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.

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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 $\Delta u(t + k t_s)$ (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 $\forall k \in \{1, N-1\}$:

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

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

Regarding the OLTC constraints, the tap position is generally not measured and thus not available in the DNCC. However, to enforce (3) regarding the OLTC, the tap position should be evaluated to keep the OLTC within the prescribed boundaries. This can be done when knowing the flows within the transformer and the voltages at the HV and MV busbar. If it is not possible to obtain an estimate of the tap position, at least the controller should be able to retrieve information in case of OLTC saturation. Hence, even if the controller is not able to anticipate (and prevent) the OLTC saturation, it can still find alternative solutions to correct the MV voltages whenever needed. In France, an alert is sent to the DNCC when the OLTC reaches its last (upper or lower) position. Then, the convergence of the MV voltages V and $tan_{MV \to HV}$ can also be specified $\forall k \in \{1, N\}$:

$$V_{\min}(k) \le V(k) \le V_{\max}(k), \tag{5}$$

$$\tan_{\min}(k) \le \tan_{MV \to HV}(k) \le \tan_{\max}(k). \tag{6}$$

When $k = N$, these constraints are named "terminal constraints". Note that these constraints can evolve inside the prediction horizon for a progressive tightening [8]. The sampling time has been assumed equal $t_s = 1$ min to account for nowadays technical limitations.

2.1.2. Infeasibility issues

The MPC controller can cope with infeasibility issues through a relaxation of the constraints using slack variables $\varepsilon(k)$ [8,9]:

$$x_{\min}(k) + \varepsilon_{\min}(k) \le x(k) \le x_{\max}(k) + \varepsilon_{\max}(k) \tag{7}$$

x can correspond to the voltages V or the $tan_{HV \to MV}$. A hierarchical relaxation of constraints has been used, the constraints are successively relaxed in case of infeasibility:

- Relaxation 1: Constraints on $tan_{HV \to MV}$ (6).
- Relaxation 2: Constraints on V (5).

Each slack variable is then penalized inside the objective function (2).

2.2. Networks and actuators modeling

MPC relies on a model to predict and anticipate the future behavior of the outputs of the system (V, $P_{MV \to HV}$, $Q_{MV \to HV}$) with respect to the inputs (references Δu and state measurements) under a temporal horizon.

Here, the network model is based on sensitivity matrices that are traditionally used [8,5,21]. These matrices can be easily derived from load flow calculations and from the inverse of the Jacobian matrix of the system. These matrices correspond to the partial derivative of the states (here V and $tan_{HV \to MV}$) with respect to the inputs (Δu). This modeling can suffer from inaccuracies. The estimates of the sensitivity matrix highly depend on the general knowledge of the network (lines parameters or load models for instance). It should be reminded that these parameters are not well known in practice [8]. However, MPC exhibits an ability to cope with uncertainties and inaccuracies in the models that can be mitigated through this closed loop approach. As a result, constant sensitivity matrices can be used as a fair approximation and in this paper, they are evaluated considering a constant load model [22]. Active and reactive powers consumed by the load are assumed to remain constant inside the prediction horizon, as well as the active power injections of DG.

In order to properly consider the actuators behavior inside the prediction horizon, one must pay attention to the different timescales. Compared to the sampling time t_s, which is equal to 1 min, the DG and CB are supposed to act instantaneously without lag. Both the communication delay t_a and computational time are also
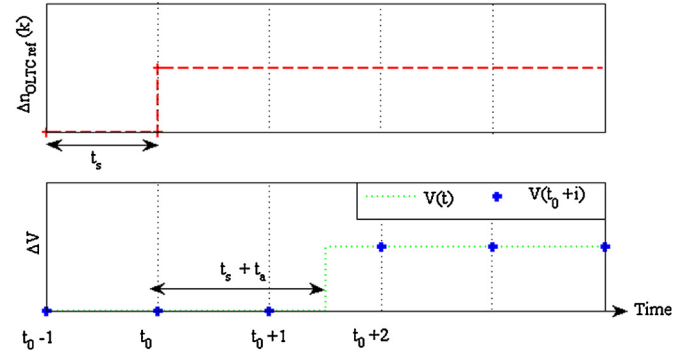

Fig. 1. Integration of the OLTC actions within the prediction horizon at $t = t_0$.

reckoned to be far smaller than t_s. In France, OLTCs act with time delay, the first one is of 1 min, while the subsequent time delay is 10 s. Given the ability of MPC to deal with time delays, these lags can be easily embedded inside the prediction model.

When a voltage reference change is sent to the OLTC, the induced tap change will take place after some time $t_a + t_s$. This is further illustrated in Fig. 1. The first sub-figure shows a change of OLTC discrete reference at t_0. The second sub-figure shows the continuous OLTC and sampled voltage response with a delay of two periods due to communication and actuation lags as explained above.

The prediction equations are detailed in the following Eqs. (8)–(10) where $\Delta u(k)$ represents the corrective action (triggered by the optimal sequences Δu).

$$V(k + 1) = V(k) + \frac{\delta V}{\delta Q_{DG\ ref}} \Delta Q_{DG\ ref}(k) + \frac{\delta V}{\delta n_{CB\ ref}} \Delta n_{CB\ ref}(k)$$
$$+ \frac{\delta V}{\delta n_{OLTC\ ref}} \Delta n_{OLTC\ ref}(k - 1), \tag{8}$$

$$Q_{MV \to HV}(k + 1) = Q_{MV \to HV}(k) + \frac{\delta Q_{MV \to HV}}{\delta Q_{DG\ ref}} \Delta Q_{DG\ ref}(k)$$
$$+ \frac{\delta Q_{MV \to HV}}{\delta n_{CB\ ref}} \Delta n_{CB\ ref}(k)$$
$$+ \frac{\delta Q_{MV \to HV}}{\delta n_{OLTC\ ref}} \Delta n_{OLTC\ ref}(k - 1), \tag{9}$$

$$P_{MV \to HV}(k + 1) = P_{MV \to HV}(k) + \frac{\delta P_{MV \to HV}}{\delta Q_{DG\ ref}} \Delta Q_{DG\ ref}(k)$$
$$+ \frac{\delta P_{MV \to HV}}{\delta n_{CB\ ref}} \Delta n_{CB\ ref}(k)$$
$$+ \frac{\delta P_{MV \to HV}}{\delta n_{OLTC\ ref}} \Delta n_{OLTC\ ref}(k - 1). \tag{10}$$

No disturbances are integrated inside the prediction equation, but any predictable disturbance could be accounted for and easily added in the model. A predictable disturbance is a disturbance that is known a priori like a planned maintenance works or the switching from peak to off-peak load tariffs. In other words, such a disturbance is measurable, should be modeled (the influence on the state variables should be known), and the instant of occurrence must be accurately determined. Besides, the active power $P_{MV \to HV}$ is assumed to be independent of the change in reference Δu_{ref}, and the reactive power $Q_{MV \to HV}$ is independent of $\Delta n_{OLTC\ ref}$.

The resolution of the MPC problem will be explained in the next section since it depends whether the number of tap changes are considered as a discrete or a continuous variable.
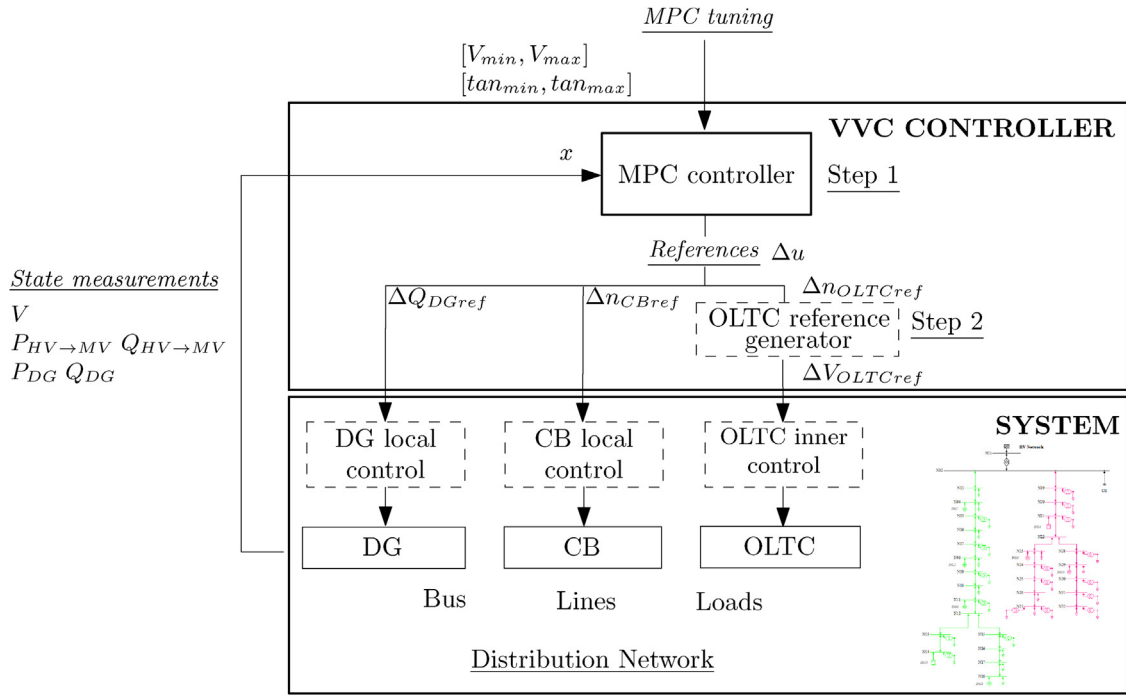
Fig. 2. Schematic of the MPC control structure.

3. Association of MPC with OLTC inner control: a two-step procedure

The MPC control presented herein computes the optimal control effort Δu to minimize the objective function (2) and subject to the following constraints (3)–(7). Among others, the resolution yields the optimal tap changes $\Delta n_{OLTCref}$. However the OLTC is controlled through the voltage reference in its existing inner control as shown in Fig. 2. As explained in the introduction, the idea is to embed the traditional OLTC inner control inside a MPC approach to avoid frequent tap changes and ensure a faster response in case of perturbations or failure of the centralized control. To do so, a two-step approach has been designed:

- Step 1: Calculation of optimal tap changes $\Delta n_{OLTCref}$ in the MPC problem detailed in Section 2. The existence of the time-delay is handled by the proposed MPC approach.
- Step 2: Generation of the voltage reference of the OLTC to induce the optimal tap changes. At this second stage, the existence of the OLTC dead-band has to be accounted for.
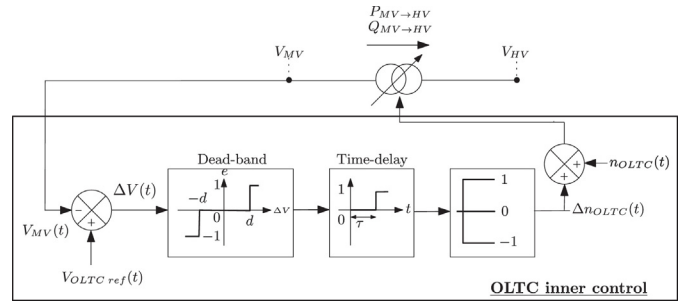
In the following, the classical inner control is first recalled and then the link with the MPC control is explained. The irrelevance of using a continuous tap change instead of a discrete tap change is shown through simulations. This approximation leads to a model mismatch and the controller can be, under specific conditions, unable to maintain the voltages within the specified range.

3.1. OLTC voltage reference generation from optimal tap changes $\Delta n_{OLTCref}$

3.1.1. Traditional OLTC inner control with AVR

As a reminder, AVR principle is to maintain the voltage at the secondary side of a transformer by automatically adjusting the ratio $\frac{V_{HV}}{V_{MV}}$ by discrete steps corresponding to a change of tap n_{OLTC} as illustrated in Fig. 3 [18,23].

Fig. 3. AVR of the OLTC.

If the difference between the voltage reference and the voltage at the secondary side of the transformer exceeds the half dead-band d for a time longer than the time-delay τ, a change of tap is triggered. Each change of tap generates a change in voltage V_{tap} at the secondary side of the transformer. The dead-band $2d$ is classically chosen equal to this voltage change: $2d = V_{tap}$.

3.1.2. OLTC voltage reference generation

The problem consists in choosing a suitable voltage reference $V_{OLTC\,ref}(k)$ which will generate the correct tap changes $\Delta n_{OLTC\,ref}$ computed by the MPC controller. Due to the existence of the dead-band no explicit inversion model can be found. Then the following voltage reference:

$$V_{OLTC\ ref}(k) = \hat{V}_{MV}(k+1) + \Delta n_{OLTCref}(k)V_{tap}, \tag{11}$$

ensures that, the prediction of voltage $\hat{V}_{MV}(k+1)$ remains in the range $[V_{OLTC\,ref}(k) - d,\ V_{OLTC\,ref}(k) + d]$. The prediction $\hat{V}_{MV}(k+1)$ is the voltage at the secondary side of the OLTC if all control actions but the change $\Delta n_{OLTCref}$ are achieved.

For instance, if $\Delta n_{OLTC\,ref} = 0$, following Eq. (11), one can check that $V_{OLTC\,ref}(k) = \hat{V}_{MV}(k+1)$, also no tap change is triggered.

However, if $\Delta n_{OLTCref} = 1$, then $V_{OLTC\,ref}(k) = \hat{V}_{MV}(k+1) - V_{tap}$. According to the OLTC inner logic illustrated in Fig. 3, a tap change will be generated.

Since the prediction is never truly realized due to external disturbances and inaccuracies in the model, this choice allows to avoid unwanted tap changes while the errors in the prediction are smaller than the half dead-band d. This will be further illustrated in Section 3.2.

This equation is used by the "OLTC reference generators" shown in Fig. 2; first, the MPC resolution gives the optimal $\Delta n_{OLTCref}$ while the OLTC reference generator gives the voltage reference that feeds the OLTC inner control. Others choices have been tested for the OLTC model inversion, however, these choices were not appropriate as the true nature of the tap changer was not accounted for.

3.2. Irrelevance of the continuous OLTC approximation

At this stage, quantization issues are not addressed, even though the correct tap change reference is generated through Eq. (11). The OLTC tap change is an integer, and more specifically $\Delta n_{OLTCref}(k) \in \{-1, 0-1\}$. A rough approximation consists in considering the OLTC as a continuous variable: $-1 \leq \Delta n_{OLTCref}(k) \leq 1$. The MPC controller is then more tractable since only continuous variables will be considered, and the use of LP solvers is possible.

For example, such a MPC controller can generate $\Delta n_{OLTCref} = 0.25$. In this case, the true value will be $\Delta n_{OLTC} = 0$. A tap change will be triggered only if $|\Delta n_{OLTCref}| \geq 0.5$.

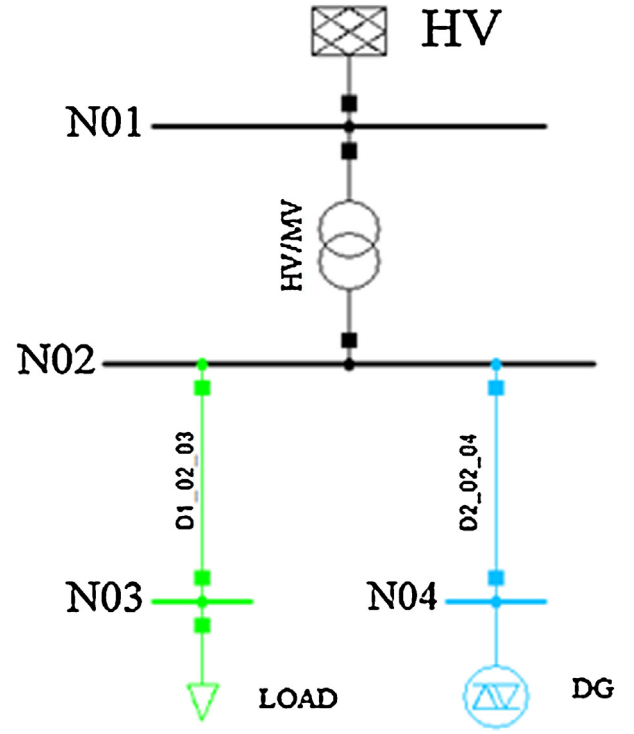The next subsection shows that the controlled system is not robust with respect to tap change rounding.

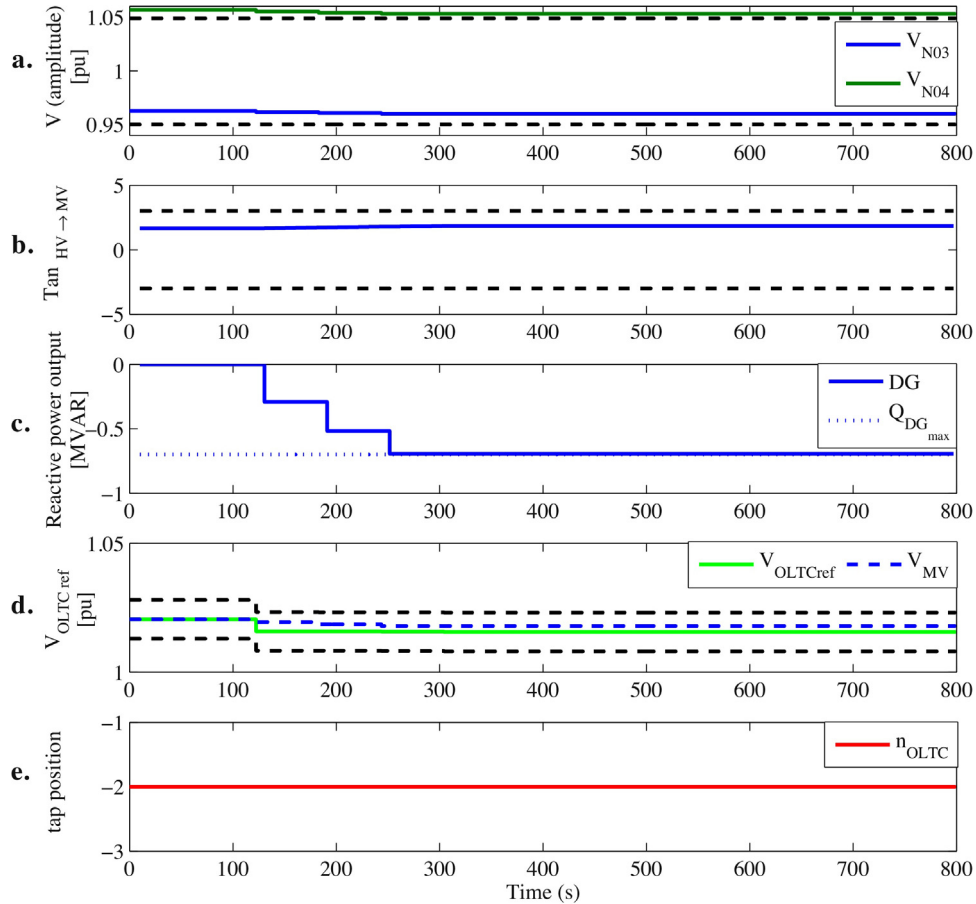Fig. 4. Three-bus simplified network.

Fig. 5. Results and control, continuous approximation.

3.2.1. Simplified network for illustrative purposes

For concision and intelligibility purposes, the first simulations presented herein have been conducted on a simplified network. The three-bus system of Fig. 4 has one infinite bus (HV network), a HV/MV transformer with an OLTC, two lines of 5 km, a load and a DG. The load embodies a feeder for which the consumption is higher than the production; the voltage at this node can be interpreted as the minimal MV voltage. On the contrary, the second feeder is a DG, and this node is prone to over-voltage.

In a way, this simple system can represent a more complex one: the load bus N_{03} can be viewed as the node that exhibits the minimal voltage while N_{04} embodies the point of maximal voltage.

The DG is assumed to be able to produce/consume reactive power in a restrained range of values $[-0.7; +0.7]$ MVAR. Transformer parameters correspond to the HV/MV transformer of the network presented hereafter, and the lines correspond to the model ARG7H1RX185 mmq presented in [9]. The load is consuming 17 MW with a 0.93 power factor, and the DG produces 14.5 MW with a unity power factor.

In this case, the objective of the controller is to maintain the voltage inside the range $[V_{min}, V_{max}] = [0.95; 1.05]$ pu by adjusting the reactive injection of the DG and the OLTC voltage reference. At the initial state, $V_{N04} = 1.0566$ pu is outside the targeted range.

The controller is activated at $t = 120$ s and is called every minute $t_s = 60$ s.

3.2.2. Control failures due to model mismatch

Fig. 5 gives the simulation results, measurements are updated every 10 s. The first graph (a) gives the voltage at typical nodes of the network, graph (b) shows the tangent at the primary side of the transformer, the third (c) gives the reactive power output of DG and the fourth graph (d) shows the voltage reference of the OLTC in green and the measured voltage at the secondary side V_{MV} in blue. The dead-band is represented by the dark dotted lines. The last graph (e) gives the tap position of the OLTC.

From this figure, several conclusions can be stated. First, using the continuous model leads to a failure of the controller. It is not able to bring the system in a satisfactory situation where $V \in [V_{min}, V_{max}]$. It could be found surprising that $V_{OLTC\ ref}(k)$ remains still after $t = 250$ s even if it can still be used. This is due to the fact that the controller is not able to accurately anticipate the behavior of the OLTC and consider continuous tap change. Thus, the final solution corresponds to a situation where lowering the voltage by $\Delta V = V_{OLTC\ ref}(k) - V_{MV}(k)$ would solve the constraints. However, this voltage change is too low (compared to the dead-band) to trigger a tap change, and the controller is not able to modify the voltage reference sent to the OLTC. In the considered situation, a possible way to correct the voltages consists in lowering the MV voltage profile with a tap change and then to slightly increase the minimal voltage with a positive reactive power injection. One can consider to move down the voltage reference $V_{OLTC\ ref}(k)$ until a tap change is triggered. However, such a solution can lead to an oscillating behavior. For instance the tap change can exceed the change anticipated by the controller and can induce voltage constraints violation. As a result, the controller will try to compensate this excessive voltage change by adjusting in the opposite direction the voltage reference.
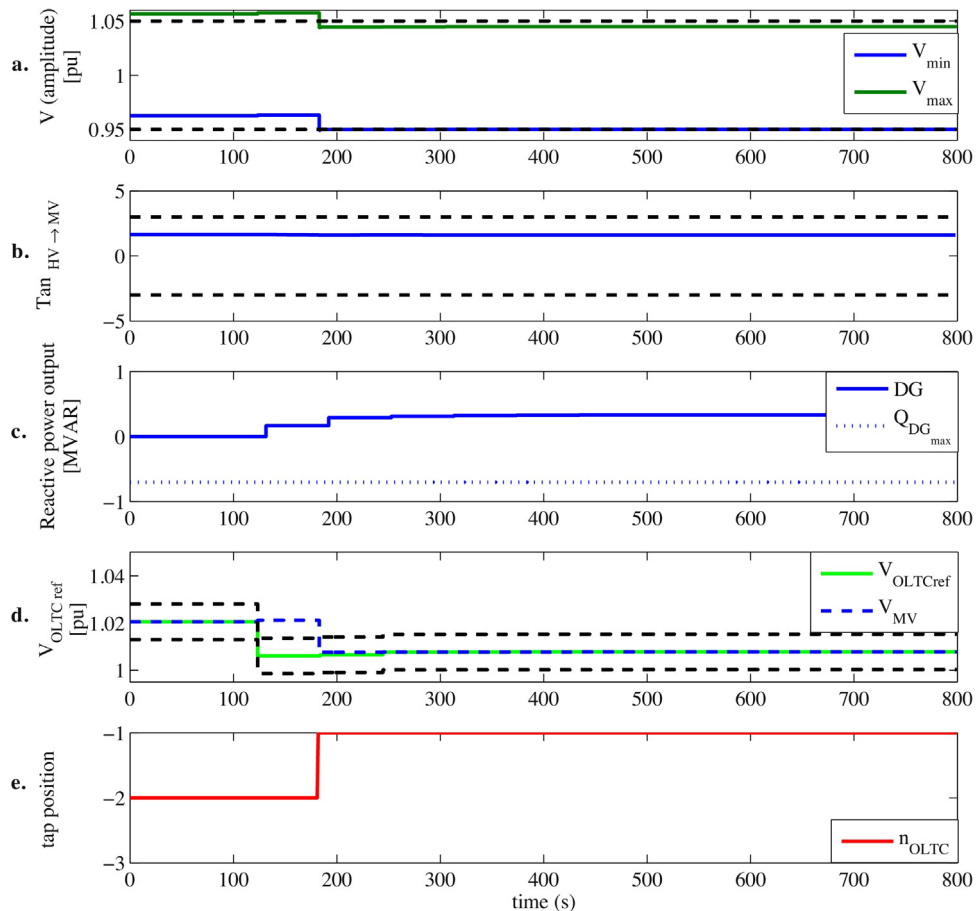

Fig. 6. Results and control, discrete model.

3.3. Correct tap change mechanism using a discrete resolution

In order to avoid such issues, the discrete nature of tap needs to be accounted for. Thus, the two-step procedure shown in Fig. 2 has been enhanced. In the MPC problem, a new constraint has been added: the change of tap $\Delta n_{OLTC\,ref}$ is enforced to take a set of integer values $\Delta n_{OLTC\,ref} \in \{-1, 0, 1\}$. $V_{OLTC\,ref}(k)$ is generated subsequently according to (11). Thus, three features of the OLTC are taken into account: the existence of time delay and dead-band as well as its discrete nature.

The resolution of the MPC turns into a problem with both integer and real values which calls for the use of a MINLP solver. Here the solver BNB of the Matlab toolbox YALMIP [24] based on an implementation of a standard branch and bound algorithm for mixed integer programming has been chosen. Note that without the proposed two-step approach, embedding all of the OLTC nonlinearities directly inside the MPC formulation would have led to a highly nonlinear problem not easily solvable; the proposed mixed approach relaxes the computational burden.

Results are given in Fig. 6 that follows the same structure as Fig. 5. To conclude, the control succeeds in correcting the voltage V and maintain $tan_{MV \to HV}$ using the proposed procedure as it can be observed.

4. Case study: a comparison of MPC VVC with discrete and continuous OLTC representations

Both MPC approaches are now being tested on a more complex network which will enlighten the relevance of the control for large-scale system distribution systems.

4.1. Presentation of the 20 kV network

4.1.1. Assumptions regarding the distribution network

In the sequel, the existence of a Distribution Network Control Center (DNCC) is assumed. This DNCC is able to retrieve local real-time measurements (every minute) of the active and reactive powers flowing through the HV/MV transformer, and the power injections of DG. As for the MV voltages, a state estimator as described in [25] is supposed to be operational. Every retrieved measurement is an average of 6 local measurements. The accuracy is assumed to be of 1% regarding the power measurements
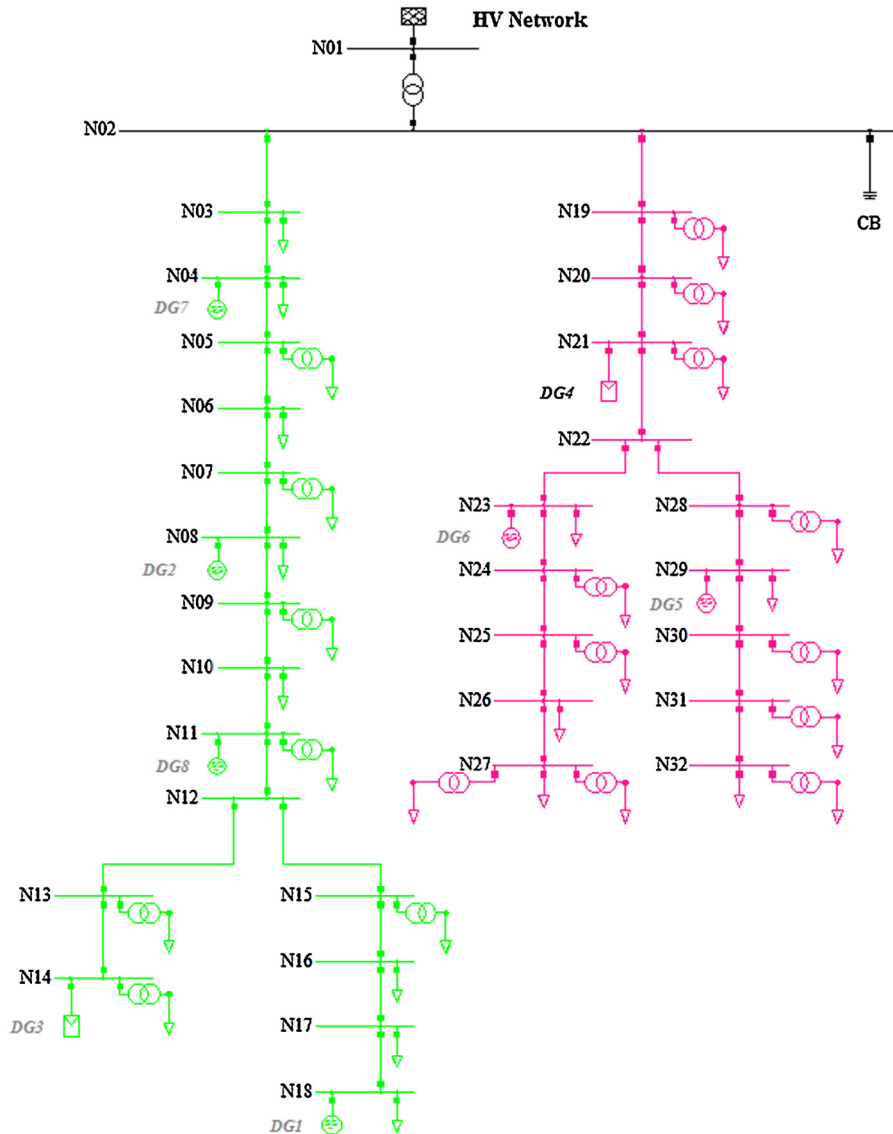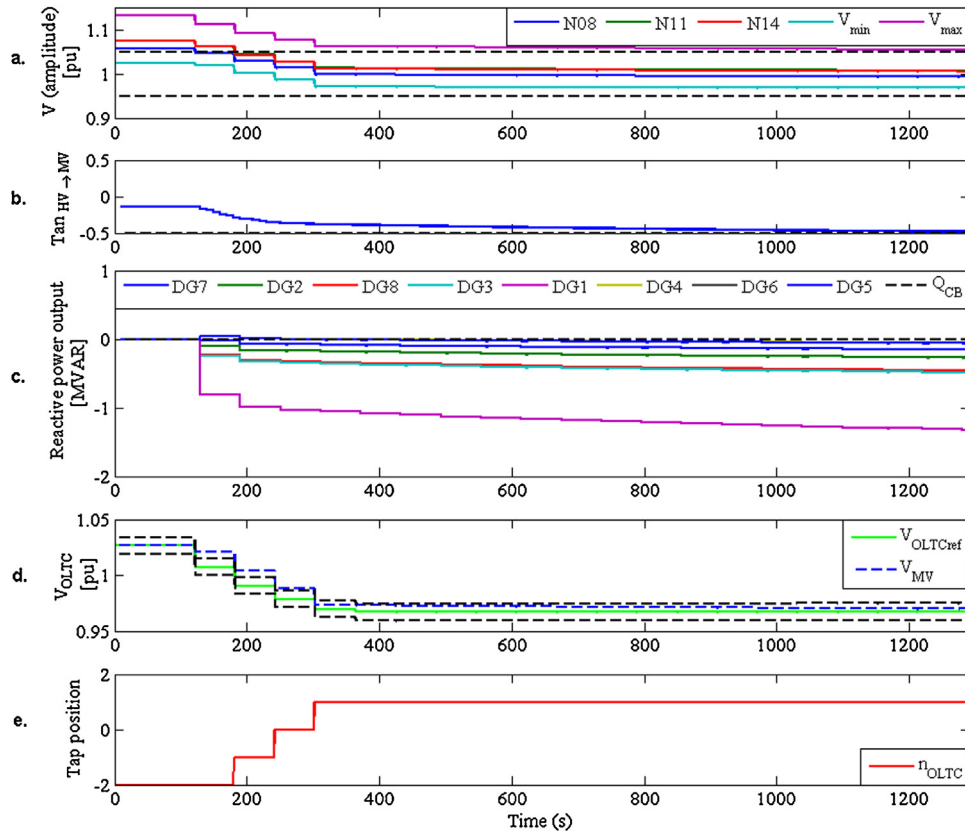

Fig. 7. Network topology.

Fig. 8. Results and control with continuous approximation.

and 0.5% for voltage estimates. DNCC tools encompass the control algorithms and are able to send control setting points to the aforementioned actuators. A general knowledge of the network such as grid topology is also available in the DNCC tools.

4.1.2. The 20 kV network

The considered network is the 20 kV radial network which was introduced in [9]. In our case, a constant current model (respectively impedance constant model) has been selected to represent the active power (respectively reactive power) for loads. Industrial loads are modeled as small motors whose parameters are available in [26]. Moreover, a CB of three 1.8 MVAR steps was added a the secondary side of the HV/MV substation as illustrated in Fig. 7. Reactive power injection of DG is supposed to be fully controllable inside the range $[-0.35, +0.4]P_{max}$.

4.1.3. MPC tuning

The controller starts at $t = 120$ s and takes action every minute. Regarding the MPC parameters, the weights of actuators have been set to 1 (i.e. the cost matrix S of (2) is the identity matrix). Slack variables inside the prediction horizon are 100 times more costly whereas slack variables at the end of the horizon are 1000 times more costly.

Note that the performances and interest of a MPC controller have already been demonstrated in [8,11]. It was also proven that this controller can cope with various and evolving situations even with uncertainties in the model (namely sensitivity matrices) and disturbances. Here, for intelligibility and concision purposes only one case study is detailed without any external disturbances. Indeed, the primary focus of the paper is to demonstrate the relevance of using a nonlinear OLTC model in the control design.

4.2. Case study

Simulations have been conducted considering the conditions at 1 a.m. described in Appendix A (Tables 3 and 9) of [9].

The objectives of the control are first to maintain the MV voltages inside the range [0.95; 1.05] pu and then to maintain the $tan_{MV \to HV}$ inside [−0.5; +0.5].

The distribution network operates under low active power consumption along with high active production of DGs. Hence some nodes are facing over-voltage especially in feeder 1 where the level of production is higher than in feeder 2. The actions and corresponding results of the controller using either a continuous or the proposed nonlinear OLTC model are respectively presented in Figs. 8 and 9.

4.3. Results and discussion

From Figs. 8 and 9, it can be observed that the controller succeeds only with the discrete model. The control efforts to bring the voltage in the targeted intervals and final states of the network will end up to be the same. However, the final state is reached after $t = 420$ s that is to say after 5 control actions with the proposed discrete model while at $t = 1200$ s (16 control actions) the final state is still not reached using the continuous approximation.

To give a more precise analysis, one can observe that the first control actions are exactly the same for both simulations. This is due to the constraints imposed on the change of OLTC voltage reference: this change must be equal or below one tap at each control instant. After those first actions, with the continuous approximation, the controller takes decisions relying on a poor anticipation of the OLTC future behavior. The changes in the reference $V_{OLTC\,ref}$ are not followed by the predicted corrective actions. It can be noticed that the controller anticipates a fictitious change in voltage ($V_{OLTC\,ref}$
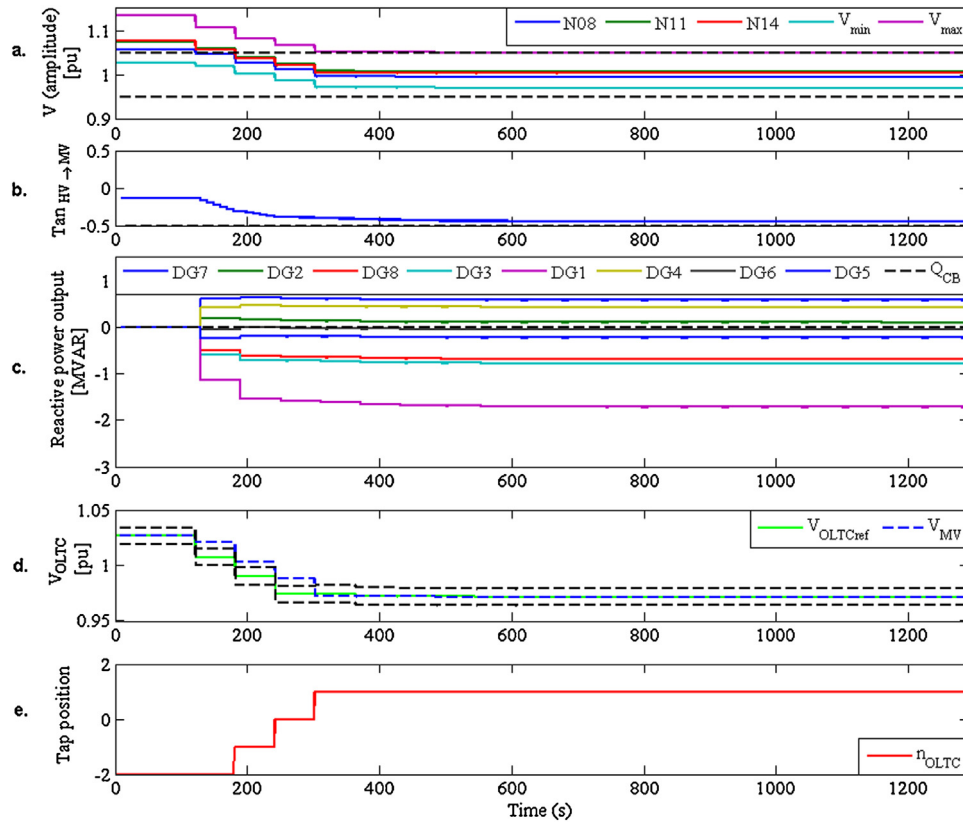
Fig. 9. Results and control with the nonlinear OLTC model.

and V_{MV} are not equal in Fig. 8d contrary to Fig. 9d), that never happens. Since reactive power levers, namely the DG are still available, the control effort is slowly shared out between the DG and OLTC as illustrated in Fig. 8c. As a result, the corrective process is considerably slowed down, and the MV voltages exceed the upper bound (1.05 pu) (Fig. 8a) for a longer time.

In any case, it should be borne in mind that the selection of the solution is strongly correlated to the costs of the objective function (2). The continuous approximation leads to a mediocre solution since the estimate of the control effort costs is biased. A continuous change in $V_{OLTC\,ref}$ is considered instead of a tap change. Thus, the costs are also poorly estimated for the DSO, since a change in $V_{OLTC\,ref}$ has no cost if it does not trigger a tap change.

To conclude, the proposed procedure designed for a MINLP MPC VVC leads to better performances of the centralized controller. Using the continuous approximation can result in a higher probability of constraints violation and control failure.

Next, with this proposed procedure, the control effort cost can be accurately estimated: every control action requested by the controller is reflected in the network contrary to the approach proposed in [11]. Thus it is possible to directly integrate constraints on tap changes and to reduce the control effort for the DSO without removing the OLTC inner control. Indeed, changing the OLTC inner control represents a nonnegligible cost (new tuning, procedure, implementation . . .).

5. Conclusion

In this paper, a Volt Var Control scheme merging Model Predictive Control and the classical On Load Tap Changer inner algorithm has been proposed. Thus, this original procedure contributes to integrate more advanced control methods in distribution systems without changing the current equipment and the operating strategies. Hence, the implementation costs are limited.

Next, the nonlinear OLTC inner control that was designed to optimize its life span is kept and is accurately considered when designing the VVC strategy. The proposed procedure consists of a two-step process. At a first stage, the optimal change of tap is yielded by the MPC problem solving which is able to consider time-delays. When using a continuous approximation of tap change, which is a quantized input, the optimization algorithm of the MPC may find an inappropriate references. Thus, it is necessary to use a Mixed Integer NonLinear Programming method. Then, at a second stage, the voltage reference of the OLTC is generated by taking the existence of the dead-band into account.

Simulation results show the effectiveness of such a procedure in case of an extreme condition. The main advantages of this control are:

- the coordination of many actuators for voltage regulation and reactive power control - similar to what can be found in other publications,
- to guarantee the minimization of the tap changes during all the life of the OLTC, since this criterion is explicitly considered in the cost function,
- keeping and considering the classical OLTC inner control to avoid fundamental modifications of the existing control devices.

The perspectives of this work are to study the sensitivity of the proposed procedure with respect to errors and inaccuracies in the model. More specifically the limitation of the DGs available reactive power, which depends on the corresponding active injection, should be addressed.

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