A POWER-HARDWARE-IN-THE-LOOP FACILITY FOR MICROGRIDS

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ABSTRACT

Power-Hardware-in-the-Loop (PHIL) simulation is an advanced tool that can support the higher integration of Distributed Energy Resources (DER) to electricity grids. This paper provides an introduction to PHIL simulation and demonstrates its applicability in the domain of DER by presenting representative applications. A description of the facility at NTUA is provided focusing on the Power Interface for PHIL simulation, the laboratory microgrid and the Multi-Agent System. A PHIL experiment is performed, where Hardware PV panels and a PV inverter are connected to a simulated rural distribution network. An irradiation sensor provides input to simulated PVs in order to achieve realistic conditions. Steady-state and dynamic simulations (i.e. solar irradiation drop) are performed, where the voltages of the different buses of the distribution network are monitored.

1 INTRODUCTION

Power-Hardware-in-the-loop (PHIL) simulation allows the connection of an actual power device or system (the Hardware under Test (HuT)) to a real-life system, which is simulated in a Real-Time Simulator (RTS), allowing testing under realistic conditions. The simulated system can be changed easily and quickly without the need for hardware adaptations, therefore various experiments can be performed repeatedly and conveniently. Extreme conditions can be studied with minimum cost and risk, while problematic issues in the equipment behavior can be revealed allowing an in depth understanding of the tested device [1].

The essential part of Hardware-in-the-Loop simulation is the Real Time Simulator which computes the simulation model and offers I/O capabilities. As the device under test works in real-time, the simulated system response with which it will interact must be computed in real-time. Therefore, the simulation time-step of the RTS must be small enough to reproduce the behaviour of the simulated system under dynamic conditions. In principle, a computer with Inputs and Outputs (I/Os) or a controller board can be used as a Real-Time Simulator. However, specially designed sophisticated simulators have been built for simulating large and complex systems in real-time.

As the RTS cannot provide or absorb power, a Power Interface is necessary to allow the connection to the tested power device. The Power Interface exchanges low level Signals with the simulated system and power with the tested device. It consists of a power amplifier which receives a reference value of a variable from the simulation (e.g. voltage) and applies it to the HUT, and a sensor which measures the reaction of the HuT (e.g. current) and inputs it back into the RTS. This closed-loop operation makes possible the interaction of the simulated system with the physical power device.

PHIL simulation is a relatively novel tool in studying the integration of Distributed Energy Resources in the transmission and distribution grids. Photovoltaic panels, wind turbines, electric vehicles or whole microgrids can be connected to simulated active networks containing various simulated DER devices. Up to now PHIL simulation has been successfully used in this field [2]-[12] and it is expected to gain high interest in the future. Four representative applications from the literature are briefly presented next.

In [2] re-synchronization issues with distributed generation were studied. A large generator connected to a local gas turbine generator and a load were simulated in the RTS and the HuT was a small variable speed wind turbine generator. A voltage sag in simulation caused the simulated circuit breaker to island the subsystem consisting of the gas turbine generator and the wind power system. During the re-synchronization event, the circuit breaker was closed only when voltages at both sides matched in magnitude and phase. It was observed, that while small changes in frequency could be handled well by the real wind turbine generator, more severe changes caused its front end converter to lose the synchronization signal and thus trip out. This is a good example of how PHIL simulation can help in revealing hidden issues associated with local and renewable generation systems.

In [3] a real hardware Virtual Synchronous Generator (VSG) was developed and tested in a PHIL environment. A Virtual Synchronous Generator consists of energy storage and an inverter and aims to substitute the rotational inertia of synchronous generators. The increased growth of small scale dispersed generation will cause the inertia constant of the power system to decrease, therefore the VSG concept can be a promising solution. Through this PHIL experiment it was demonstrated that the hardware VSG can decrease the size of frequency variations caused by load variations performed in the simulation.

In [4] a transformer-less PV inverter was manufactured and tested in a PHIL set-up. A PV array model was executed in the RTS and a DC power amplifier was used to connect it to the DC side of the hardware PV inverter. In addition, a power grid was simulated in the RTS which was “connected” to the AC side of the PV inverter via an AC power amplifier. The behavior of the PV inverter under irradiance changes and grid perturbations was tested as well as its islanding performance.

In [5] synchronization issues of three-phase power converters connected in parallel were addressed, utilizing the PHIL concept. A microgrid was simulated in the RTS comprising a gas turbine-generator, a step-up transformer and a pulse load. An actual induction motor driven by a variable speed drive was mechanically coupled to an identical motor-drive set. The Power Interface amplified the simulated microgrid voltage (from the RTS) and provided power to the motor. In addition, a real STATCOM controller was developed and connected to the microgrid system in order to compensate for reactive power. In the RTS a control scheme that ensured precise phase synchronization of the two parallel converters (i.e. the Power Interface and the STATCOM) was implemented in-order to achieve minimum current circulation between the two converters.

In this paper work in progress related to PHIL tests on PV connections and Microgrid interactions is described. Initial results are provided in Section 3. In the following section, the PHIL facilities at NTUA laboratory are briefly presented.

2 A PHIL FACILITY FOR MICROGRIDS

A PHIL simulation environment focusing on DER devices and microgrids is developed at NTUA. A low voltage distribution grid is simulated in the Real Time Simulator and a microgrid consisting of PVs, a small Wind Turbine, Batteries, corresponding inverters and loads is the Hardware under Test. An overview of the PHIL laboratory set-up is presented in Figure 1.

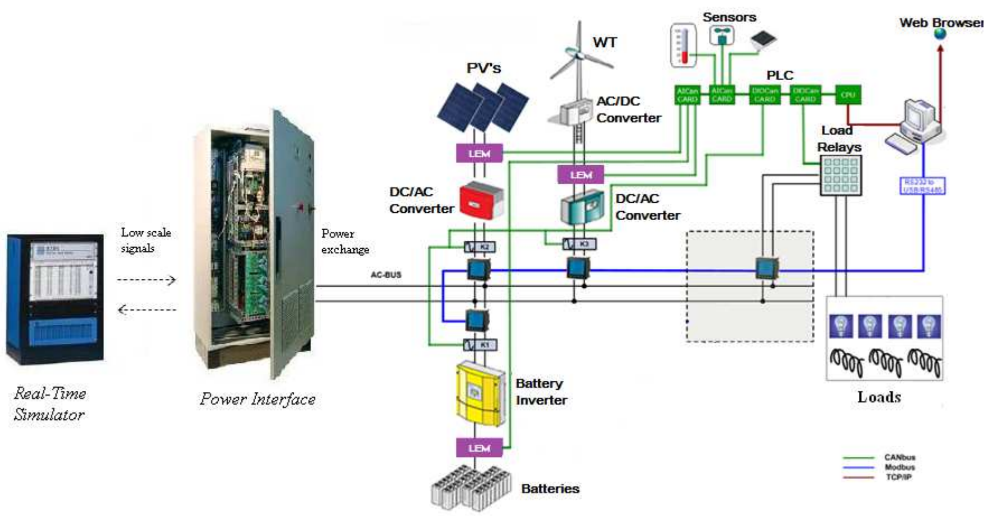

Figure 1: *Overview of the laboratory set-up for performing PHIL simulation.*

The Real Time Digital Simulator RTDS® [13] used contains several processing cards that work in parallel as well as various analog and digital inputs and outputs. Dedicated software (RSCAD) is used to design the electric circuit, control parameters in real-time, monitor simulation variables etc.

The main elements that comprise the PHIL simulation, as well as the low-level signals and power exchange are depicted in Figure 2. The RTS exchanges low level signals with the Power Interface through D/A and A/D converters and appropriate scaling up and scaling down is performed. The low level reference voltage (labeled V_N*) from the RTS is sent to the power amplifier that produces the requested voltage (V_N). This voltage is applied to the HuT (e.g. a PV inverter) resulting in current flow. The current of the HuT is measured by the sensor of the Power Interface and is sent back to the RTS in-order to close the loop. A current source is added in the simulated network in the RTS representing the current provided by the HuT. It is noted that the power absorbed or produced by the HuT, derives from or is injected to the utility grid via the power amplifier.

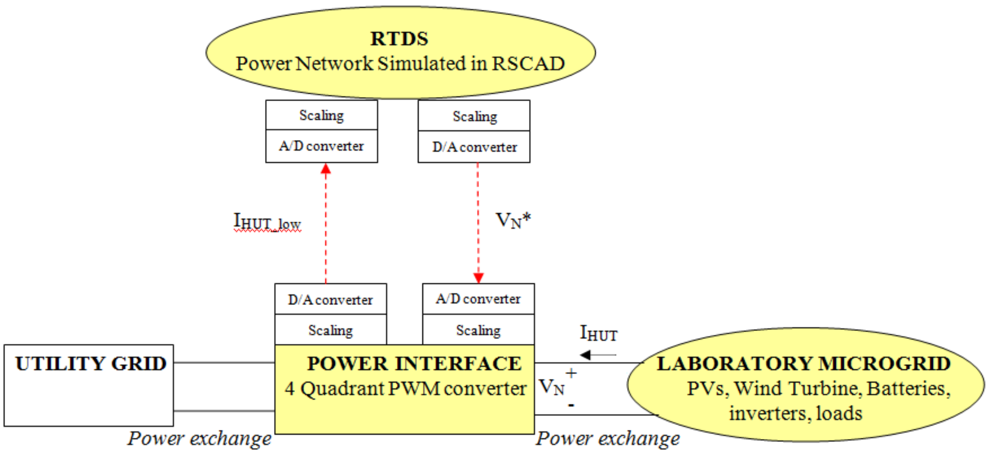

Figure 2: *Detailed view of the PHIL environment: V_N*, I_{HUT_low}: low level signals. VN, IHUT: power exchange*

2.1 The Power Interface

The selection of suitable Power Interface is a key issue for the successful implementation of a PHIL simulation. The Power Interface consists of a power amplifier and a sensor. The main requirements for the power amplifier are: sufficient nominal power, suitable voltage and frequency range, 4 quadrant operation, fast response, high accuracy, wide bandwidth and fast I/Os. A comparison of different types of Power Interfaces has been performed in [14].

The Power Interface used consists of a switched-mode converter with a powerful control unit [15]. The power electronic converter platform allows the use of a control scheme designed in Matlab/Simulink, with easy access to the available measurements and the possibility to change some control parameters online. The control unit is a powerful Linux server that interacts with the inverters, passes on commands from the user and gathers data requested by the user, like current and voltage measurements. The platform allows the user to design a Matlab/Simulink control model, upload it to the Target PC and connect the user's PC to the control unit to allow real-time control of and interaction with the inverter cabinet [16]. A dedicated Field-Programmable Gate Array (FPGA) passes the PWM firing pulses to the IGBTs. In addition, several inputs and outputs equipped with A/D and D/A converters are available for receiving and sending signals to the external world.

The power converter is an unconventional single-phase bidirectional AC/DC/AC converter consisting of 3 IGBT half-bridges [17], [18]. This configuration results in lower cost and size. The converter is coupled to the utility grid on the one-side and operates as a voltage source of variable voltage and frequency on the other-side.

The two functions that a Power Interface must provide in a PHIL simulation are fulfilled by this converter: power amplification as well as measuring and providing feedback signal. Current and voltage measurement devices are already employed in the execution of the control algorithm of the converter and can be used to provide the low level feedback signal to the RTS.

A control algorithm for the single phase AC/DC/AC converter was provided by the manufacturer. The algorithm was modified in-order to allow the operation of a Power Interface for PHIL as described in [12].

2.2 The NTUA Laboratory Microgrid and the Multi-Agent system

A single phase low voltage microgrid has been developed within NTUA's laboratory [19]. The primary power sources of the microgrid are a PV generator and a small wind turbine generator. Both are interfaced to the AC bus via fast-acting DC/AC PWM inverters. In addition, a battery bank is interfaced to the AC bus via a bi-directional PWM voltage source converter. A total amount of 5kW of controllable ohmic loads and 1 kVAr of controllable inductive loads are also installed. A PLC (Programmable Logic Controller) system is used to control the loads, to switch on and off the inverters and acquire measurements both in the DC and AC side of the microgrid. The laboratory microgrid and the SCADA system are depicted in Figure 1.

When the microgrid is connected to the main grid the loads are served both from the local sources and the grid. In case of grid disturbances the microgrid can smoothly transfer to island mode, until the grid is restored and the microgrid is reconnected. The main component of the microgrid is the battery inverter. In grid-connected mode the battery inverter follows the grid voltage and frequency, while charging or maintaining the 60 V lead acid batteries of 250 Ah total capacity. In island mode the battery inverter regulates the voltage and frequency of the system, while controlling the active and reactive power flow. The system includes a PV generator of 1.1kWp and a small wind turbine generator of 1 kW nominal power which was designed and manufactured in NTUA lab [20]. Microgrid control is achieved via the battery inverter's droop curves, as described in [21]. In grid-connected mode active and reactive power of the battery inverter can be controlled by changing the "idle" frequency and voltage of the droop curves. In island mode and when the batteries are fully charged, the battery inverter increases the microgrid’s frequency, thus reducing the PV's active power according to the PV's inverter droop curve.

A Multi Agent System (MAS) consisting of six controllers is installed in the laboratory. The MAS is implemented in the JADE platform for developing Intelligent Systems. Similar systems have been developed and installed in the Kythnos microgrid, aiming to optimize the operation of 12 houses taking into account the available energy stored, and in three remote test sites in Athens, including NTUA [22] in order to simulate the operation of a Virtual Power Plant (VPP) in a market environment.

The NTUA MAS is able to interact with the laboratory microgrid and specifically with the battery inverter by controlling battery power consumption/production. The controllers interact with their environment by acquiring grid measurements, such as voltage, current, active power and frequency and by turning ON/OFF loads by means of relays via Power Line Communication. The MAS can use measurements both from the AC and DC side of the microgrid acquired from the SCADA system and use any available data in order to perform system optimizations (i.e. cost or active energy consume minimization) in a distributed manner.

3 PHIL TESTING OF A PHOTOVOLTAIC INVERTER

The actual PV panels and the PV inverter of the laboratory microgrid comprise the HuT for performing PHIL experiments at this stage. An extension to include the microgrid described in Chapter 2.2 is in progress. The single phase PV inverter consists of a DC/DC converter to perform the Maximum Power Point Tracking (MPPT) and a DC/AC inverter. If there is sufficient solar irradiation, (i.e. sufficient DC voltage) the PV inverter is capable of providing power. When a grid of suitable voltage and frequency is connected at its AC terminals synchronization occurs and the inverter starts supplying current. The same operation is performed in this application with the difference that, instead of the utility grid, the PV inverter is connected to the controllable AC grid produced by the power amplifier.

In the RTS a rural low voltage distribution grid is modeled which contains a MV/LV transformer, low voltage lines, loads and photovoltaics (Figure 3). A test scenario which contains six households under low load and high PV production is considered. In the RTS five PVs are simulated (buses 1,2,3,5,6), whereas the real PV inverter is connected at bus 4 and is represented in the RTS as a current source. The RTS apart from the HIL capabilities offers the possibility of receiving input signals from external equipment. In this way an irradiation sensor located on the plane of the PVs provides irradiation measurements, as input to the PV models in the RTS. Therefore, the experiment is more realistic, as the power production of the simulated PVs varies according to the irradiation in the same way as the power of the hardware PV inverter does.

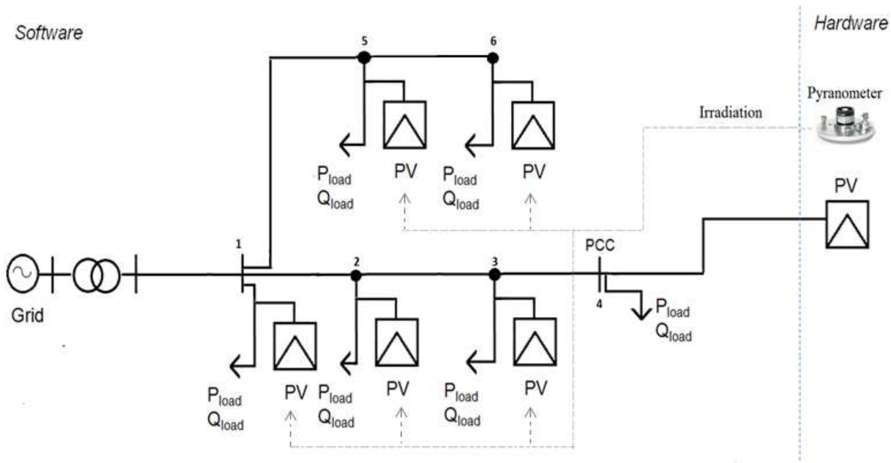

Figure 3: *Rural distribution grid with PVs modelled in the RTS and external Hardware devices.*

The low voltage set-point from the RTS (at bus 4), the voltage produced by the power amplifier and the current provided by the hardware PV inverter are shown in Figure 4. The resulting voltages in steady-state conditions *(irradiation=1200 W/m², P_{pv_RTDS}=4 kW, P_{HuT}=950 W)* are presented in Figure 5. It can be seen that the voltage of all buses increases due to the PVs active power production, while the most remote bus presents the largest increase.

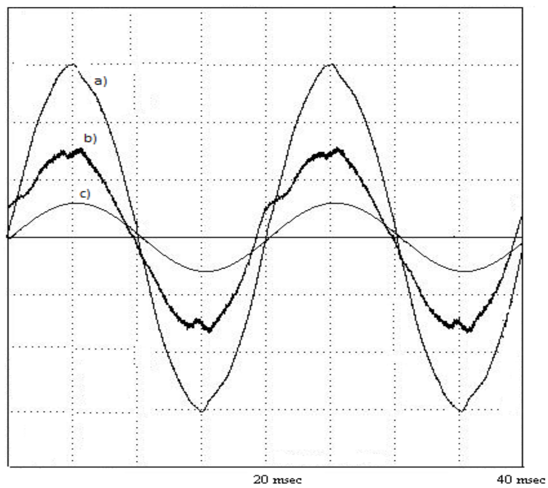

Figure 4: *(a)* Voltage produced by the power amplifier, *(b)* Current provided by the PV inverter and (c) set-point from the RTS.

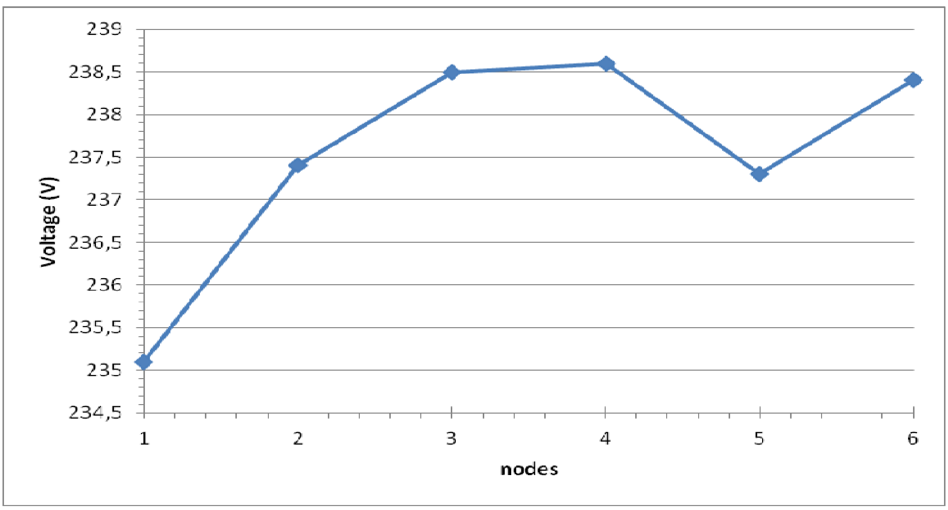

Figure 5: *Node voltages during a steady-state PHIL experiment*

A dynamic PHIL experiment is performed, where a drop occurs in solar irradiation (Figure 6). The power produced by the simulated PVs and the hardware PV inverter is reduced resulting in the voltages of Figure 7.

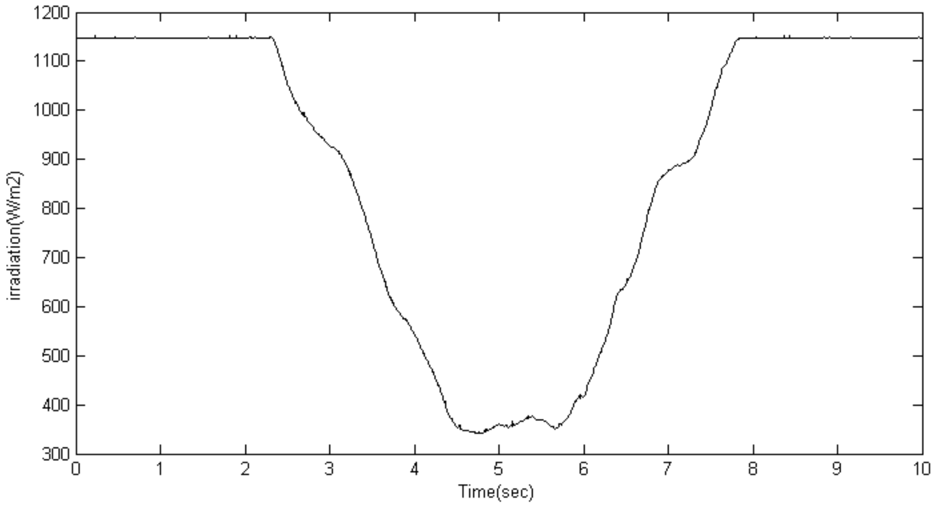

Figure 6: *Measurement of the irradiation sensor*

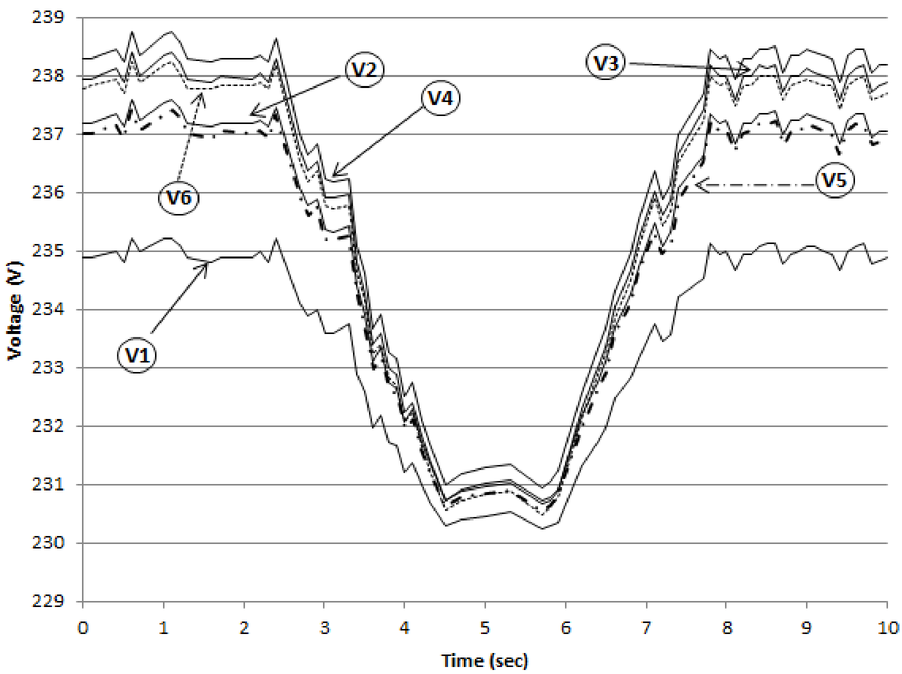

Figure 7: *Node voltages during the irradiation drop (PHIL experiment). Steady-state conditions: irradiation=1150 W/m^2, P_{pv_RTDS}=3.8 kW, P_{HuT}= 900W*

4 CONCLUSIONS

The transition to active electricity networks requires powerful tools for simulation and testing. Power-Hardware-in-the-Loop (PHIL) simulation, as a combination of simulation and experimental testing provides an efficient environment for performing studies in order to achieve higher penetration of DER.

This paper addresses the applicability of PHIL simulation in the domain of DER by presenting representative applications. The Power Interface for PHIL simulation, the low voltage Microgrid and the Multi-Agent System of NTUA are described next. PHIL experiments are performed with PV panels and a PV inverter as the HuT, while simulated PVs receive input from an irradiation sensor. Steady-state and dynamic simulations are performed, where the node voltages of the simulated grid are monitored. Satisfactory operation of the PHIL facility is achieved.

The development of the PHIL set-up allows for testing a PV inverter in an environment that is not possible by conventional testing. The extension of the PHIL facility to include other hardware parts of the microgrid and the Multi-Agent System is in progress. Further work on testing with PHIL advanced functionalities of DER, such as reactive power provision is in progress.

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