Enhanced power grid evaluation through efficient stochastic model-based analysis

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Abstract—Electrical infrastructures provide services at the basis of a number of application sectors, several of which are critical from the perspective of human life, environment or financials. Following the increasing trend in electricity generation from renewable sources, pushed by the need to meet sustainable energy goals in many countries, more sophisticated control strategies are being adopted to regulate the operation of the electric power system, driving electrical infrastructures towards the so called Smart Grid scenario. It is therefore paramount to be assisted by technologies able to analyze the Smart Grid behavior in critical scenarios, e.g. where cyber malfunctions or grid disruptions occur. In this context, stochastic model-based analysis are well suited to assess dependability and quality of service related indicators, and continuous improvements in modeling strategies and system models design are required. Thus, my PhD work addresses this topic by contributing to study new Smart Grid scenarios, concerning the advanced interplay between ICT and electrical infrastructures in presence of cyber faults/attacks, define a new modeling approach, based on modularity and composition, and start to study how to improve the electrical grid dynamics representation. In this article these studies are briefly presented and discussed.

I. INTRODUCTION AND RESEARCH LINES DESCRIPTION

The complex, digital world around us requires electric power for fundamental aspects of societal needs, business and consumer activities. It is therefore widely recognized that electric power systems are among the most critical infrastructures, whose protection is more and more a priority for many countries. The increasing trend in electricity generation from renewable sources, pushed by the need to meet sustainable energy goals in many countries, poses additional challenges with the need to adopt more sophisticated control strategies to regulate the operation of the three-level electric power system: transmission, characterized by High Voltage (HV), distribution, characterized by Medium Voltage (MV), and consumer, typically characterized by Low Voltage (LV). In this panorama, studies devoted to analyze the effectiveness of control operations and their ability to face critical scenarios, such as in presence of failures, are certainly well motivated.

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. Analyses devoted to assess dependability-related indicators have already appeared in the literature. However, the emphasis has been mainly given to reliability and availability [1] of Information and Communication Tecnology (ICT) infrastructure employed to guarantee power supply, without considering explicitly the dynamics of the underlying Electrical Infrastructure (EI), as for example in [2], or lightly introducing it. Other studies, instead, focused mainly on the grid infrastructure, assessing, for instance, survivability [3] or reliability as defined in the electric sector, i.e., the ability of the power system to deliver electricity in the quantity and with the quality demanded by users, as in [4], neglecting the cyber control system and communications.

A more comprehensive viewpoint, targeting the interplay between the cyber control system with the underlying controlled grid, is needed, especially when failures occur and propagate their effects from one level to the other. As contribution in this direction, the SEDC research group at ISTI-CNR has been working in the last years on a stochastic modeling framework to perform quantitative estimations of resilience-related indicators, accounting for failure events and interdependencies between EI and ICT. The outcome of these analyses are especially helpful to understand the dynamics of relevant phenomena and the reaction of critical components to them, so to provide guidelines towards design improvements. Our modeling framework, from now on called SG model, is based on Stochastic Activity Network (SAN) [5] formalism and the analysis is performed via simulation so that domain specific (probability) measures are obtained with statistical inference. Although at a suitable level of abstraction to cope with the inherent complexity of the modeling effort and related solution methods, the framework accounts for both the EI and its ICT distribution control system, both at MV and LV level, to properly capture the impact of dependencies among the system components. The focus is on the analysis of accidental faults, malicious attacks and their propagation through existing interdependencies. Notwithstanding the great effort already invested in this modeling framework, the current implementation still needs enhancements. Especially, the ability to address large grid topologies is at the moment rather limited.

To this purpose, advancements in the adopted solutions would be greatly beneficial, in terms of both structural approaches supporting the development models and analytical solvers. This is the context where my PhD thesis intends to
provide contributions. In particular, two major aspects of our framework that strongly impact on performance, and so the ability to tackle large grid infrastructures, have been identified:

- the model composition operator, at the basis of a modular modeling approach as adopted in the framework,
- the Power Flow Problem (PFP) solution strategy, essential for the electrical grid state estimation.

Both definition of new model composition operator and PFP solution strategy are considered in my proposal, and of course these are assumed as basic starting points for the planned research investigations. Another category of enhancements is new scenarios and measures definition and analysis. In fact, the main research line promoted by our lab at SEDC-ISTI is the development of realistic scenarios of accidental failures or intentional attacks and the analysis of their impact on control operations. In nowadays distribution EIs, control strategies need to be tested upon dynamic environmental changes and with respect to a gamut of measures (voltage quality, demand fulfillment, power losses, propagation of blackouts, etc.), thus our framework has to be continuously refined to address analysis of sophisticated grid configurations and failure models.

Summing up, my PhD work is focused on three research lines: new scenarios definition and analysis, new model composer strategies definitions and implementation, and the study of PFP solution methods, as depicted in Figure 1.

![Research lines](image)

Fig. 1. Research lines, dashed boxes, with respect to SG model. PFP and Model composer have a direct impact on performance, while considering new scenarios enlarges model complexity and consequently can have also an impact on performance.

Structure of the paper: Section II presents interesting scenarios studied so far, describing the effects of faults or attacks originating from EI or ICT components; Section III briefly discusses three modeling choices we have already tested on a more general case study with the aim to select the best from the performance point of view; Section IV presents the PFP and discusses investigation directions; in Section V conclusions are drawn and future work is sketched out.

II. SMART GRID SCENARIOS DEFINITION AND ANALYSIS

The focus is on the MV level, that is composed by the Medium Voltage Electric Infrastructure (MV-EI) and the Medium Voltage Monitoring and Control System (MV-MCS). Considered complex control policies pose our model in the so called SG scenario [6]. In the following the name SG will refer to both EI and Monitoring and Control System (MCS) together. From a modeling point of view, the MV-EI can be represented as a radial or partially meshed graph, where:

- an arc 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. Those considered in the proposed modeling framework are:
  - Distributed Generator (DG): Volatile small-scale energy generating unit, producing electricity from, e.g., Renewable Energy System (RES) (such as wind, hydro, solar or photovoltaic). It can offer flexibility in the power profile, through power curtailment or re-dispatch.
  - Inflexible Load (IFL): Classic load for which a loss of power is a blackout.
  - Flexible Load (FL): Load that offers flexibility in the power profile. Electrical charging stations can be considered an example of flexible load.

Thus, both integer and real state variables are employed in order to capture the MV-EI dynamics in continuous time. In addition, the MV-EI state is evaluated via the solution of a PFP. These aspects pose modeling challenges and motivates the choice of SAN formalism.

As an example, consider the grid shown in Figure 2 taken from [7], that is composed of 11 BUSes, 10 power lines, one OLTC between BUSes $B_1$ and $B_2$, two DGs (photovoltaic at BUS $B_4$ and wind at BUS $B_{11}$), and five loads, among which four are IFLs and one (INDUSTRY at BUS $B_3$) is FL.

The MV-MCS is supposed to have a perfect knowledge of the MV-EI state and control actions are performed after an optimization problem is solved. These control actions pose modeling challenges that are addressed by our SG model taking advantages in particular of SAN gates [7], [8].

One aspect that has been emphasized in conceiving the modeling framework is the ability to account for a variety of failures, involving either the cyber control, or the grid infrastructure, or both. At the moment, only the effect on MV-MCS and MV-EI of failures are modeled, e.g., if the communication link between the MV-MCS and the OLTC fails at a given time instant then the voltage drop at the ends of the transformer is considered fixed from that moment on, but details about how and why the link has failed are not modeled. Once a failure occurs, its propagation inside the system is accounted for and the resulting impact evaluated. The analyses progressed by first considering the presence of individual failures, and then enlarging the failure events, to also appreciate the effects of simultaneous combinations thereof. In this paper, only failures affecting the cyber infrastructure responsible for the distribution grid control are presented; specifically, three types of failure have been considered in [7]:

- timing malicious failure, modeled as delayed/omitted application of (part of) the control actions;
- control device failure, modeled as an incomplete application of the control actions. Specifically, the failure of
following indicators have been evaluated:

- the voltage $V_i(t)$ on bus $i$ measured at each time instant $t$ within the considered analysis period;
- the probability that the value of $V_i(t)$ on bus $i$ is out of bound of the nominal voltage: either undervoltage $UV_i(t)$ or overvoltage $OV_i(t)$;
- the probability $P_{MV}^{\hat{i}}$ that 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 is not met on bus $i$ (in order to simplify the analysis the requirement has been evaluated over the considered analysis interval of 24 hours);
- the average unsatisfied power demand $UD_i(t)$ on load $i$ at each instant of time $t$.
- the average curtailment of available power $CA_i(t)$ on generator $i$ at each instant of time $t$.

Metrics 2) and 3) are representative of the degree of reliability of the smart grid in delivering its service, while metrics 4) and 5) express the effectiveness of the analyzed voltage control functionality in satisfying customers expectations. As an example, in Figure 3 measure 3), i.e., the probability $P_{MV}^{\hat{i}}$ that the voltage requirement is not met, is depicted for every BUS $i$ of the grid illustrated in Figure 2 comparing the impact of timing failure with respect to failures of the control device of Wind Power Plant (WP).

In order to compute measures 2) and 3) with a reasonably small confidence interval (e.g., $10^{-5}$) exercising grids of the size of Figure 2 or with 48 BUSes, as in [8], several hours of computation are needed on a Intel(R) Core(TM) i7-5960X with fixed 3.50 GHz CPU, 20M cache and 32GB RAM, an up to date GNU/Linux Operating System and using the Möbius Modeling Framework [9]. Being interested in addressing electrical grids with hundreds or thousands BUSes, such as in the IEEE118, IEEE300 testbed [10], [11] and the Illinois Center for a Smarter Electric Grid’s Texas synthetic grid [12], directions for improvements are presented in Sections III and IV.

III. NEW MODELING STRATEGIES DEFINITION

Abstracting away from the SG scenario, the logical structure of the considered systems comprises:

- A large number of cyber-physical components, weakly interconnected with each other according to physical and cyber topologies.
- One or more generic components. Each generic component groups all the specific components having common characteristics, i.e., homogeneous system components,
which, although different, share the same behaviour, structure and parameters. This means that a template model built for the generic component is adequate to represent the set of its specific components.

- A central MCS capable to communicate with each specific component.

As examples of weakly interconnected electrical components, in the IEEE118, IEEE300 testbed [10], [11] and the Illinois Center for a Smarter Electric Grid’s Texas synthetic grid [12], the interconnection degrees are numbers between 2 and 3 on average, with maximum value of 16 for the configuration with 2000 nodes. Electrical nodes are representable as instances of a generic component, called BUS; different electrical components, e.g., DGs and OLTCs, can be attached to each BUS, thus electrical nodes are identified by their position in the electrical grid and the list of components attached on them. In the rest of the paper, as an example of communication topology, we will consider the MV-MCS connected directly to all the MV electrical components.

In order to describe how the system logical structure is translated in our SG model, why the model can not scale at increasing the number of electrical nodes and my proposal for a new strategy to overcome the problem, some additional information concerning the modeling formalism and composition operators are needed. As already mentioned in Section 1, we opt for the SAN formalism [5], a stochastic extension of Petri nets based on four primitives: places, activities (transitions), input gates, and output gates. Primitive data types of the programming language C++, like short, float, double, including structures and arrays, are represented by data types of the programming language C++, like short, float, double, including structures and arrays, are represented by

Primitive data types of the programming language C++, like short, float, double, including structures and arrays, are represented by special places, called “extended places”. Input gates define both the enabling condition of an activity and the marking changes occurring when the activity completes. The output gates define the marking changes occurring when the activity completes, but they are randomly chosen at completion of the activity from a probability distribution function, defined by “cases” associated to the activity. The modeler defines input and output gates writing chunks of C++ code, thus having a great expression power. Composed models are obtained through two compositional operators, based on the sharing of places [13]:

- Join, composes, i.e., brings together two or more (composed or atomic) submodels. The expression

\[ M = \mathcal{J}(\{p_1, \ldots, p_m\}; SM_1, \ldots, SM_n) \]

means that the submodel \( SM \) is copied \( n \) times and the places \( \{p_1, \ldots, p_m\} \) are all shared among all the replicas. In [14], issues in modeling a large population of similar and weakly interconnected components were introduced and \( \text{NARep} \) served as starting point for the following discussion. We have identified three different modeling strategies that match the system logical structure. Starting from a model of the generic cyber-physical component, these strategies guide the automatic definition of \( n \) specific components:

- State-Sharing (SS): the generic component model \( \text{GENCOMP} \) comprises an indexing mechanism, the index-dependent behaviour model and the set \( \{s_1, \ldots, s_n\} \) of places, where \( s_j \) describes the portion of component \( j \) state that is relevant for some other component. \( \text{GENCOMP} \) is replicated \( n \) times and \( \{s_1, \ldots, s_n\} \) is globally accessible. Formally:

\[ \mathcal{R}_n(\{s_1, \ldots, s_n\}; \text{GENCOMP}) \]

This strategy, already presented in [15], is momentary implemented in our SG model [7]. It is a general solution, but its efficiency is limited by the fact that it assumes a complete graph of interactions among the replicated components. This assumption does not match with the great majority of real-world systems, typically composed by many loosely interconnected components according to regular dependency topologies (tree, mesh, cycle, etc).

- Channel-Sharing (CS): the generic component model \( \text{GENCOMP} \) comprises an indexing mechanism, the index-dependent behaviour model, a communication channel \( ch \) and the submodel \( CHMAN \) that manage the channel. Formally:

\[ \mathcal{R}_n(\{ch\}; J(\{ch\}; \text{GENCOMP}, \text{CHMAN})) \]

\( \text{GENCOMP} \) is replicated \( n \) times but only \( ch \), a light extended place, is shared among all the replicas. \( \text{CHMAN} \) regulates the channel usage and maintains in sync, inside each replica, a copy of portion of other components’ state. Synchronizations take place by means of instantaneous actions, thus dependability measures are not impacted by \( \text{CHMAN} \), but the price to pay is the increase of the events number. Details about this strategy and comparisons with SS will appear in EPEW2017 workshop proceedings [16].

- Dependency-Aware Replication (DARep): the generic system component is modeled by means of the template model \( \text{TEMPLATE} \) and the interdependency topology \( T_n \). Starting from \( \text{TEMPLATE} \) and \( T_n \), \( n \) new models \( \text{COMP}_1, \ldots, \text{COMP}_n \) are automatically created, where \( \text{COMP}_i \) contains \( s_j \), a portion of component \( j \) state, only if component \( i \) depends on component \( j \). All the component models are joined together, but each \( s_j \) is shared only among those models that need it. Formally:

\[ J(\{s_1, \ldots, s_n\}; \text{COMP}_1, \ldots, \text{COMP}_n) \]

A new composition operator that is capable to produce \( \text{COMP}_1, \ldots, \text{COMP}_n \) starting from \( \text{TEMPLATE} \) and
be observed the different trend of the two approaches with respect to \( d \). In fact, while the impact of \( d \) on \( \Delta \tau(1000) \) is very small in the table relative to \( SS \), in the case of \( DARep \) the value of \( \Delta \tau(1000) \) for \( d = 500 \) is about 1.6 the value for \( d = 1 \). This is not surprising, since \( SS \) always works under the implicit assumption of maximum interconnection among component replicas, so its sensitivity to variation of \( d \) is minimal, while \( DARep \) is influenced by \( d \), given the applied principle of considering only real replicas interdependencies. With respect to increasing values of \( n \), as expected the results obtained for \( \Delta \tau(1000) \) increase for both approaches. However, \( DARep \) can be about one order of magnitude faster than \( SS \) when \( n = 1000 \) and \( d \) up to 9.

### IV. Power Flow Problem Solution Improvements

In our SG model, the EI state is determined \([21]\) from the knowledge, for all BUS \( i \), of:

- injected power phasor \( S_i^q \).
- demanded power phasor \( S_i^d \).
- lines characteristics (admittance bus matrix \( Y_{bus} \)).
- relationship between power \( S_i^{bus} \) and voltage \( V_i \) given by

\[ S_i^{bus} = V_i \sum_{k} (Y_{bus})_{ik} V_k^* \]

- power balance equations

\[ G_i(V_1, \ldots, V_n) = S_i^{bus} + S_i^d - S_i^q = 0. \]

The PFP consists in extracting relevant information from the equations \( G(V) = 0 \). Notice that \( S_i^q \) is the sum of powers produced by DGs attached at BUS \( i \) and \( S_i^d \) is the sum of powers consumed by loads attached at BUS \( i \). Thus, during the simulation of the stochastic process described by our SG model, each new event, e.g. failure of a DG, can induce different values of power generated/requested and then a new PFP has to be solved. The most common strategy to solve the PFP consists in breaking up the complex set of non-linear equations \( G(V) = 0 \) in real and imaginary parts, and in considering the polar decomposition of voltages in order to obtain the real set \( F = 0 \) of \( 2n \) non-linear equations. The Newton-Raphson method \([21]\) is adopted to solve \( F = 0 \) but its standard formulation is inefficient and constitutes a relevant bottleneck during the SG model simulation.

To mitigate the impact of this computation, the Inexact-Newton-Krylov GMRES method \([22]\) have been proposed and implemented so that a gain in scalability with respect to the number \( n \) of BUSes is expected. TheINK GMRES is impacted by the equations ordering, as preliminary discussed in \([23]\), and particular choices of orderings can result in even better performance. Another strategy, originating from \([24]\), to solve the PFP requires the introduction of a new complex parameter \( s \) and the analysis of the set of \textit{functional} equations \( G(V(s)) = 0 \). This strategy, still to be detailed, is a promising alternative to the Newton-Raphson method in the SG scenario because, with adequate adjustments, can handle many similar PFPs with a single computation, with benefits in terms of computational cost over the entire model simulation.

### TABLE I

\( \Delta \tau(1000) \) in seconds for the SS Approach.

| \( n \)  | \( d = 1 \) | \( d = 9 \) | \( d = 99 \) | \( d = 500 \) |
|---------|------------|------------|------------|------------|
| \( 10^1 \) | 0.087 | 0.102 | | |
| \( 10^2 \) | 9.203 | 9.197 | 9.357 | |
| \( 10^3 \) | 1613.246 | 1723.666 | 1732.983 | 1754.996 |

### TABLE II

\( \Delta \tau(1000) \) in seconds for the DARep Approach.

| \( n \)  | \( d = 1 \) | \( d = 9 \) | \( d = 99 \) | \( d = 500 \) |
|---------|------------|------------|------------|------------|
| \( 10^1 \) | 0.0015 | 0.0022 | | |
| \( 10^2 \) | 0.774 | 0.817 | 0.972 | |
| \( 10^3 \) | 104.939 | 109.799 | 131.880 | 167.160 |

Tables I and II depict \( \Delta \tau_{SS}(k) \) and \( \Delta \tau_{DARep}(k) \) respectively, where \( k \) = 1000 simulation batches are considered for a variable number \( n \) of system components, each being dependent on a variable number \( d \) of other components.

Although the values shown by \( DARep \) are very small and significantly lower than the corresponding ones of \( SS \), it can.

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\( T_n \) have been defined; its implementation, in conjunction with the Möbius framework, is based on XQuery \([17]\). Details about this operator will appear in ISSRE2017 conference proceedings \([18]\).

All three approaches have been tested on a case study that is effective in demonstrating the features of the mechanisms, and can be considered as a basis to be easily extended and adapted to represent a great variety of real contexts, far beyond the SG scenario. We have considered \( n \) working stations dedicated to perform the same task in parallel. At every time instant, each station can either be working or failed, and the change of status takes place after an exponentially distributed random time. The failure of a station implies a reconfiguration of the workload assigned to the other stations, to continue accomplishing the tasks of the failed station. Just before failing, a station redirects its tasks to one or more other stations it is connected with, i.e. neighbouring stations according to the dependency topology. The stations that receive new tasks increase their workload, implying also a change of their failure rate. Thus, the model is a pure death process \([19]\) with monotone load sharing \([20]\).

We have modeled the case study following all the three strategies (\( SS \), \( CS \) and \( DARep \)) studying in particular how to transform the model that implements \( SS \) into models that implement \( CS \) and \( DARep \) in order to facilitate the change of strategy inside our SG model. Performance comparisons have confirmed the expected improvements. Results of a complete analysis will appear in \([18]\), and here, to illustrate the improvements, only time measures about \( SS \) and \( DARep \), obtained with the terminating simulator of the Möbius tool \([9]\), are briefly discussed. In particular, consider \( \Delta \tau(k) \) the difference between the total amount of CPU time, in seconds, used by one execution of the Möbius simulator that runs \( k \) batches and the amount of CPU time, in seconds, used by one execution of the Möbius simulator to initialize the data structures of the simulator.

- \( \Delta \tau_{SS}(k) \) is about one order of magnitude faster than \( SS \) when \( n = 1000 \) and \( d \) up to 9.
V. CONCLUSIONS

Moving from considerations on the need to promote efficient dependability and performability model-based analysis to properly address the increasing size of modern and future SGs, this paper presented three research lines I am addressing in the context of my PhD studies. New SG scenarios definition with high interaction between ICT and EI, and increasing level of details, is the main topic of my research. It presents modeling challenges from the performance point of view and then addresses new modeling strategies and new EI state representation via advanced PFP solution strategies. The main idea of new modeling solutions, CS and DARRep, is to exploit the actually existing dependencies among components of the system under analysis, instead of relying on the pessimistic situation of point-to-point connections as assumed by the already existing SS approach. The main idea of PFP solution improvements is to re-think the Newton-Raphson method and to study the applicability of its alternatives.

Extensions of the presented studies are foreseen in several directions, some of which are:

- new scenarios definition, in particular, introducing the interaction between HV and MV by means of a limited power interchange between them and new measures about the quality of service perceived not only by the electrical service provider but also by consumers,
- tackle source of failure, not addressed at the moment,
- re-design our SG model to include the DARRep approach and test it on large SGs,
- study different orderings of the equations arising from the PFP to increase the model simulation performance,
- study the feasibility of new PFP solution techniques, such as elaborations on $\bar{G} = 0$, application in the SG scenario,
- apply the DARRep approach in modeling system outside the SG scenario,
- a long term objective would be to define and making native in the adopted evaluation tool a new non-anonymous replica operator, based on the principle of DARRep.

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