Quantification of the effectiveness of medium voltage control policies in smart grids

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***Abstract*—Electricity generation from renewable sources is increasing significantly, pushed by the need to meet sustainable energy goals in many countries. Control is a key enabling technology for the deployment of renewable energy systems in smart grids and to guarantee high-performance and reliable operation. To this purpose, a large variety of control strategies have been proposed or are still under investigation, posing the challenge of understanding the effectiveness of the individual solutions and their ability to face operation in critical scenarios, such as in presence of failures.**

In this paper we focus on the medium voltage grid control and propose a stochastic modeling framework appropriate to represent a variety of voltage control strategies and to quantify their effectiveness in terms of suitably defined metrics to trade among multiple requirements such as imposed grid stability, reliability and cost. We exercise the developed modeling framework on a benchmark grid to show concrete quantification of medium voltage control solutions in interesting grid scenarios.

***Keywords*-Cyber-physical systems; Stochastic model-based analysis; Smart grids; SAN Formalism; Power system control.**

I. Introduction and related work

There are today growing interest and investments in electricity generation from renewable sources in many countries, pushed by the need to meet sustainable energy goals. The implications are that deploying renewable energy systems in smart grids requires revisiting traditional control technologies. In fact, solar and wind power require advanced control techniques for high-performance and reliable operation. To this purpose, a large variety of control strategies have been proposed or are still under investigation, posing the challenge of understanding the effectiveness of the individual solutions and their ability to face operation in critical scenarios, such as in presence of failures.

Model-based analysis is a suitable approach to perform quantitative estimations of a system since early stages, that is since the design phase. Therefore, it shows as a powerful means to support design decision, either allowing to make the most appropriate choice among several available alternative solutions and to facilitate tuning of parameters when parametric solutions are employed.

In this paper we focus on the medium voltage grid control and propose a stochastic modeling framework appropriate to represent a variety of control strategies and to quantify their effectiveness in terms of suitably defined metrics to trade among multiple requirements such as imposed grid stability, reliability and cost. Emphasis is posed on the occurrence of failures, both accidental and malicious ones affecting the cyber control system, and on their impact on the ability of the smart grid system to provide correct service as perceived by final customers as well as distribution system operators. The evaluation framework has been developed following the principles of generality and composability, to promote wide applicability in a variety of grid configurations and reuse also in further, potentially extended, scenarios. The developed analysis framework can be exploited for several purposes: i) to understand the relative benefits in employing a certain control algorithm among a set of available ones, so to operate the most convenient choice in accordance with defined criteria; ii) to support design and tuning of parametric control functions; iii) to analyze the dynamics of failures and potential system vulnerabilities, against which appropriate countermeasures need to be identified.

With reference to the distribution grid, most of the proposals in the literature address the analysis of the ICT infrastructure employed to guarantee efficient and reliable power supply, without considering explicitly the dynamics of the underlying grid infrastructure, or lightly introducing it. Our approach has a wider perspective, aiming at understanding the impact of ICT based control functionalities on the grid operation, especially in critical scenarios when failure events occur. Several studies present modeling approaches of cyber attacks to reveal vulnerabilities, perform impact analysis and assess the cyber risk, e.g. [1]–[3]. Our framework targets a comprehensive characterization of the fault model, including both accidental faults, affecting either the ICT control infrastructure or the electric grid, and cyber attacks to the ICT control, in addition to a special focus on the reciprocal dependencies originating failure cascading effects. In [4], a simulation study is presented to analyze the dynamics and mutual impacts of both the electrical grid and the smart ICT control; however the focus is on the evaluation of real-time performance indicators, while our objective is to assess resilience and QoS indicators, explicitly accounting for failures and their propagation.

The importance of analyzing the power grid and its supporting ICT together in one common model has been recognized as necessary to address interdependencies between the two infrastructures. Previous studies have mainly focused on interdependencies at the level of the electric transmission grid, such as [5]–[7]. More recently, in [8] a meta-model has been developed to combine the states of ICT and power grid components in smart grids, as a support to understand at high level the propagation phenomena through interdependencies. The analysis framework we deal with accounts for dependency aspects, trying to address the new challenges introduced when the distribution grid is considered and modeled at a rather detailed and realistic level.

The paper is structured as follows. Section II presents the Smart Grid logical architecture, whose representation in the modeling framework is then discussed in Section III. The benchmark grid, analysis scenarios and metrics are described in Section IV, with analysis results illustrated in Section V. Finally, conclusions are summarized in Section VI.

II. Logical architecture of the Smart Grid

In this section, we describe the main logical components of the Smart Grid (SG) to be considered in the modeling framework and their relationships, inspired by the EU SmartC2Net project [9]. The focus is on the Medium Voltage (MV) level of the SG, that is composed by: the Medium Voltage Electrical Infrastructure (MV-EI) and the Medium Voltage Monitoring and Control System (MV-MCS).

A. The Medium Voltage Electrical Infrastructure

The MV-EI is responsible for generating electric power at medium voltage, and for transporting towards the final users the electric power, partially received from the transmission system and partially generated at medium voltage. The MV-EI, physically connected to the high voltage grid and to the low voltage grid according to a hierarchical structure, is divided in areas, each containing a primary substation and electrical components located along the emanated feeders.

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 switch, On Load Tap Changer (OLTC) (transformer having voltage regulator) and protection breakers, if any. Each node is structured like a Bus-Bar (BUS) with the associated electrical equipment, namely:

- Distributed Generator (DG): Volatile small-scale energy generating unit, producing electricity from, e.g., Renewable Energy System (RES) (such as wind, hydro, solar/ photovoltaic). It can offer flexibility in the power profile, through power curtailment or redispatch.
- Inflexible Load (IFL): Classic load for which a loss of power is a blackout.
- Flexible Load (FL): Load that offer flexibility in the power profile. Electrical charging stations can be considered an example of flexible load.
- Distributed Storage unit (DS): Electrical device that can be considered either (flexible) generator or (flexible) load, depending on the state of the power system.
- Capacitor Bank (CB): Voltage regulator based on the injection of reactive power.

In [9], the characterization and behaviour of the considered electrical components have been detailed.

B. The Medium Voltage Monitoring and Control System

The MV-MCS is composed by three major components: Medium Voltage Grid Control (MVGC), Wide Area Network (WAN) and Logical Controller (LC). One MVGC is associated to each different primary substation. Each MVGC monitors and controls all the MV electrical components located along the feeders emanating from the primary substation, and that can be remotely controlled by an operator. Since MVGCs are not directly connected to the controlled components, the control operations are actuated through the pertinent LC, i.e., ICT-based components devoted to monitor and control an electrical component. A WAN for each MVGC connects MVGC and LC.

Different control functions are in place, to accomplish the overall control task. Research activity on control functionalities for future smart grids has gained much interest within both academia and industry since the introduction of the smart grid concept; the functionalities currently under investigation by the EU SmartC2Net project are demand management, energy balancing, loss minimization and voltage control.

- Demand management: it schedules the consumption of flexible consumers (loads) at times of low energy prices, to save money for the customers.
- Energy balancing: it must ensure that there is a balance between supply and demand in the electrical system. Thus, the responsible party for this functionality is the Transmission System Operator (TSO).
- Power loss minimization: it is in the interest of the Distribution System Operator (DSO), which must pay for the power losses in the distribution system. This functionality mainly operates redispatch of active power injected from Distributed Energy Resource (DER), such that power loss is minimum.
- Voltage control: it is under the responsibility of the DSO, who must ensure that the following requirements are satisfied for every bus bar of the MV grid: i) the 10 min mean value of the supply voltage must be within 10% of the nominal voltage for 99% of the time, evaluated over a week (requirement MV1) and ii) the 10 min mean value of the supply voltage must be within 15% of the nominal voltage (requirement MV2). Moreover, for cost reasons, it is important to minimize curtailment of production from RESs.

In this paper, we concentrate on the last three functionalities, although the proposed modeling framework can easily accommodate also demand management control.

C. Failure model

The performed analyses accounts for both correct and incorrect behavior of the MVGC system. In particular, timing failures are considered, which can result in delayed/omitted application of a setpoint when necessary. The cause for such failures can be either an accidental fault (e.g., a computer crash) or a deliberate attack (e.g., DoS attack). Propagation of the effect of the failure on the controlled MV-EI is then analyzed, by capturing in the analysis model the dependencies existing between the two infrastructures.

Although not exploited in this paper, the developed modeling framework allows to account also for content and inconsistent failures of the control system, resulting in wrong application of a setpoint (either when effectively required or a spurious one), as well as failures of selected grid components (namely, generators and loads).

III. Overview of the modeling framework

In this section, the developed modeling framework for SGs analysis is briefly outlined, following the logical architecture presented in Section II.

A. MV-EI state model

The state of MV-EI is composed by: (i) the discrete values representing the components that are connected to or disconnected from the electrical network, (ii) the continuous quantities active power (P), reactive power (Q), voltage (V) and voltage phase angle (δ) associated to each component, and (iii) the quantities representing the settings of the electrical control devices, such as OLTC or CB. The quantities P_h, Q_h, V_h and δ_h associated to each bus $h = 1, \ldots, n$ of a generic area are related by the following power flow equations:

$$P_h = V_h \sum_{k=1}^{n} V_k y_{hk} \cos(\theta_{hk} - \delta_h + \delta_k)$$
$$Q_h = -V_h \sum_{k=1}^{n} V_k y_{hk} \sin(\theta_{hk} - \delta_h + \delta_k) \quad (1)$$

where y_{hk} and θ_{hk} are, respectively, the amplitude and phase angle of the hk–th entry of the admittance bus matrix

$$y_{hk}(\cos\theta_{hk} + j\sin\theta_{hk}),$$

with $\theta_{hk} = 0$ and $y_{hk} = 0$, when the buses h and k are not connected by a line. The constraints of the electrical quantities are omitted for sake of brevity.

The system of $2n$ equations (1) can be solved using Newton–Raphson method [10], exploiting different types of buses according to $2n$ known and $2n$ unknown quantities, depending on the electrical parameters to be evaluated.

B. *Control functionalities model*

All the control functionalities performed by MVGC on MV-EI are not represented in detail, but a simplified model is considered where only their effects on the distribution grid are accounted for. In our model, the energy balancing and the loss minimization are accomplished periodically, while the voltage control is accomplished each time an event of over/under voltage occurs.

1) Energy reference and energy balancing: We assume that an energy reference, consisting in the values of the active and reactive power imported from the grid external to the area, is provided by an external system to the MVGC and that it is updated periodically by the external system. In our model, this energy reference is determined assuming both minimum curtailment of production from RESs and minimum curtailment of power demand, following the same method adopted for the energy balancing, as shown below.

The inputs of the energy balancing are: (i) the forecasted values of the active and reactive power imported from the grid external to the area for the next interval of time d, (ii) the forecasted energy available from the generators and the forecasted energy required by the loads for the next interval of time d, (iii) the flexibility, i.e., the possibility to increase or decrease the production or the consumption. The forecasted available and required energy are modeled by stochastic processes in terms of active P and reactive Q power associated to each generator or load at time $t >= 0$.

Both the energy reference and the new set points for the energy balancing are calculated by MVGC by searching the best combination of values of the control variables for which the values obtained for the unknown quantities satisfy the power flow equations (1).

The resulting Optimal Power Flow (OPF) problem is the following:

$$\min \sum_{i \in \mathcal{RES}} w_{curt} |\bar{P}_i^{fres} - u_i| + \sum_{i \in \mathcal{RES} \cup \mathcal{FL}} w_{flex} |u_i - P_i^{flex}|, \quad (2)$$

where,

- $\mathcal{RES}$ and $\mathcal{FL}$ are the sets of RES and FL, respectively,
- $w_{curt} > w_{flex}$,
- P_i^{flex} is the current active power injected or absorbed (negative value) by the flexible asset i,
- u_i is the control variable, representing the active power injected or absorbed by the flexible asset i, the corresponding reactive power is obtained based on the constant power factor of the asset,
- $\bar{P}_i^{fres}$ is the available active power for the RES i, as forecasted in the next interval of time $[t, t+d]$, given the current time t,
- $\bar{P}_i^{fres} - u_i$ is the curtailment of forecasted production from the RES i,
- $u_i - P_i^{flex}$ is the fluctuation between subsequent values of injected or absorbed active power,
- bounds and nonlinear constraints are provided by equations (1).

Equations (1) are evaluated at time t for the forecasted values of $\bar{P}_i^{fres}$ and $\bar{P}_i^{fd}$, being $\bar{P}_i^{fd}$ the demand of active power for the load i, as forecasted in the next interval of time $[t, t+d]$.

This is a non linear and non convex optimization problem, with mixed control variables. From its solution, we derive:

- the energy reference $P_{ref} = -P^{slackbus}$ (and the corresponding value for the reactive power Q_{ref}), where $P^{slackbus}$ is the active power imported from the grid external to the area,
- the total power to be produced or absorbed by the flexible assets $u_{ref} = \sum_{i \in \mathcal{RES} \cup \mathcal{FL}} P_i^{flex}$ (note that P_i^{flex} is negative for the flexible loads).

2) Power loss minimization: Power loss minimization is executed by MVGC each time interval d. Like for energy balancing, MVGC uses both available producers and consumers to minimize the power loss. The OPF problem solved is the following:

$$\min \frac{1}{2} \sum_{i,j=1}^{N} g_{ij}(V_i^2 + V_j^2 - 2V_iV_j \cos(\delta_i - \delta_j)), \quad (3)$$

with

$$\sum_{i \in \mathcal{RES} \cup \mathcal{FL}} u_i = u_{ref}, \qquad u_i^{min} \leq u_i \leq u_i^{max}, \quad (4)$$

where,

- $g_{ij} = Re(1/z_{ij})$, with z_{ij} the impedance of the power line (i, j),
- u_i is the control variable, representing the active power injected or absorbed by the flexible asset i, the corresponding reactive power is obtained based on the constant power factor of the asset,
- u_{ref} is the output of the energy balancing functionality, as described in Section III-B1,
- other bounds and nonlinear constraint equations are provided by equations (1),
- the objective function is the total power loss, as formulated in [11].

3) Voltage control: Voltage control is executed by MVGC each time an event of over/under voltage occurs. MVGC can use various traditional voltage control devices, including CB and OLTC. Moreover, like for power balancing and power loss minimization, it can use both producers and consumers, e.g., it can curtail the active power production of RES. Thus, the voltage control variables adopted in our model are:

- The discrete variable q_i^*, representing the reactive power injected or absorbed by the i-th CB, that is equal to cq_i^*, being c the parameter of the CB.
- The discrete variable T_{ij}^*, that is the tap position of the OLTC linked to the nodes i and j; different values of the tap position determine different values of the entries of the admittance bus matrix, thus changing the voltage on the nodes (buses) of the grid.
- The real variables u_i, defined in Section III-B2.

The OPF problem is the following:

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

where,

- $\mathcal{OLTC}$ and $\mathcal{CB}$ are the sets of OLTC and CB, respectively,
- $w_V > w_{curt} > w_{flex} > w_{tap} > w_q$ in order to guarantee that: (i) voltage is in 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_{oltc} and w_{cb}),
- P_i^{avres} is the current RES i active power,
- bounds and nonlinear constraint equations are provided by equations (1).

C. The composed model

The overall modeling framework consists of a general and composable stochastic model populated by templates, i.e., generic atomic or composed models, so as to be able to account for a variety of grid configurations and critical situations. The Stochastic Activity Network (SAN) formalism [12] and the Möbius tool [13], a powerful multi-formalism/multi-solution tool that has features adequate to the needs of our effort, have been employed for our purpose. By using the *join* and *rep* state-sharing compositional operators, which, respectively, compose or replicate sub-models, composed models are obtained.

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 [14]. The OPF problem represented in the SAN models is solved using the C++ library ParadisEO [15], 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.

Given the complexity of the system under analysis, tens of template models have been defined. Selected examples of such models are briefly introduced in the following, to give a taste of our compositional approach. Full details of the developed models are in [16].

The overall model is defined using the *join* operator by the composition of three submodels representing the MV level and the associated Central Management and Control System (CMCS) and Low Voltage (LV) levels, that are indirectly considered in the paper. The MV level is represented by the model MV_M defined composing the submodels MV_MCS_M and MV_EI_M, as shown in Figure 1. These sub-models represent, respectively, the components MV-MCS and MV-EI.

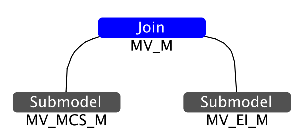

Fig. 1. Composed model representing the SG at MV.

The composed model MV_EI_M, depicted in Figure 2, is defined composing the atomic SAN models MV_EI_INIT_SAN and MV_ESTATE_SAN with the submodel MV_N1AN2_Ms. The submodel MV_N1AN2_Ms is defined replicating (assigning a different index to each replica) the template submodel

MV_N1AN2_M, that represents a generic arc of MV-EI with the generic associated starting and ending nodes [9]. The atomic SAN MV_EI_INIT_SAN initializes, at starting time 0, the index of the replicas of the template MV_N1AN2_M.

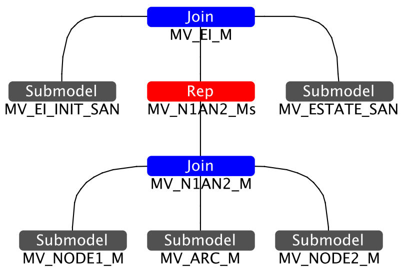

Fig. 2. Composed model representing the MV-EI.

The atomic SAN model MV_ESTATE_SAN, shown in Figure 3 updates the electrical state of MV-EI, at completion of the activity $UpdateES$, and updates the cumulated time measure for which the voltage control requirements are not satisfied, at completion of the activity $Trew$. The activity $UpdateES$ is enabled by events occurred in MV-EI such as the variation of the power generated by volatile generators or of the power demand on loads or failures, when the shared place $UpdateEState$ is updated. The new state is obtained in the outptut gate $NewES$ solving for each involved area the power flows equations (1). Each new electrical state of MV-EI can trigger control actions in the model MV_MCS_M, updating shared places $Control$ and $VOLT\_CTRL$.

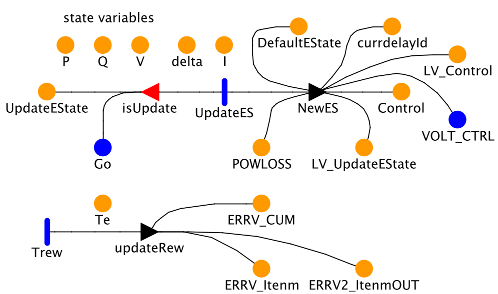

Fig. 3. SAN model MV_ESTATE_SAN.

The composed model MV_MCS_M, depicted in Figure 4, is defined composing the atomic SAN models MV_MCS_INIT_SAN with the composed submodels MVGCMs, MV_LC_Ms and MV_NCC_Ms.

The model MVGCMs is defined replicating (assigning a different index to each replica) the template submodel MVGC_M, that represents the MVGC with the associated WAN. The atomic SAN models MVGC_ATTACK_SAN and WAN_ATTACK_SAN are the templates representing the malicious failures of MVGC and WAN, respectively, caused by an attack to these components. The atomic SAN model MV_SP_SAN is the template representing the changes of the state of MV-EI at the actuation by LCs of the new set points derived by MVGC.

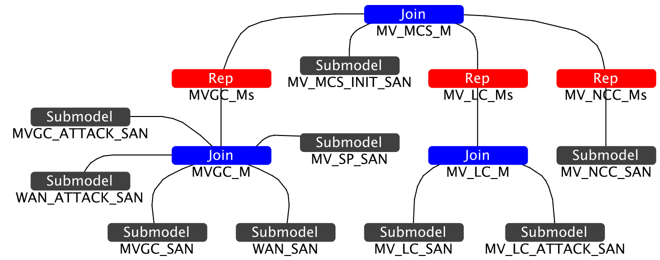

Fig. 4. Composed model representing the template model for MV-MCS.

The SAN MVGC_SAN models the activation condition and the execution of the control functionalities defined in Section III-B. All these activities are based on the state of the WAN and LC defined in WAN_SAN and MV_LC_SAN, respectively.

IV. Analysis scenarios, settings and metrics

Our modeling framework is well suited to analyze the effectiveness of control functionalities in terms of suitably identified indicators. Therefore, we exercised the three control functionalities, to understand the benefits deriving from the application of control in smart grids. We note that the developed framework is a generic one, not limited to the control functionalities currently implemented; new ones can be easily introduced, by properly setting the OPF problem with the objective function representative of the new control functionality. Hence, the framework is open to future extensions and can cover the needs of a variety of actors involved in the smart grids sector.

To exercise our modeling framework and collect evaluation results in interesting scenarios, we adopted the MV testbed grid developed in the context of the EU project SmartC2Net [17]. 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 5, is composed of 11 buses and 10 power lines. The line parameters are shown in Table I. Two DER, a Photovoltaic

TABLE I
LINE PARAMETERS.

Power line	Resistance (Ohm/km)	Reactance (Ohm/km)	Length (km)
L1, L2	0.10	0.10	1
L3, L5, L7	0.13	0.09	5
L4, L9	0.13	0.09	10
L6, L8	0.32	0.15	5

Plant (PVP) and a Wind Power Plant (WP), are linked to buses $B2$ and $B9$, respectively. The values of the active power P generated from each PVP and WP is 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 $(0.5\mu, 1.5\mu)$, where $\mu =$ 6min is the mean. The expected values obtained from our model are shown in Figure 6. Five loads are considered, representing different consumer

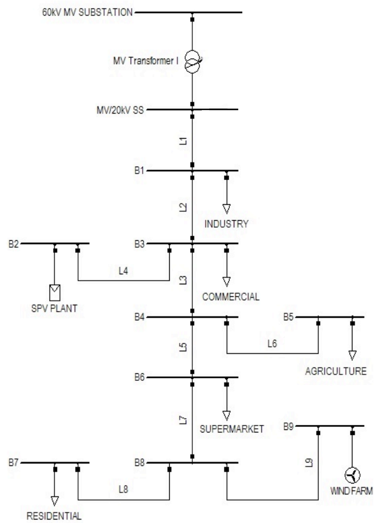

Fig. 5. Diagram of MV smart grid from SmartC2Net.

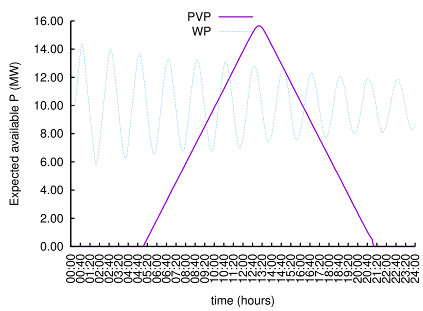

Fig. 6. Expected P available from PVP and WP.

types: Industry, Agriculture, Commercial, Supermarket and Residential. For the sake of simplicity, the values of loads are considered constants as shown in Table II. An OLTC is linked

TABLE II
LOAD PARAMETERS.

Consumer	P(MW)	Q(MW)
INDUSTRY	5.7077626	2.7643956
AGRICULTURE	0.4566210	0.2211516
COMMERCIAL	0.5707763	0.1876051
SUPERMARKET	1.1415525	0.3752102
RESIDENTIAL	3.7956621	0.9512826

to buses $SS60kV$ and $SS20kV$, with rating 50MVA, 60/20kV, resistance 3Ohm,reactance 13Ohm, 10 tap values and voltage per tap 1.25%.

The considered control functionalities are explored with reference to two scenarios: the case where no failure occurs, and the case where a failure affects the control functionality, namely the communication network supporting the control system and resulting in a delayed application of the setpoints elaborated by the control. Moreover, the case where no control is applied is also evaluated, to better understand the improvements brought by the control functionalities.

The stochastic model-based analysis is developed to allow assessment of a variety of measures of interest to final customers, service providers and operators. In this paper, we concentrate on the following indicators of interest:

- the voltage on bus h at time t ($V_h(t)$), measured at each time interval (e.g., at each time instant) within the considered analysis period;
- the probability that the 10 min mean value of $V_h(t)$, denoted as $V_h^{av10min}$, is not within 10% of the nominal voltage.
- the probability indicating the fulfillment of the requirements MV1 (exposed in Section II-B) for every bus bar of the medium voltage grid, as dictated by the European standard EN50160:2010. It somehow quantifies the deviation from optimal voltage profile, and is therefore an indicator of the power grid stability (in order to simplify the analysis the requirement has been evaluated over the considered analysis interval of 24 hours);
- ploss (i.e., the lost energy), at each time interval (e.g., at each time instant) within the considered analysis period.

These metrics are representative of the effectiveness of the analyzed control functionalities, since they express the degree of stability and reliability of the smart grid in delivering its service.

V. Analyses Results

The results of the performed analyses are illustrated in the following. For each numerical result we executed 120 simulation runs (batches).

A. Analysis of Voltage values

To understand the contribution of the control functionalities to keep voltage values within the requested bounds, we analyzed several scenarios, namely: (i) the case where no control is applied and no failure is experienced (labelled "no control"), (ii) the case where full control is applied, meaning that all the three control functionalities considered in the paper are in place and no failure is experienced (labelled "no failure"), (iii) the case where the failure of the control device of WP is experienced at time 12:00 for an interval of 1 hour, i.e. when all the available power generated by WP is injected being the control disconnected (labelled "WP CTRL failure"), and (iv) the case where full control is applied, but in presence of a Denial of Service (DoS) attack to the communication network supporting the ICT control, leading to a delay of 10 minutes in the application of the computed setpoints (labelled "delay=10min"). The results relative to voltage values are depicted in Figure 7, within the observation window of 24 hours. As expected from Figure 7, in case of absence of control, voltage values go outside the required bounds several times, while in the cases relative to the presence of control voltages values are always in bound (of course, with better voltage profile shown when no delay occurs). The effectiveness of control in keeping voltage within correct values is therefore immediately perceived.

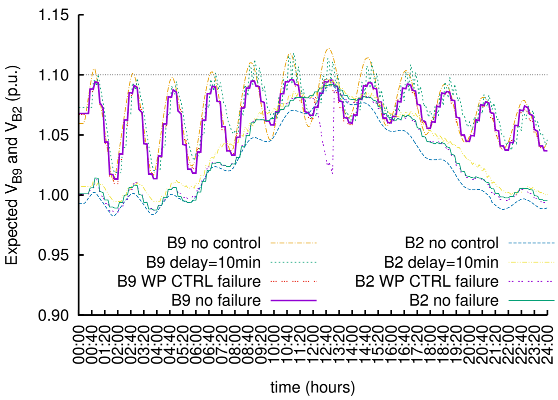

Fig. 7. Voltage of bus $SS20kV$ for different scenarios.

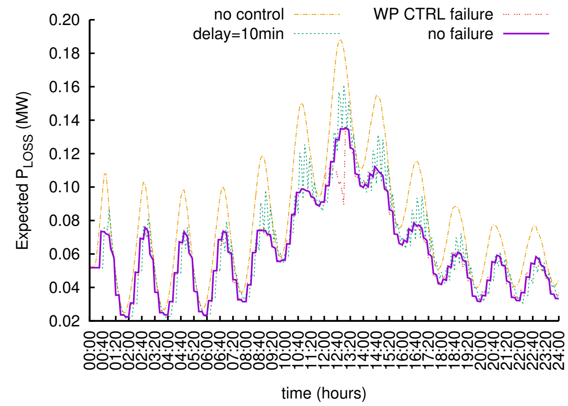

Fig. 9. Expected Power loss in different scenarios.

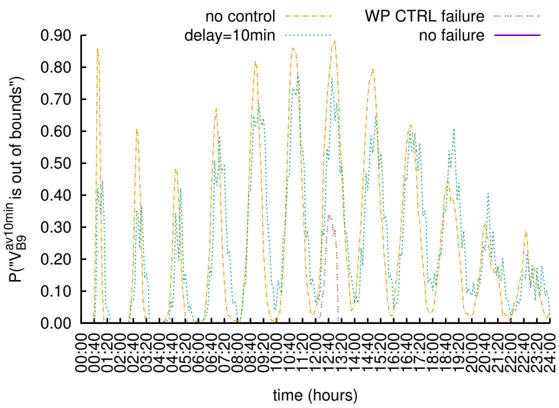

Fig. 8. Probability that the 10 min mean value of $V_h(t)$ is not within 10% of the nominal voltage, for buses $SS20kV$ for different scenarios.

B. *Analysis of energy loss*

The study of the power loss indicator has been performed considering the same three scenarios as in the case of the voltage indicator, identified with the same labels as in Figure 7. The results are shown in Figure 9, again considering the observation window of 24 hours. Not surprisingly, the best behavior is shown by the curve representing the full control in absence of failures. The curve relative to the absence of control shows rather significant fluctuations with expected loss up to 40%. However, surprisingly the worst performance is obtained by the curve relative to delayed control. Further investigations are currently in progress to shed light on this rather counterintuitive behavior.

C. *Analysis of power grid stability*

The probability indicating the fulfillment of the MV1 requirements for every bus bar of the medium voltage grid is shown in Figure 10. The four scenarios of absence of control in absence of failure ("no control"), full control in absence of failures ("no failure"), disabled control of WP ("WP CTRL failure") and delayed control in presence of a DoS attack to the communication network ("delay=10min") are compared. Following the trend already shown in Figure 7, the $MV1$ requirement is never satisfied in absence of control, it is satisfied in around 50% of the cases when delayed control is applied and it is almost always satisfied when full control acts in absence of failures.

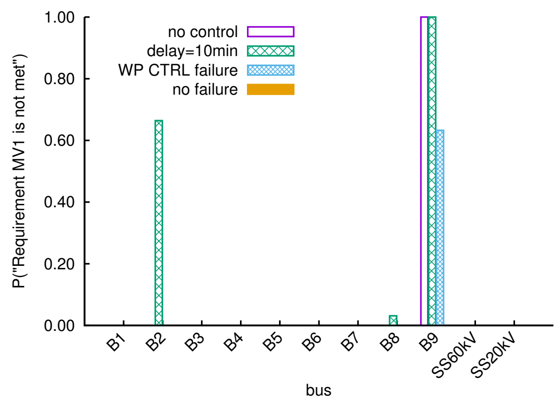

Fig. 10. Probability that the requirement $MV1$ is rejected for different scenarios.

VI. Conclusions

This paper has addressed the stochastic modeling and analysis of smart grid systems, to evaluate indicators useful to quantify the effectiveness of control functionalities, therefore expressing the ability of the system to assure delivery of correct service. The proposed general, modular and compositional modeling framework has been presented, with focus on three control functionalities employed to provide correct operation of the smart grid, in presence of flexibility in production and demand offered by high penetration of renewable energy resources. Analysis results are shown with reference to a benchmark grid taken from the real world, to demonstrate the applicability and usefulness of our solution.

The characteristics of generality and ability to be extended empower the developed framework with great potentialities to analyze electrical systems in a variety of critical scenarios. The results obtained so far invite to extend the investigations in a number of directions. Among those currently included in our future work, we list: i) extension of the scenarios under analysis, both in terms of additional failure events (such as the failure of selected electrical grid components) and in terms of considering flexibility at demand level; ii) analysis of additional indicators, to have a wider picture of the benefits of developed control functionalities as a guidance on how to potentially improve their design towards a greater effectiveness; iii) include in the modeling framework also control functionalities at LV voltage level, to explore scenarios involving both MV and LV grid levels.

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