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Embedding OLTC nonlinearities in predictive Volt Var Control for active distribution networks

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ABSTRACT

This paper presents an original procedure to embed the On Load Tap Changer (OLTC) nonlinearities in a predictive real-time Volt Var Control (VVC) for distribution systems. These commonly disregarded nonlinearities are namely the OLTC time-delays, the dead-band and the discrete nature of tap change. It is shown that using a continuous approximation can lead to control failures. The proposed nonlinear controller accurately anticipates the response of the system and the costs associated with control efforts. Demonstrations are performed in a 20 kV network to assess the performance of such a procedure compared to a predictive VVC using an OLTC continuous approximation.

1. Introduction

Electricity networks are nowadays confronting deep changes that put into question the relevance of traditional voltage control and reactive power management schemes. Indeed with the massive insertion of Distributed Generation (DG) along with the replacement of overhead lines by underground cables, distribution systems are prone to over-voltage and difficulty to manage reactive power exchanges between transmission and distribution systems. The modification of these reactive flows can induce as well over-voltage in High Voltage (HV) networks [1] increasing the probability of saturation of On-Load-Tap-Changer (OLTC) in HV/MV (Medium Voltage) substations [2], one of the main devices that adjusts the voltage in distribution networks. In case of OLTC saturation, there is no more uncoupling between the HV and MV voltages. In order to cope with these new operational concerns and keep fostering the penetration of DGs in MV systems, new schemes for voltage and reactive power control are unavoidable. Moreover, this need is stressed by the future requirements of the European Grid Code on Demand and Connection (DCC) [3]. According to this code, new distribution systems could be requested to have the technical capacity to restrain the reactive power flowing upwards transmission system at low active power consumption.

Recent breakthroughs in communication and sensors technologies are paving the way for smart grid solutions and favor real time control. This could enable Distribution System Operators (DSO) to reduce or postpone expensive grid reinforcements to cope with the aforementioned issues. The topic of voltage control in distribution systems has been extensively studied in literature promoting global coordinated schemes using optimal control. The levers involved in such a control are generally the voltage reference of the Automatic Voltage Regulator (AVR) using OLTCs, the power injection of DGs and Capacitor Banks (CB) connected at the MV busbar of the HV/MV substations. Handling the HV/MV networks reactive power exchange implies new control strategies since actuators must henceforth act in a coordinated manner to achieve a common goal (reactive power exchange) while maintaining the voltage (local objective). Indeed, OLTCs which are generally located at the HV/MV substation have a global influence on the MV voltages, while the DG reactive power outputs have a local influence regarding the voltage level but a global influence regarding the reactive power at the HV/MV interface. This raises the relevance of designing centralized

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control structures. A number of real-time Volt Var Control (VVC) methods can be found in the literature based on an optimal control strategies using either a global controller [4,5] or multi-agents systems [6,7]. Compared to other methods, Model Predictive Control (MPC) exhibits attractive performances [8–11] notably for economic strategies minimizing operational costs [12]. MPC generates an optimal control under a temporal horizon while accounting for the future behavior of the system using a numerical model [13–15].

Distribution systems voltage and reactive levers include discrete and continuous actuators. Designing hybrid continuous-discrete or nonlinear MPC methods is not trivial and raises complexity and numerical issues [16,17]. More specifically, the OLTC is a slow acting device integrating time-delays and a dead-band in its low level control [18]. Usually, only few papers consider the nonlinear nature of the OLTC (and more generally of actuators) in the design of their real-time controller [19]. For instance, in [11] the OLTC is considered inside the MPC algorithm as a continuous non-delayed variable, while future predicted tap changes at an instant t are included as a known disturbance inside the corresponding prediction horizon. In [9], OLTC is not considered as a control lever in the MPC corrective process, but called for only in case of failure of the control. In [20], an online reconfiguration of the OLTC set-point is proposed based on a MPC strategy to correct the MV voltages. However, DGs and CBs are not considered as voltage control levers, and a continuous approximation is used for the OLTC dynamics.

An industrial control system is integrated in the OLTC, which has been designed to optimize its life span and this inner loop control cannot be removed. The closed-loop model of the OLTC should be embedded in advanced control approaches such as MPC. To date, no advanced control algorithms explicitly account for the OLTC nonlinearities but use a continuous approximation [11]. Thus, the minimization of tap operations is never fairly addressed. Still, tap change should be avoided insofar as possible since OLTC are fragile devices with expensive maintenance costs. The cost of a tap change, which is derived knowing the maximal number of tap changes before maintenance, is indeed one of the major source of expenses for the DSO. Next, disregarding the complex behavior of the OTLC can lead under specific conditions to control failures in a MPC scheme: the controller is not able to bring the system in a state that respects every specified constraints. This important aspect will be shown in the paper.

Hence, this paper fills in a gap and proposes an improved VVC embedding OLTC nonlinearities using a two-step approach. The OLTC time-delay is integrated inside the MPC problem as the discrete nature of the OLTC tap position. Then, the OLTC references are generated by explicitly taking into account another nonlinearity, namely the dead-band. As a result, quantization issues are addressed avoiding the failure of the control algorithm. Moreover, the controller is able to estimate the true OLTC tap changes and not only the voltage references fed to its inner control loop. Thus the control costs for the DSO are accurately known and can therefore be reduced.

The paper is structured as follows: part one is dedicated to the presentation of a MPC scheme for coordinated voltage and reactive power control in distribution systems. The second part presents the original procedure embedding OLTC nonlinearities. The irrelevance of the continuous OLTC approximation is shown through simulations. Then, both of the approaches (continuous and discrete model) are further compared by simulations performed on a 20 kV network.

2. MPC of voltage and reactive power for distribution systems

MPC is a particularly attractive approach for real-time VVC applications due to its ability to handle multi-input multi-output systems through optimization routines involving several types of constraints.

The MPC principle is based on a receding horizon and uses a prediction model to anticipate the response of the system. At each control instant t_s, based on current states measurements, an optimal control sequence of N actions $\Delta u(t+kt_s)$ (that will be noted $\Delta u(k)$, $k \in \{1, N-1\}$ in the sequel) is calculated in order to minimize an objective function and to meet the specified constraints inside the horizon N. Only the first element $\Delta u(1)$ of the sequence is applied. The whole process is then started again at the next sampling time t_s once a new set of measurements is available [13,14].

2.1. *Definition of the MPC problem for a distribution grid*

2.1.1. *Objectives and constraints*

The system considered herein is a radial distribution network with DG, OLTC, and CB connected at the secondary side of the HV/MV substation. The controller should meet two objectives:

1. Maintain the n nodes voltages ($V \in \mathbb{R}^n$) in the distribution network inside a predefined range of values $[V_{min}, V_{max}]$.
2. Regulate the reactive power exchange at the interface of MV/HV networks by maintaining the ratio of reactive consumption over active consumption of the distribution network ($\tan_{MV\to HV} = \frac{Q_{MV\to HV}}{P_{MV\to HV}}$) around a target value inside $[tan_{min}, tan_{max}]$. Thus, the DSO can comply with the technical or regulatory requirements regarding reactive power exchange with the transmission system.

To reach these aforementioned objectives, the controller takes advantage of some of the MV networks flexibilities, adjusting:

- the reactive power of DG (Q_{DGref}),
- the number of activated steps of CB (n_{CBref}),
- the reference of the OLTC tap position ($n_{OLTCref}$).

Thus, the MPC computes the optimal tap position and it is possible to reduce or even avoid tap changes when required.

If needed, the active power of DG could easily be integrated as a control variable. The change in control effort are defined by:

$$\Delta u(k) = [\Delta n_{OLTC\ \ ref}, \Delta Q_{DG\ \ ref}, \Delta n_{CB\ \ ref}](k). \tag{1}$$

The objective of the control is to minimize the DSO expenses that are linked with the control effort and the active losses P_{loss}. This objective can be written as:

$$\min (J)_{\Delta u} = \sum_{k=1}^{N-1} [\Delta u(k) R \Delta u(k)^T + \alpha P_{loss}(k)^2], \tag{2}$$

where R is the costs matrix associated with control efforts, α is linked with the active losses in the distribution network. If losses estimates are not available or not accurate enough, this parameter can be set to zero. In the sequel, $\alpha = 0$, since losses estimation are highly correlated with current estimates and load models that are unfortunately one of the major sources of uncertainty for the DSO. Moreover, the main objective selected in this paper is to minimize the control effort.

A reference trajectory can be defined as well as complex constraints on the evolution of inputs, outputs and control variables since MPC controls have the ability to deal with various constraints, time delay, and can anticipate any predictable disturbances. First, physical limits of actuators can be considered $\forall k \in \{1, N-1\}$:

$$u_{\min} \le u(k) \le u_{\max}, \tag{3}$$

$$\Delta u_{\min} \le \Delta u(k) \le \Delta u_{\max}. \tag{4}$$