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Co-Simulation and Discrete Event Simulation for Reliability Assessment of Power System and ICT: A Comparison

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***Abstract*—Modern power systems are increasingly relying on Information and Communication Technologies (ICT) to support their operation. This digitalization process introduces new complexity, which requires novel methodologies to assess the reliability of power systems. Currently, co-simulation and Discrete Event Simulation (DES) are the most popular approaches to analyse the complexity of power grids seen as cyber-physical systems, and to help decision makers in identifying potential sources of failures and implement mitigation actions. This paper compares these two methods. Co-simulation and DES approaches are applied to a power system voltage regulation case study, and the capability of the methods to assess unsolved overvoltages due to simultaneous failures of power system and ICT system is comparatively discussed. Simulation time and assessment of voltage regulation operational costs for both methods are also compared. The paper's main goal is to provide guidance to researchers in evaluating and developing the most suitable simulation approaches for reliability studies in cyber-physical power systems.**

***Index Terms*—Co-simulation, Discrete Event Simulation (DES), Smart Grid, Reliability Assessment, Cyber-physical system modelling**

I. Introduction

During the last decades, electric power systems have been increasingly dependent on Information and Communication Technology (ICT) for monitoring, control and protection of the power system. In this context, traditional methods for studying power system reliability [1], [2] must be adapted. In fact, the advantages of a digitalized operation of the power system is accompanied by an increase of potential sources of failures, hidden vulnerabilities and overall complexity of the power system. For this reason, new methods for reliability assessment of modern cyber-physical power systems are currently being developed, which specifically take into account, in addition to the intrinsic failures on power grid components, ICT system failures and the interdependencies between ICT and power systems. Cyber-physical power system reliability assessment methods' main goal is to help decision makers and planners in identifying potential sources of failures and mitigation actions. In order to assess the economic sustainability of these mitigation actions, novel reliability assessment methods are required to provide a quantification of the impact of cyber-physical failures.

In general, reliability assessment methods for cyber-physical power systems are based on simulation, and can be classified in two categories:

- *Co-Simulation*. This method generally merges two different simulation approaches, according to the most suitable simulation approaches for the different subsystems: the power systems are typically simulated iteratively with a fixed discretization time step (Continuous State-Discrete Time – CS-DT), whereas the ICT system is simulated with a Discrete Event approach (Discrete State - Continuous Time – DS-CT).
- *Discrete Event Simulation (DES)*. This method implies the full discretization of both systems in the state domain (DS-CT) and is *event-driven*, in the sense that only time instances where a change in the state domain occurs are simulated.

CS-DT simulation is the most frequently used approach in simulation of power systems. Power system state variables, such as voltages and currents, are defined in the continuous state domain. A time discretization, for example from 15

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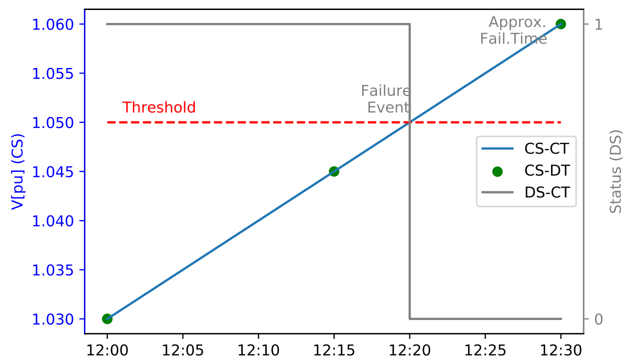

Fig. 1: Differences between CS-CT, CS-DT and DS-CT approaches

minutes to 1 hour, is used to perform iterative simulations to inspect a sequence of snapshots of the state of the system.

DES approaches (DS-CT) are dominant in simulation of ICT systems. In this case, a set of discrete states is assumed (for example, working state and failed state), and events take place in the continuous time domain and may cause a change of state.

Fig. 1 presents a simple graphical illustration of how a specific voltage level is dealt with by the different simulation approaches. Continuous state - continuous time (CS-CT) simulation implies a continuous representation of the state variables both in state and time domains. Typically, in power system applications, state variables time series are available with a discrete time step, therefore the information available will be represented by the green dots in the figure (CS-DT). It can be observed that with this approach the exact time when the voltage crosses the threshold of 1.05 is not available, and the failure time will be approximated to 12:30. With DS-CT representation, the state of the variable is approximated to two states: 1 (acceptable operational state) and 0 (failed operational state). With this approach the time to failure is correctly represented, nevertheless the information regarding the actual voltage at time t is lost.

In order to increase the accuracy of the model, the number of time discretization points or state discretization points can be increased. This decision typically implies an increased computational time of the simulation, therefore a compromise between computational time and accuracy of the model must be found when designing the model. Discretization of the state space should be defined taking the need for state information into account. E.g., to estimate the time average of the voltage level we need a fine grained discretization, while we need only two states to distinguish between over-voltage and not over-voltage.

Co-simulation methods are used in different works to study the impact of combined ICT – power system reliability in smart grids. The availability of solid power system and ICT simulators (both commercial and open source) increases the trustfulness of co-simulation results compared with alternative approaches. The main challenge with this approach is related to the necessity of a shared scheduler that is able to synchronise ICT and power system simulators, and allow data sharing between the two parallel simulations [3]. Nevertheless, co-simulation can also be implemented with ad-hoc simulators purposely developed and coupled [3]. Co-simulation is widely used for studying most of the operational contexts in smart grid domain, such as monitoring [4], [5], control [4]–[7] and protection [4].

Among DES-based methods, sequential Monte Carlo is the approach most frequently used for studying ICT-power system joined systems [8]–[10]. These methods typically require long time for achieving a statistical significance of simulation results, especially when the events inspected (such as simultaneous failures of ICT and power systems) are rare. Alternative approaches are based on agent-based modelling [11], Petri Nets [12], and Stochastic Activity Networks [13], [14]. An overview of some of the above mentioned methods and other approaches identifying interdependencies that arise in time dependent processes, for analysing the reliability of combined ICT and power system, can be found in [15].

In this paper, both the co-simulation- and DES- based approaches are used to formulate reliability models and assess a combined ICT and power systems. Both approaches are developed exploiting open-source python libraries: pandapower [16] for power flow calculation, and SimPy [17] for discrete event modelling and simulation. The simulators developed are employed for studying the impact of ICT failures on a voltage regulation application in a radial distribution grid with high penetration of distributed generation. Advantages and disadvantages of both approaches are thoroughly discussed, and future research directions are suggested.

II. Methodology

In this section, the voltage regulation process is first discussed in II-A. In II-B, a co-simulation approach for voltage regulation modelling is presented. In II-C, an alternative approach based on DES modelling is presented.

A. Voltage regulation process

The system analysed is a distribution network centralised control system for voltage regulation.

The system is formed by:

- **The power network**. A radial distribution network is considered; distributed generation (DG) is assumed to be connected to the grid, with availability to support voltage regulation.
- **The ICT system**. A simple information and communication infrastructure is considered: a remote server monitors the bus voltages, and sends a signal through a communication link to the Distributed Energy Resources (DERs) when a voltage regulation support is needed with the new generation set points. Each DER is equipped with an Intelligent Electronic Device (IED), which converts

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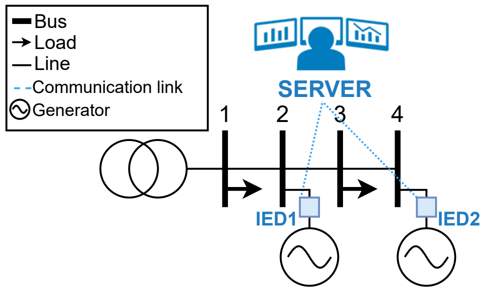


Fig. 2: Illustration of the combined ICT-Power System modelled

and actuates to the DER the signal computed by the server.

In Fig. 2, an illustration of a simple combined ICT and power system is shown. Two DERs are connected to the power system, and are digitally connected to the server through a communication link and an IED. The communication link represents a generic communication channel where the dependability of additional networking devices such as switches and routers is included. For simplicity, a star topology is adopted in the paper.

The voltage regulation process is graphically explained in Fig 3. Input data is provided by a trace database of load and generation power profiles, which are applied to the different loads and generators connected to the radial distribution network. These profiles are converted to voltage traces through a time-series power flow (Fig 3a) The voltage trace represents the result of an ideal perfect state estimation algorithm. In this paper non-idealities in the power system monitoring are not considered, therefore failures in monitoring devices and monitoring communication system are neglected.

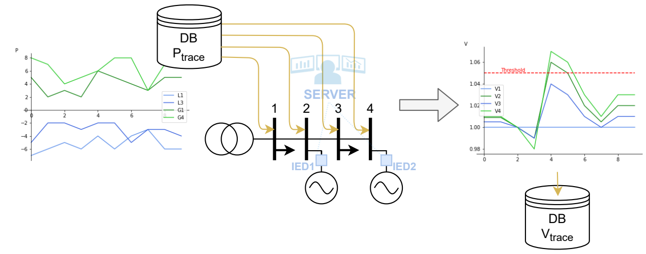
When an overvoltage is detected on a network bus, the server computes an optimal control on DERs: power variation from the scheduled generation are calculated with an Optimal Power Flow calculation (OPF) and delivered to the DER through the ICT infrastructure (Fig. 3b). If server, communication link and IED are unaffected by failures, the signal is correctly delivered and the power variation applied; otherwise, the generation units inject the scheduled power to the network.

B. Co-Simulation platform

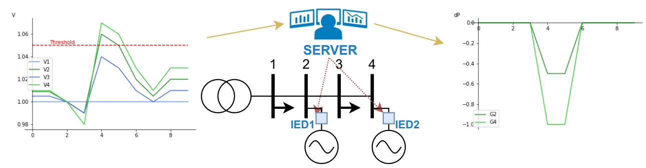
An example of a co-simulator for modelling the voltage regulation process explained in II-A is represented by the activity diagram in Fig. 4.

It can be observed that the diagram is composed of two main sections:

1) **Power System**: the simulation is stepped forward in discrete time intervals, i.e., it implements a CS-DT model. At each time step t:
   - Load and generation profiles are obtained from the input database DB $\mathtt{P_{trace}}$ referring at time t.
   - Voltage profiles are calculated through power flows, and Overvoltage condition is checked.



(a) Voltage trace creation from Power trace database (load and generation profiles)



(b) Server computation of new DG set points during overvoltage

Fig. 3: Voltage regulation application to Distributed Generation

   - If no voltage violation is detected, then proceed to the next time step $t + 1$.
   - Otherwise, optimal power flow is calculated. Two modes are represented:
     – *Smart operation*: DERs are queried before OPF calculation. Preliminary query allows to check if the resources are reachable through the ICT infrastructure, or if the ICT connection is out of service (see paragraph II-B.2), and to blacklist temporarily unreachable DERs from the resources dispatching.
     – *Naïve operation*: OPF is calculated without preliminary query of DERs' reachability through ICT infrastructure, then the new set points are delivered and applied to the resources if the ICT connectivity is available, i.e. if no failure is occurring in the ICT connection to the DERs.

2) **ICT system**: the ICT resources are modelled with a pure DES approach: each DER is controlled through a centralized server, a link and an Intelligent Electronic Device (IED). These ICT devices allow the signal from the server to be delivered and applied to the resource. In order for the DER to be available, IED, Link and Server should all be simultaneously available.
   - The time to failures ($\mathtt{TTF}$) and time to repair ($\mathtt{TTR}$) of the links ($\mathtt{L}$) are random variables denoted $\mathtt{TTF_L}$ and $\mathtt{TTR_L}$, respectively.
   - The servers ($\mathtt{S}$) and IEDs ($\mathtt{IED}$) can fail both due to hardware ($\mathtt{hw}$) and software ($\mathtt{sw}$). The random variable for the time to failures is denoted $\mathtt{TTF}_i$, and the time to hardware and software repair $\mathtt{TTRhw}_i$ and $\mathtt{TTRsw}_i$ ($i = \mathtt{S}, \mathtt{IED}$).
   - Software failures are typically resolved by restart or reboot, and hardware failures repaired by a repairmen with physical presence. After failure is

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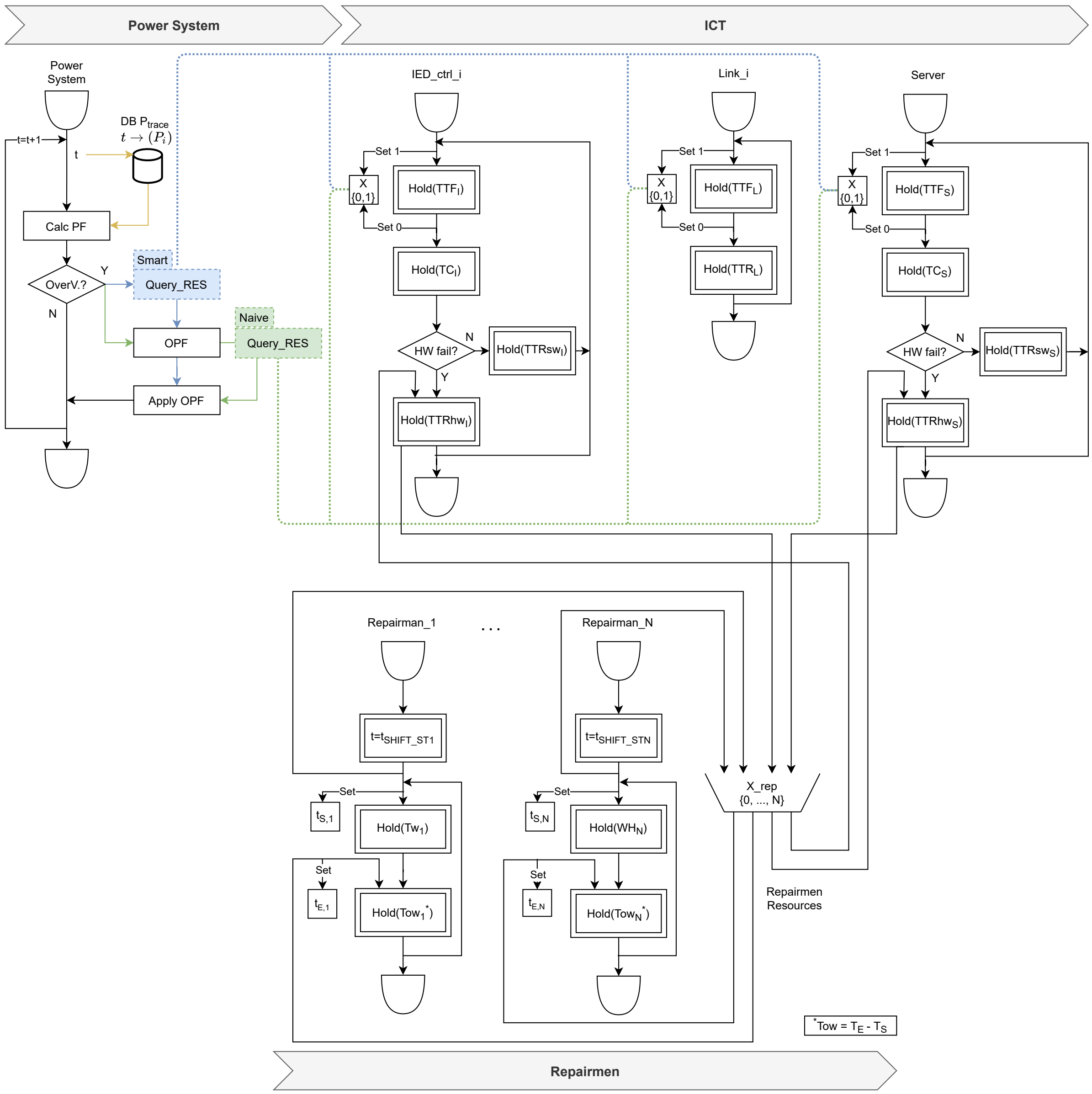

Fig. 4: Activity Diagram of combined ICT-Power System model for Smart Grid control according to co-simulation principles.

detected, a process (TC) checks if the failure state is due to hardware or software failure. The probability of hardware failure Phw is modelled with a uniform probability distribution.

- Each repairman (R) is either at work or off work. During working hours, the repairman is available for repairing hardware failures on both the IEDs and the server. When a hardware failure occurs, a repairman is requested and must be available (and granted) before the repair process is initiated. The time at work is $T_{\mathtt{w}}$ and offwork is $T_{\mathtt{ow}} = 24 - (t_E - t_S)$, where t_S is the shift starting time and t_E is the shift ending time ($t_E - t_S$ can be higher than Tw when a repair process terminates over the shift: it is assumed that the repairman does not leave work until a repair process, if initiated, is completed).
- During the uptime, the state variable (X) of the resource is set to 1, and during downtime it is set to 0.

Due to the fixed discretization time-step, this modelling approach emulates a voltage regulation process where the server intervention occurs with specific time intervals. If power trace databases discretization and voltage regulation time interval coincide, the simulation should provide an accurate assessment of operation costs. Nevertheless, any voltage violation between two consecutive time-steps cannot be captured by this method, therefore overall overvoltage duration and power quality - related costs may be not correctly assessed.

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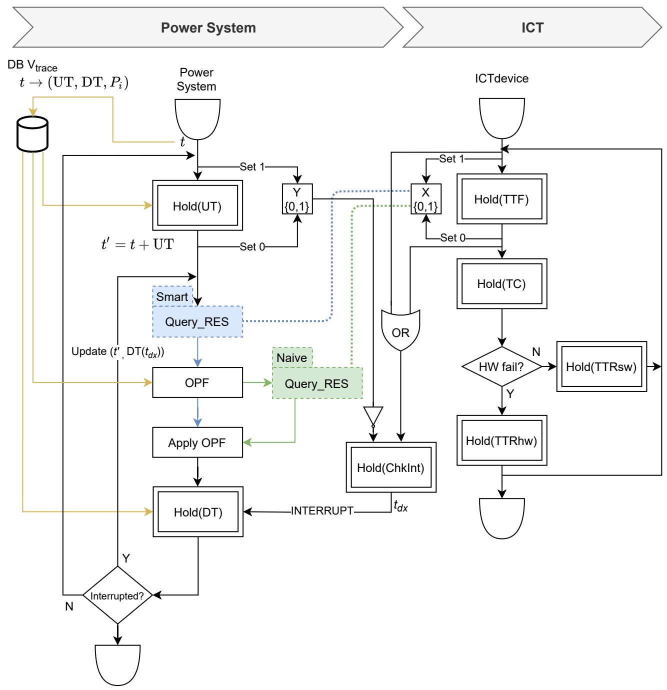

Fig. 5: Activity Diagram of the redesigned Power System model for Smart Grid control according to DES principles

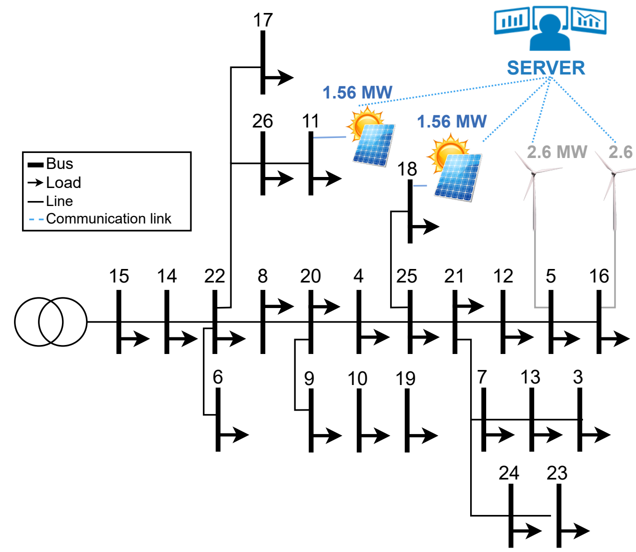

Fig. 6: Test network: single feeder rural distribution grid.

C. Discrete Event Simulation

The ICT system in previous section is already modelled using the DES approach. In order to have a full compliant DES model, the power system has to be remodelled with the same approach (see Section I).

Fig. 5 shows the activity diagram that models the power system in DES approach. First, a pre-processing of the input data is done: a time-series power flow is performed on the `DB P`$_{\texttt{trace}}$, and the voltage profiles are stored in a new database trace (`DB V`$_{\texttt{trace}}$, see Fig. 3a); uptime (UT) and downtime (DT) of the power system are then identified, i.e., the average time after which a power system contingency (e.g. an overvoltage) occurs. Typically, in power system operation these time intervals show a daily and weekly quasi-periodicity, therefore different UT and DT can be extracted and applied for each weekday. Power profiles P_i are also stored in the database for OPF calculation. When a failure occurs in the power system, the OPF (and the resources query) is calculated for the time instance where the voltage state change has occurred ($t = UT$) and applied for all $t \in DT$. In order to capture the interdependencies between power system and ICT devices states, these models share their state variables, Y and X, respectively. In particular, in order to capture the effect of a state transition in ICT devices during power system downtime, which affects the OPF application to the DERs, the process `Hold(DT)` is interrupted, and the OPF calculation during DT recomputed by taking into account the state variation in t_{dx}. Also in DES approach, *smart* and *naïve* operation modes are implemented.

Due to the event-driven approach, the Discrete Event Simulation emulates a voltage regulation process that continuously monitors the voltage state and intervenes when a violation occurs. If the voltage trace database is sufficiently fine grained, an accurate estimation of overvoltage duration can be obtained with a relatively low computational costs (see section IV for details). Nevertheless, information regarding power and voltage magnitudes is lost in the state discretization described, therefore costs assessment may be imprecise.

III. Case Study

The simulators described in Section II have been applied to the network shown in Fig. 6. The network is a rural network that is based on a reference network of the ATLANTIDE project [18]. The feeder is about 15 km long with several lateral branches, with 26 MV nodes supplied by one HV/MV substation. Four Distributed Energy Resources (DERs) power plants are installed in the network: two PV power plants of 1.56 MW size are connected to nodes 11, and 18, two wind turbines of 2.6 MW size are connected to nodes 5 and 16. In addition to power generation, these power plants provide ancillary services to the network, such as availability to generation curtailment for supporting voltage regulation. Load and generation profiles are represented with a half an hour time-step discretization.

Each generation plant is provided with an IED, which is connected to a central controller through a wireless communication link. Each ICT device (IED, communication link and controller server) is subject to random failures and repair processes. These failures and repair processes are modelled with negative exponential probability distribution. The usage of negative exponential distribution is due to the lack of empirical information about the distribution of these events, combined with the lack of sensitivity in the results to their distribution. This is considered a fair assumption, as long as

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TABLE I: Failure rate and repair time of ICT components of the power grid communication system (adapted from [13])

	TTF [1/h]	TTRsw [h]	TTRhw [h]	Phw
IED	$1.08 \cdot 10^{-3}$	1	2	0.1
Server	$6.94 \cdot 10^{-4}$	1	2	0.1
Link	$3.6 \cdot 10^{-1}$	$2.77 \cdot 10^{-4}$	-	-

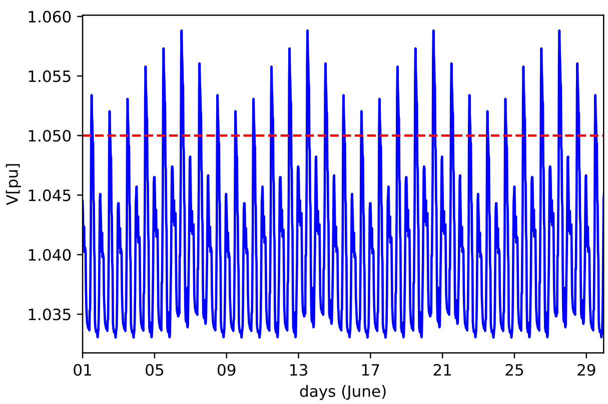

Fig. 7: Preliminary investigation of overvoltage occurrences in the network.

the repair and recovery times are short compared to the time between failures. Failure rates and repair time values of each device are reported in Table I.

The power plants have two cost components, (i) c_{OPF}, is the cost associated to the generation curtailment service provided to solve overvoltage contingencies (1), and (ii) c_{PQ}, is the cost is associated to power quality issues: distribution grid is subjected to a penalty cost for each load supplied with voltage over the $1.05pu$ threshold for each hour (2).

$$c_{\text{OPF}} = 42.14 \cdot P_C \cdot t \ [€] \tag{1}$$

where in P_C is the power curtailed by the OPF calculation (in MW) and t is the curtailment time, and

$$c_{\text{PQ}} = \begin{cases} 10^5 \cdot P_L \cdot (V - 1.05) \cdot t & [€], \text{ if } V > 1.05 \\ 0 & [€], \text{ otherwise} \end{cases} \tag{2}$$

where V is the bus voltage, P_L is the load of the buses where overvoltage occurs (in MW) and t is the overvoltage time.

Simulations are performed to analyse the month of June 2021. June is chosen because of the high penetration of PV power plants in the grid, which make it more subjected to overvoltage due to high sun radiation over the PV panels. A preliminary investigation on network overvoltage occurrences is reported in Fig. 7, which shows the maximum voltage over the 26 buses of the network.

From the figure, a periodic behaviour on a weekly basis is observed. This is due to the input profiles from the ATLANTIDE project, which are described with a daily, weekly and monthly periodicity. Based on this input data, specific uptime (consecutive time while voltage is lower than $1.05pu$) and downtime (consecutive time while voltage is higher than $1.05pu$) have been calculated for each day of the week. The behaviour has been proven to be deterministic, and the data extracted is reported in Table II. This information is specifically used in the analysis conducted with the DES modelling approach.

TABLE II: Power system uptime and downtime for different days of the week.

	UT [h]	DT [h]
Mon	22.0	2.0
Tue	23.0	1.0
Wed	22.0	2.0
Thu	21.0	3.0
Fri	21.0	3.0
Sat	21.0	3.0
Sun	21.0	3.0

The studies are organized in the following cases:

I. Perfect ICT: ICT components never fail;
II. Imperfect ICT with naïve control mode;
III. Imperfect ICT with smart control mode.

The *perfect ICT* case is used as reference scenario in terms of overall operation costs to solve contingencies. Imperfect ICT with naïve and smart control are both solved with the two approaches mentioned in Section II:

a. Co-Simulation
b. Discrete Event Simulation

Results are compared in terms of unsolved overvoltage time due to contemporary failure of ICT devices, total costs (operational + penalty costs), and simulation time.

As simulation convergence arrest criterion, the standard error of the unsolved overvoltage time mean has been used (3):

$$S_{\hat{X}} = \frac{S}{\sqrt{n}} \tag{3}$$

where $\hat{X}$ is the mean of the unsolved overvoltage time calculated at the repetition n of the observed month, and S is the standard deviation. When the standard error is below 20% of the estimated value, the simulation is assumed to be converged.

Simulations are run on an Intel Core i7, 1.90GHz CPU, 16 GB RAM, with Ubuntu 20.04 OS. The model is coded on Python 3.8.5 programming language, using as main libraries SimPy 4.0.1 for the DES modelling, and pandapower 2.6.0 for power flow calculations [16], [17].

IV. Results and Discussion

A. Case I. Perfect ICT

First, a time-series simulation has been performed in pandapower to simulate a perfect ICT case: every time an overvoltage is detected, OPF set points are applied. Since ICT is perfect, no unsolved overvoltages are detected during the simulation, and the total costs are determined only by the operational cost in remunerating DERs for the availability to curtail the generation. The costs associated with the analysed month are 5222.62 €.

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TABLE III: Results of Imperfect ICT - Naïve control mode case

	Co-simulation	DES
Unsolved overvoltage time [h]	0.306	0.204
Operational costs [€]	5206.75	5458.77
Penalty costs [€]	76.03	76.79
Total costs [€]	5282.78	5535.56
Simulation time [h]	1.32	0.842
N. repetitions	72	275

TABLE IV: Results of Imperfect ICT - Smart control mode case

	Co-simulation	DES
Unsolved overvoltage time [h]	0.080	0.046
Operational costs [€]	5219.38	5483.79
Penalty costs [€]	5.85	1.72
Total costs [€]	5225.23	5485.51
Simulation time [h]	7.15	1.53
N. repetitions	401	521

B. Case II. Imperfect ICT - Naïve control mode

In this case, when an overvoltage is detected, OPF calculation is run and then the new DERs set-points are sent to the resources blindly, without a previous check of communication availability. Results of the simulations, both with co-simulation and Discrete Event Simulation approaches are reported in Table III. Convergence of results is reached in 275 repetitions of the analysed scenario (June 2021) with the Discrete Event Simulation approach, compared with the 72 repetitions of the co-simulation approach. Nevertheless, the overall simulation time with the DES approach is decreased by 36.2%, due to reduced computation burden in both failure and non-failure states.

C. Case III. Imperfect ICT - Smart control mode

In this case, first the OPF checks for communication availability with the DERs, then performs the optimization calculation based on the resources detected as available with the preliminary query. This approach avoids considering unavailable resources in the calculation, and increases the percentage of success in the overvoltage solutions. Results of the simulations, both with co-simulation and Discrete Event Simulation approaches are reported in Table IV. Compared with results from Case II (ref. Subsection IV-B), it can be observed a significant increase in number of repetitions and simulation time: due to the smart control mode, unsolved overvoltage occurrences are reduced, therefore the algorithm requires more repetitions to find convergence of results. Exactly like case II, DES approach requires more repetitions to reach the algorithm convergence, nevertheless the required simulation time is reduced by 78.6%. Moreover, due to the preliminary query of the ICT devices availability, a significant reduction of penalty costs is observed compared with case II.

D. Discussion

Despite observing a similarity of results in terms of costs and unsolved overvoltage time between co-simulation and DES approaches, a comparison based on these figures can be challenging, due to the different synchronization methods applied in the two models. Co-simulation modelling approach emulates an optimization of the DERs which occurs every 30 minutes, therefore any states variation within the time interval (both of ICT devices or temporary voltage violation) are neglected. This weakness may be overcome by increasing the granularity of the time-discretization, nevertheless this adjustment may increase the simulation time dramatically.

On the other side, DES modelling approach emulates a continuous control of the DERs: ICT devices states are continuously monitored, and the approach allows modelling voltage violations in the continuous time domain; on the other hand, when voltage state remains unchanged in a time interval, no voltage or power magnitude variation is detected with this approach, and operational costs are uniformly applied within the interval. An improvement from this side may be represented by an increased state discretization of power system variables, or to adopt a discrete power system variables sampling. This second approach may nevertheless increase the computational time, and compromise the advantages of a pure DES approach.

Based on the above considerations, in the specific cases II and III it is reasonable to consider the unsolved overvoltage time result more accurate in the DES approach than in the co-simulation approach, due to the event-driven synchronization that capture all time instances when a state change occurs. On the other hand, time-driven energy billing may motivate a co-simulation approach for accurate assessment of operational and penalty costs. Nevertheless, the number of contemporary failures of ICT and Power System may, for penalty costs assessment, be underestimated.

V. Conclusion

In this paper, two approaches for reliability assessment of combined ICT and power systems are presented and compared. The approaches are based on co-simulation and Discrete Event Simulations, and are applied on assessing the impact of ICT failures on voltage regulation application in a radial distribution grid with a high penetration of distributed generation.

The analysis shows that a significant advantage in terms of computational time can be obtained by applying a state-discretization in simulations of power systems. The DES approach shows computational time reduction, compared with traditional co-simulation approaches, up to 78.6%.

Despite observing a similarity of results in terms of operational and power quality - related costs, a validation of the co-simulation and DES models' results is a challenging issue. Neither the results from the co-simulation or the DES approach application can be considered more accurate for the overall cyber-physical system. Nevertheless, results discussion suggests a better suitability of DES for event-based quantities assessment, such as unsolved overvoltage time due to simultaneous failures in the ICT and power systems.

Further research directions are suggested to investigate the suitability of co-simulation and DES approaches for reliability assessment of cyber-physical power systems, and validate the

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proposed approach in more complex power system operational applications. Among these: reliability assessment with non-periodic power system contingencies, based on pre-processing of real data; reliability assessment and test of communication protocols for power system operation; cyber-attacks mitigation actions of communication protocols for power system operation.

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