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Improving Voltage Control in MV Smart Grids

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***Abstract*—Smart grids aim at evolving the traditional electrical grid system by making increasing use of sophisticated control and communication network technology, to properly deal with the high penetration of controllable assets, such as distributed generators and flexible loads, and their associated challenges. Since electrical grids are critical infrastructures, control strategies regulating their operation need to face both efficiency and cost aspects, as well as resilience related ones in order to assure reliable service. Keeping the focus on the medium voltage control functionality, in this paper we present a study of the event-triggered voltage control algorithm to satisfy voltage control requirements. In particular, the opportunity to introduce soft bounds to improve preserving voltage values in bounds notwithstanding the effect of control delay is explored in a variety of scenarios, including fault presence due to attacks to the communication network. Through a developed stochastic model-based framework, quantitative analyses are performed on a realistic MV testbed grid, to demonstrate the feasibility and utility of the proposed contribution.**

***Keywords*-Electrical Smart Grid; Voltage Control Delay; Soft Bound; Model Based Simulations**

I. Introduction and Related Work

Smart grids aim at evolving the traditional electrical grid system by making increasing use of computer remote control and communication network technology. In order to improve efficiency, reliability and economics, more sophisticated electrical and control infrastructures to account for high penetration of controllable assets, such as distributed generators and flexible loads, are employed. In particular, due to the uncertainties and fluctuation characteristics of the new grid components, challenges are posed on several aspects, including the voltage quality from which depends the correct operation of the grid. Given that smart grids are critical infrastructures delivering services to a variety of resilience-critical sectors, such as transportation and health, requirements on keeping voltage values within specified bounds are imposed. Therefore, to satisfy such voltage requirements, a control strategy suitable for smart grids has to be developed and evaluated. In this paper, we adopt a typical hierarchical control structure, such as the one considered in [1] and [2]. It consists of four levels: the central management level, the medium voltage level, the low voltage level and the customer level. Each level of the hierarchy has an associated controller, with different objectives and different controlling scope. We restrict to the Medium Voltage grid controller, which typically accounts for four major functionalities: demand management, energy balancing, power loss minimization and voltage control. In the following, we focus on the voltage control.

A large variety of smart grids voltage control algorithms have been proposed. One classical control makes use of On Load Tap Changer (OLTC) [3]. Another approach exploits control of the active power or reactive power injected by distributed generators [4]. [5] presents an MPC-based algorithm to act on both OLTC and distributed generators. A genetic algorithm is presented in [6], where also a heuristic selection of control devices participating in the algorithm is employed to improve control efficiency. By applying these methods, a good voltage profile is maintained. However, these methods may encounter problems when used practically. In fact, one implicit assumption of these methods is that the voltage control is executed without any delay, but this is unrealistic in many scenarios since even a long delay is possible in presence of communication attack and other faults affecting the control infrastructure. Our study aims at overcoming this limitation, by addressing the study of voltage regulation in presence of disturbing conditions which impact on the ability of the control to avoid voltage values out of bounds.

The contribution of this paper is twofold. First, following the approach in [1], the formulation of an event-triggered voltage control strategy, is provided. Second, the analysis of the proposed control strategy is performed through a stochastic model-based approach, to investigate on the opportunity of enriching the voltage control formulation with soft bounds to activate the control in advance. The aim is to enhance control by preserving satisfaction of voltage requirements, in presence of delay and partial unavailability of voltage control functionalities, such as curtailment operations performed on renewable energy resources. In addition, cost aspects incurred by control are also considered. The rest of the paper is organized as follows. Section II is about the structure of medium voltage grid. Section III analyzes the voltage control algorithm, the effect of control delay and the control approach activated by the soft bounds. Simulation results and related analyses are described in Section IV. Section V draws the conclusions.

II. The Structure of the Medium Voltage Level

The adopted structure and characterization for the Medium Voltage (MV) level is the same as in [2]. It is composed of the Medium Voltage Electrical Infrastructure and the Medium Voltage Monitoring and Control System. The topology of each MV area can be modeled as a radial or partially meshed graph.

An arc (or branch) of the graph represents a power line with the associated electrical equipment, such as: switch, OLTC (transformer having voltage regulators at primary substations) and protection breakers, if any. A node represents a generator, a load or a substation or a combination of them. For simplicity of representation, each generic node, representing a station or substation, can be structured like a Bus-Bar (BUS) with the associated electrical equipment, such as: Distributed Generators (DGs) (volatile small-scale energy generating units, such as wind power plant and photovoltaic power plant), loads (both flexible and inflexible) and Capacitor Banks (CBs).

The state of the grid is monitored by MVGC. It interacts with the distribution management system and controllers local to the medium voltage grid components through a communication network. Concisely, the MVGC receives the values of the energy reference from the central control, and assigns to each distributed generator the values of power to inject on the node. Among the several control functions employed to accomplish the overall control task (as recalled in the Introduction), voltage control is addressed in the following.

III. Voltage Control

Voltage control on a distribution network is one of the most important functionalities for both the power suppliers and consumers. The voltage magnitudes of the busbars are required to be maintained within statutory limits for efficiency, security and reliability reasons. With a high penetration of inflexible loads whose power demand varies over time as well as the changing power generation of distributed generators, voltage problems like overvoltage and undervoltage possibly occur in the power network, negatively impacting on the delivered power supply. In fact, overvoltage conditions can create high current draw and cause the unnecessary tripping of downstream circuit breakers, as well as overheating and putting stress on equipment, while undervoltages can create overheating in motors, and can lead to the failure of non-linear loads such as computer power supplies. In order to keep the voltage within predefined bounds, the voltage control signals are issued to various voltage control devices, including CB, OLTC etc.

A. *Quantization of Control Requirements*

The aim of voltage control is to keep the voltage on each bus always within the bounds. More specifically, according to EN50160:2010 standard ”Voltage characteristics of electricity supplied by public electricity networks”, the voltage in the medium voltage level should satisfy the following requirement:

- MV. The $10\,\text{min}$. mean value of the supply voltage must be within 10% of the nominal voltage for 99% of the time, evaluated over a week.

In order to evaluate the effectiveness of the control algorithm, it is necessary to quantify the ability of the control to satisfy imposed requirements. To this purpose, the probability that the requirement is not met has been chosen as the representative measurement and it is defined as follows:

$$P_{\widetilde{MV}} = P(T_{out}(0, t_{eval}) > (1 - cl\%)t_{eval}), \tag{1}$$

where:

- cl is the percentage of evaluation time that the supply voltage must be within bounds.
- $\epsilon(t)$ is the relative voltage error between the nominal voltage $V_{ref}(t)$ and the actual voltage $V_{act}(t)$, defined as:

$$\epsilon(t) = \frac{V_{act}(t) - V_{ref}(t)}{V_{ref}(t)}. \tag{2}$$

  For simplicity, V_{ref} is assumed to be 1 voltage unit ($V_{ref}(t) = 1$). The upper bound and lower bound of the voltage relative error are ϵ_{max}, ϵ_{min}.
- $e(t - l, t)$ is l minutes mean value over time interval $[t - l, l]$ of the error at time t:

$$e(t - l, t) = \frac{\int_{t-l}^{t} \epsilon(u)du}{l}. \tag{3}$$

- $T_{out}(0, t_{eval})$ is the duration over the interval $[0, t_{eval}]$ for which the voltage goes out of bounds, defined as:

$$\int\limits_{\substack{0 \le t \le t_{eval} \\ |e(t-l,t)| > \epsilon_{max}}} 1dt. \tag{4}$$

B. *Optimal Voltage Control*

1) Voltage Control Formulation.: In the MV electrical grid, the voltage profile is sustained by controlling different devices and assets, like OLTC, capacitor banks, power plants, etc. The solution to typical optimal power flow problem [7] may indicate rapid changes of Tap positions of OLTC or reactive power injected/absorbed by the CB, which could bring damage to such kinds of electrical devices. The amount of operations on the devices can be considered as the cost of the control function. Moreover, the curtailment of active power production from the DGs should be minimized in order to maximize the use of the renewable energy. Taking the control cost and power curtailments into consideration, the objective function is decided to be:

$$\begin{aligned} \min & \sum_{i \in \mathcal{BUS}} w_V |V_i^{ref} - V_i| \\ & + \sum_{i \in \mathcal{RES}} w_{curt} |u_i^{max} - u_i| \\ & + \sum_{i \in \mathcal{RES} \cup \mathcal{FL}} w_{flex} |u_i - P_i^{flex}| \\ & + \sum_{(i,j) \in \mathcal{OLTC}} w_{tap} |T_{ij}^* - T_{ij}| + \sum_{i \in \mathcal{CB}} w_q |q_i^* - q_i|, \end{aligned} \tag{5}$$

subject to

$$P_h = V_h \sum_{k=1}^{n} V_k y_{hk} \cos(\theta_{hk} - \delta_h + \delta_k), \tag{6}$$

$$Q_h = -V_h \sum_{k=1}^{n} V_k y_{hk} \sin(\theta_{hk} - \delta_h + \delta_k), \tag{7}$$

$$u_i^{min} \le u_i \le u_i^{max}, \tag{8}$$

where,

- $\mathcal{OLTC}$ and $\mathcal{CB}$ are the sets of OLTC and CB, respectively.
- V_i^{ref} is voltage reference on bus i, P_i^{flex} is the current active power injected or absorbed (negative value) by the flexible asset i, q_i is current reactive power injected or absorbed by the i-th CB, T_{ij} is current tap position of the OLTC liked to the nodes i and j. Variables q_i^*, T_{ij}^* are corresponding reconfiguration values for grid component i after applying voltage control.
- $w_V, w_{curt}, w_{flex}, w_{tap}, w_q$ are the associated cost in order to guarantee that: (i) voltage is not out of bounds (w_V), (ii) curtailment of production is minimum (w_{curt}), (iii) fluctuation between subsequent values of controlled parameters are minimum (w_{flex},w_{tap} and w_q),
- u_i^{min} and u_i^{max} are minimum and maximum active power injected by the flexible asset i.
- The symbols in equations (6) and (7) have the same meaning as usual in the electrical field.

Although not listed, the typical constraints for the optimal power problem, such as the voltage and current limitations for each component in the grid, are considered by default. The control variables are the discrete variables q_i^*, the discrete variables T_{ij}^*, and the real variables u_i, the active power injected by the flexible asset i. V_i, which is voltage on bus i, is given by the solution of equations (6) and (7).

2) Failure Model: The voltage control is activated when the voltage reaches the strict bounds V_{max}^{hard} and V_{min}^{hard} (like voltage below 10% or above 10% of the reference voltage). The time taken by the control to compute and apply voltage control actions may crucially impact on the values assumed by the voltage. In fault-free conditions, the computation time of the control function, transmission time between the controllers at the different voltage levels and the time taken by the actuator (time required for OLTC to move from one tap position to the next one) account for a very small amount of time. Therefore, in most studies in the literatures, this amount of time is considered negligible. Instead, the occurrence of faults and attacks may delay the control to an extent which exposes the smart grid to the (potentially severe) effects of over/under-voltages. In our analysis, we focus on faults which generate the following failure conditions:

- *timing failure*, which induces a delay in the application of control (until potential omission of the control itself). Causes for such a failure can typically be an attack or a transient fault affecting the communication network;
- *control device failure*, which prevents control operation locally to a distributed generator, e.g. because affected by a crash fault. The impact of this kind of failure is that curtailment operations are not possible during the time the failure lasts, with effects on the resulting voltage profile.

3) Soft Bound: Obviously, when failures are experienced, the voltage of power system evolves for periods of time without control and could possibly go out of bounds.

One way to solve this problem is to trigger the control before the voltage reaches the bounds by introducing the soft bounds V_{max}^{soft} and V_{min}^{soft}, defined as:

$$V_{max}^{soft} = V_{ref} + K_{VCTRL}(V_{max}^{hard} - V_{ref}), \qquad (9)$$

$$V_{min}^{soft} = V_{ref} - K_{VCTRL}(V_{ref} - V_{min}^{hard}). \qquad (10)$$

where K_{VCTRL} is the reduction factor, with $0 \leq K_{VCTRL} \leq 1$. When the voltage is beyond V_{max}^{soft} or below V_{min}^{soft}, the voltage control will be triggered.

From the given formulation, it is expected that smaller values of K_{VCTRL} ensure better voltage quality, since actual voltage values are closer to the voltage reference. Instead, as K_{VCTRL} increases, the probability that voltage goes out of bounds becomes higher. However, better voltage quality is paid by higher control cost, since the control is activated more frequently. Our analysis framework allows comparing the quality of voltage and control cost at varying the values of soft bounds, thus resulting in a powerful support to identify the most suitable soft bound values for the system at hand.

IV. Soft Bound Analysis

In this section, the previously introduced concept of soft bound is analyzed. The study is performed through a stochastic modeling framework, developed to model structure and behavior of both the grid and control infrastructures. The framework is then exercised on a reference grid, considering failure scenarios in line with the assumed failure model. Obtained simulation results are presented and discussed.

A. The Modeling Framework

The Stochastic Activity Network (SAN) formalism [8] and the Möbius tool [9], a powerful multi-formalism/multi-solution tool have been employed to implement the smart grid modeling framework. This framework consists of a general and composable stochastic model populated by templates, i.e., generic atomic or composed models, each one representing a logical component of either the control subsystem (including the voltage control algorithm addressed in this paper) and the grid infrastructure. Full details of the developed models are out of the scope of this paper; they can be found in [10] [11].

The power flow equations represented in the SAN models are solved using the C++ library KINSOL, that is a solver for nonlinear algebraic systems based on Newton-Krylov solver technology, included in the suite SUNDIALS [12]. The Optimal Power Flow (OPF) problem represented in the SAN models is solved using the C++ library ParadisEO [13], that is a general-purpose software framework dedicated to the design and the implementation of single solution based metaheuristics and tools for fitness landscape analysis.

B. Testbed Grid

To exercise the proposed voltage control method and collect evaluation results in interesting scenarios, we adopted the Medium Voltage (MV) testbed grid developed in [1]. The definition of the grid topology and parameters are based on a small part of a Danish distribution grid, with parameters provided by the Danish DSO HEF. The grid, shown in Figure 1, is composed of 11 buses and 10 power lines. The

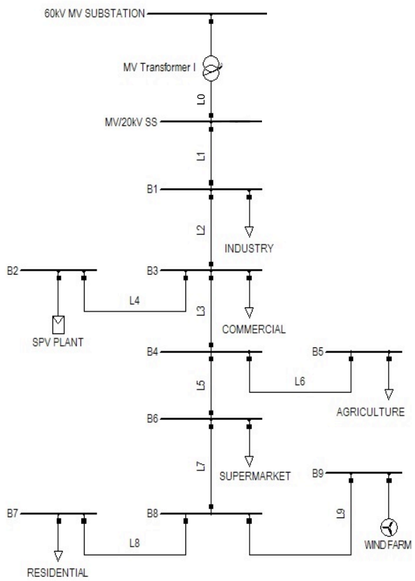

Fig. 1. Diagram of MV smart grid from SmartC2Net.

TABLE I
LINE PARAMETERS (BASE VOLTAGE 20 kV).

Power line	Resistence $(p.u)$	Reactance $(p.u)$
L0	0.0750	0.3250
L1, L2	0.0025	0.0025
L3, L5, L7	0.0163	0.0112
L4, L9	0.0325	0.0225
L6, L8	0.0400	0.0187

line parameters are shown in Table I. Two Distributed Energy Resource (DER), a photovoltaic power plant(PVP) and a wind power plant (WP), are linked to buses $B2$ and $B9$, respectively. The values of the active power generated from each PVP and WP are modeled by a stochastic process, representing the value of P, and the associated Q, at each instant of time t, where the time between two consecutive updates is a random variable with distribution uniform and parameters $(0.5\mu, 1.5\mu)$ ($\mu = 6\,\mathrm{min}$ is the mean). Five loads, representative of different consumer types, are considered; for the sake of simplicity, they are assumed constant, as shown in Table II. An OLTC is

TABLE II
LOAD PARAMETERS (BASE POWER $10MW$).

Consumer	P (p.u.)	Q (p.u.)
INDUSTRY	-0.57077626	-0.27643956
AGRICULTURE	-0.04566210	-0.02211516
COMMERCIAL	-0.05707763	-0.01876051
SUPERMARKET	-0.11415525	-0.03752102
RESIDENTIAL	-0.37956621	-0.09512826

linked to buses $60kVSS$ and $20kVSS$, with rating $50\,\mathrm{MVA}$, $60/20\,\mathrm{kV}$, 10 tap values and voltage per tap 1.25%.

C. Simulation Results

The simulated time for each experiment is one day. Considered failure scenarios include both a timing failure leading to a control delay and a failure of the control device used to actuate the set-points of the wind power plant. For the former, three values are considered: $10\,\mathrm{min}$ (delay=10min) and $30\,\mathrm{min}$ (delay=30min), and $0\,\mathrm{min}$ which represents the nominal fault-free condition (no delay). For the latter, a fault occurring at 12:00 and lasting for 60 minutes is assumed, leading to the injection of all available power generated by WP to the grid for the whole fault duration. So no power curtailment on WP is possible from 12:00 until 13:00. This WP failure is always considered in all the following analyses.

To address the problem brought by the considered failures, three different soft bounds are used to evaluate potential improvements on voltage profile, corresponding to the reduction factors $K_{VCTRL} = 0.4, 0.6, 0.8$. We take the probability $P_{\widetilde{MV}}$, defined in equation (1), as the metric to assess the effectiveness of applying soft bounds.

In Figure 2, the curves representing the active power generated by the two distributed generators WP and PVP are shown. This figure serves as reference of produced power at the two distributed generators, and it is helpful to better understand the voltage behavior shown in the other figures.

To have an overview of the whole addressed grid, Figures 3, 4 and 5 illustrate voltage failure probability $P_{\widetilde{MV}}$ for all buses, considering different control delays and different voltage soft bounds. Figure 3 shows that, even in absence of control delay, there is a small probability, about 0.016, that using hard bounds for the control activation results in voltage failure on buses $B1$, $B2$, $B3$ and $20kVSS$; instead, smaller soft bounds avoid voltage failure. When a control delay is considered, as in Figures 4 and 5, using hard bounds results in high values of $P_{\widetilde{MV}}$ for the majority of the buses, while smaller soft bounds significantly alleviate the problem.

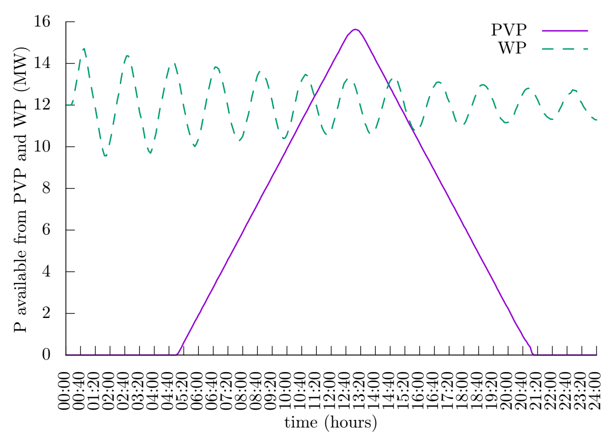

Fig. 2. Active power generated by PVP and WP.

To explain the reason leading to voltage requirements failure, in particular whether the failure is due to the peaks on the profiles of the power generated by PVP and WP (corresponding to the peaks on the voltage) or to the failure of the WP control device, we measured for each bus the expected voltage and the probability that the $10\,\mathrm{min}$ mean value of the voltage goes out of bounds at each instant of time. Figures 6

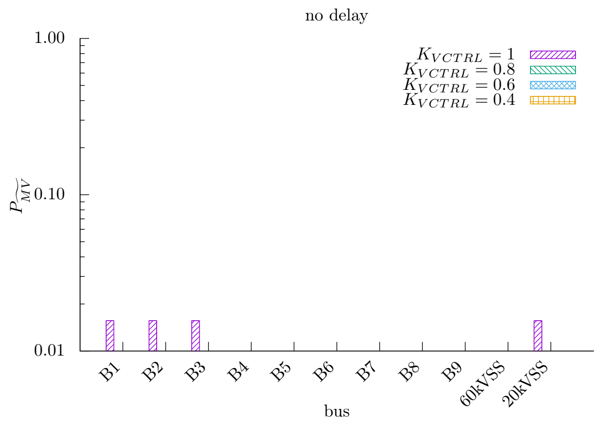

Fig. 3. Probability that the grid voltage requirement is not met, for all buses in the grid, when the control is not delayed.

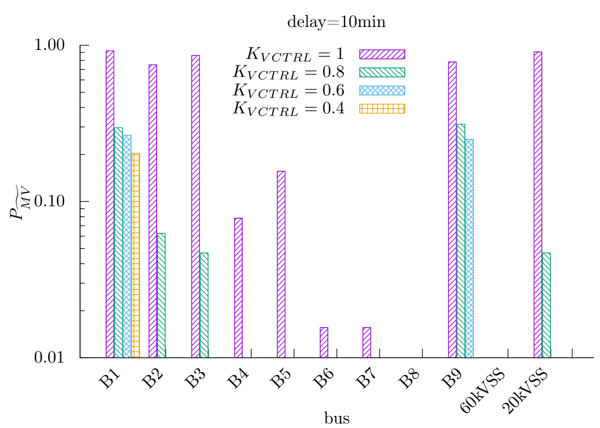

Fig. 4. Probability that the grid voltage requirement is not met, for all buses in the grid, when control delay is 10 min.

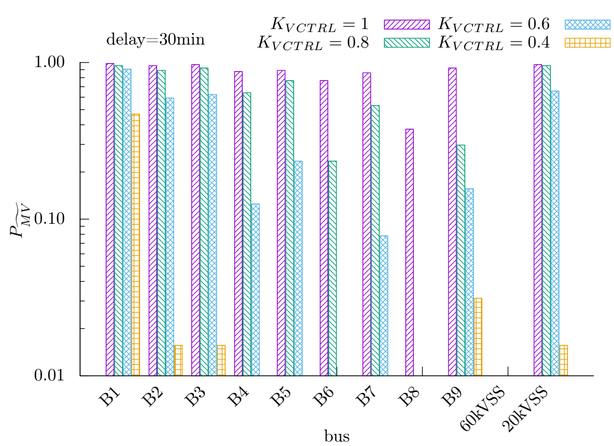

Fig. 5. Probability that the grid voltage requirement is not met, for all buses in the grid, when control delay is 30 min.

and 7 focus on the buses $B1$ and $B9$, when the control delay is 10 min and the soft bound is $K_{VCTRL} = 0.6$. Interestingly, although the mean values of voltage are in bound, in both figures there are time intervals where the probability to exceed the bound is greater than zero. In particular, Figure 6, compared with Figure 2, shows that the voltage failure on bus $B1$ is due to the variations of power generated by WP, while the failure of the WP control device does not show any noticeable impact. Figure 7 shows that the voltage failure on bus $B9$ is due to the failure of the control device of WP, that occurs at $12:00$, when the voltage exceeds the upper bound.

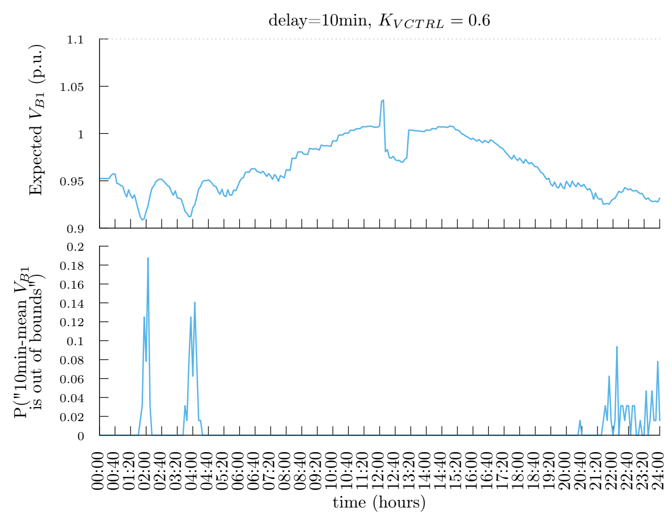

Fig. 6. Expected V_{B1} voltage profile and probability that V_{B1} goes out of bounds at different time, for $K_{VCTRL} = 0.6$, when control delay is 10 min.

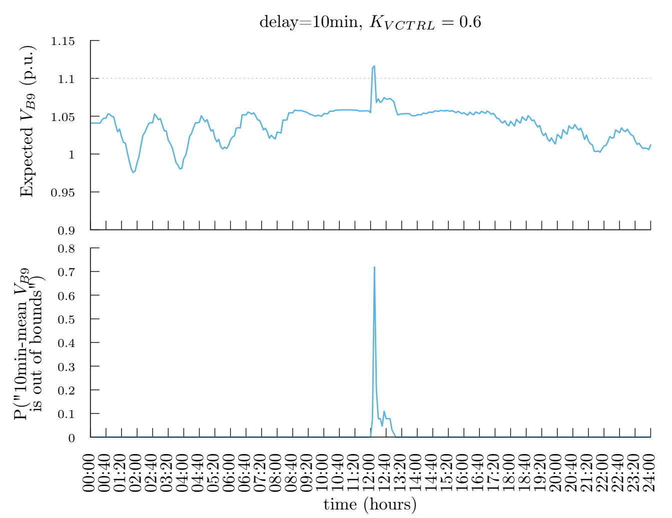

Fig. 7. Expected V_{B9} voltage profile and probability that V_{B9} goes out of bounds at different time, for $K_{VCTRL} = 0.6$, when control delay is 10 min.

The analyses so far have demonstrated the usefulness of soft bound to mitigate the effect of faults and delay in voltage control. However, the voltage profile is maintained by soft bounds at some additional cost. In fact, each control operation may imply the state changes of electrical components, such as OLTC and CB. Here, we measure control cost by the number of control activations over the analysis interval (24 hours) and by the overall curtailment of renewable active power generated by PVP and WP at each instant of time, as shown respectively in Figures 8 and 9, fixing the control delay to $10\,\mathrm{min}$ for three different soft bounds. As can be seen, control cost increases at

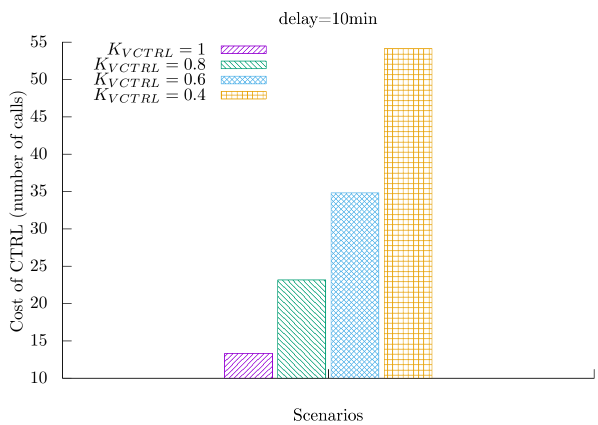

Fig. 8. Number of control operations under different soft bounds, when control delay is $10\,\mathrm{min}$.

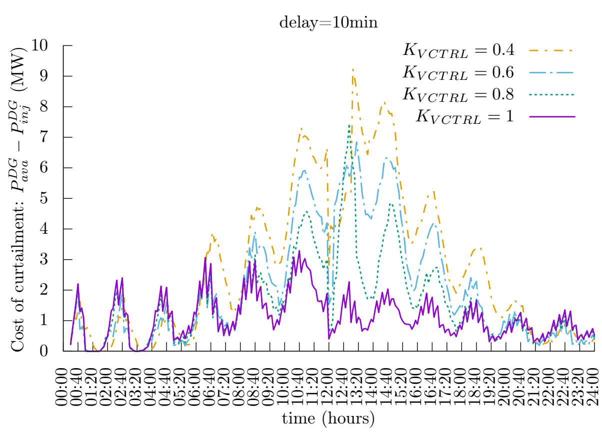

Fig. 9. The overall curtailment of renewable active power generated by PVP and WP, when control delay is $10\,\mathrm{min}$.

decreasing the value of soft bounds, meaning a higher number of activated control operations and a higher curtailment of renewable active power. Developing a convenient cost function which integrates these two aspects is postponed as future work.

V. Conclusion

This paper focused on the analysis of MV voltage control through a stochastic model based analysis framework. Based on the proposed voltage control algorithm, the goal was mainly to explore the opportunity to introduce soft bounds to guarantee grid voltage requirements when accounting for failure conditions affecting control operations. The proposed soft bounds bring benefit to keep voltage profile within predefined limits at increasing the delay of control operation, which typically occurs in presence of faults affecting grid components. Introducing control cost associated to changes of electrical components performed by control operations enriches the analyses and allows to investigate interesting trade-offs.

Although limited to the considered fault and power scenarios, this initial study has shown a good potential brought by introducing voltage control strategies adopting soft bounds. Refinements and extensions are desirable in several directions, including: i) more sophisticated fault scenarios, as source of a wider characterization of delay times; ii) more sophisticated cost function; iii) extended grid topologies.

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