-based controllers have been implemented using MATLAB and the time domain simulation has been performed with the help of DIgSILENT Powerfactory, which are both commonly available simulation platforms. Hence, DSOs and researchers can readily adopt the proposed MPC controllers within their simulation framework without significant effort.

The rest of the paper is organized as follows: Section 2 gives a description of the active/reactive controllers of PV and BESS along with the local voltage controller, Section 3 provides a mathematical formulation of the centralized, decentralized and distributed MPC-based coordinated voltage control schemes, Section 4 outlines the test system used along with assumptions and data needed for the simulation studies, Section 5 provides results from the case study and the corresponding discussions and finally, concluding remarks are made in Section 6.

2. Local voltage control

Multi-loop PI controllers are most commonly used for local control at the equipment level. For full power converters, there is typically an inner PI current control loop and an outer PI control loop where active and reactive power or voltage at PCC can be regulated as shown in Figs. 1 and 2 for BESS and PV, respectively. Their control structure is described more in detail below.

2.1. BESS local control structure

The battery is assumed to be interfaced with the network through a full power converter. With this converter, it is possible to independently control both the active and reactive power output from the battery. The overall structure is henceforth referred to as BESS in this paper and its model adapted from [26] is shown in Fig. 1. The active power P_{meas} and reactive power Q_{meas} output from the BESS are controlled independently by controlling the (d,q) axes current references to the full power converter, i^{*}_{dref} and

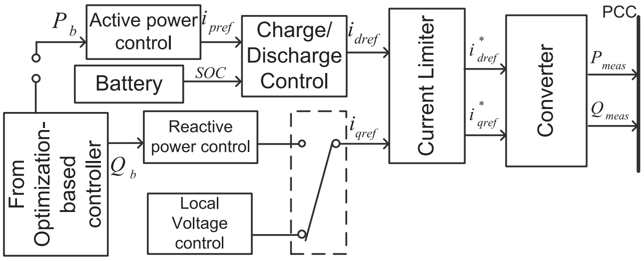

Fig. 1. BESS local controllers for dynamic studies [26].