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► To cite this version:

Thai Phuong Do, Grégory Païs, Yassine Naimi, Saïd Daoudi, Xavier Le Pivert, et al.. Microgrid realtime control for transient modes: development, simulation and experimental validation in full-scale. ISGT Europe 2023 - IEEE PES Innovative Smart Grid Technologies Europe, Oct 2023, Grenoble, France. , 2023, 10.1109/ISGTEUROPE56780.2023.10407254 . cea-04772392

HAL Id: cea-04772392

<https://cea.hal.science/cea-04772392v1>

Submitted on 7 Nov 2024

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Microgrid realtime control for transient modes: development, simulation and experimental validation in full-scale

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Abstract— In many regions, microgrids with photovoltaic (PV) production and electrical storage become a choice adopted by more and more industrial and community energy systems. Microgrid control design is a complex topic, as it has to deal with technical constraints, guarantee and economic optimization on different time scales. CEA-INES has developed a complete multiple-levels controls system architecture for microgrid together with methodology for such controls validation. This paper focuses on operation control short-term development and validation through various steps starting from simulation validation to experimentation. A study case of a microgrid integrating production mix of photovoltaic and diesel generators production, together with a battery storage with a black-start management will be performed for illustration.

Index Terms—microgrid, control, transient dynamic, simulation, experimentation

I. INTRODUCTION

Previous works presented in [1][2] focus on the control considered as “high level”, namely Energy Management System (EMS), addressing long-term economic optimisation design for microgrid. In this study, the focus is operational control, generally named PMS (Power System Management), which handles mainly short-term power management, and relays control during various operation modes in both steady state and transition states. In this paper, the validation methodology of such control algorithm is realized within three stages that will be described. Firstly, a static simulation for a step-by-step verification of the actions decided by the controllers. Secondly, a dynamic simulation where Electromagnetic Transients (EMT) modelling is used to observe detailed transients’ behaviours of each component as well as microgrid power quality and stability. In the last step, algorithms are implemented for Hardware In the Loop (HIL)

validation in order to verify control performance regarding communication issues and physical components behaviours.

Control algorithms and modelling are developed based on Matlab for static simulation, and Matlab/Simulink Simscape for dynamic simulation

II. MICROGRID CONTROL DEVELOPMENT

Specification in IEEE Standard for Microgrid controller [3] mentions a list of functions to be covered by a controller, which gathers both microgrid steadystate and transient modes. The two steadystate modes are “grid connected” where microgrid is connected to the main grid and works as a controllable of the later and “islanded” where microgrid is an independent system. The transients modes are intermediate operations while microgrid is moving from one steadystate to an other, such as “islanding” (planned or unplanned) when microgrid changes from “grid connected” to “islanded” mode, or reversely “reconnection” to switch back to a connected state. “Black start” is a special transient mode, allowing the microgrid restart from a black out situation. Fig.1 illustrates those modes and their interrelationships. However, it is not mandatory for microgrid controller to handle all these modes. In detail, control algorithms for microgrid operation may vary from one site to another. Our development approach aims to emphasize the functional aspect as it helps to build a framework for algorithm development and validation. Hence, core functions of microgrid controls in the various mentioned modes are divided into two categories: dispatching function and transition functions. Dispatching functions’ objectives are to compute all microgrids assets power set points and apply them to the controllable devices. Transition functions aim to handle the connection and disconnection of devices before applying dispatching orders on them. With this hierarchical

decomposition approach, control algorithm design procedure is standardized through the following steps:

1. Define control objectives and related actions which leads to controlling the assets
2. Define related inputs, outputs and parameters sets. Their global architectures are common for all microgrid projects
3. Work out algorithms diagrams
4. Code the algorithm within a pre-defined control function. In CEA-INES simulation platform, microgrid modelling is carried out using a template, which pre-designs communication links between the control part and physical plant model part.

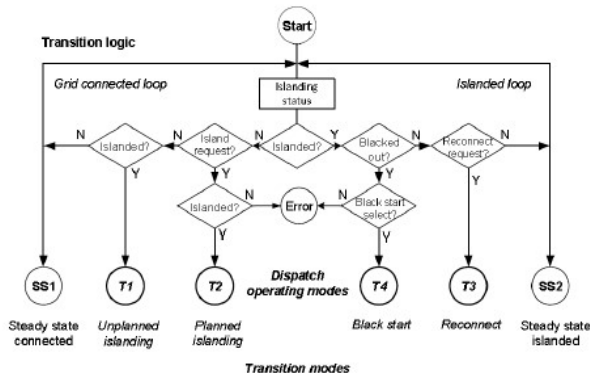


Figure 1 Sequences associated with the transition function [3]

Control algorithms then go through validation steps within a procedure that will be detailed in the next section, followed by a study case application on a microgrid configuration composed of two diesel generators (GE), PV production, a battery storage and three loads as illustrated in Fig. 2.

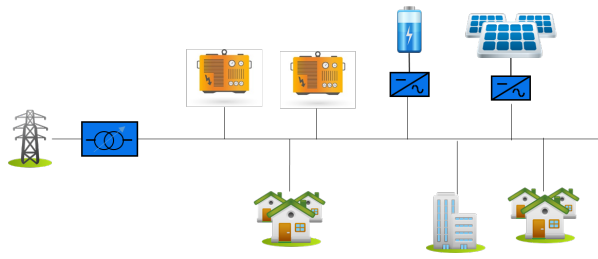


Figure 2 Microgrid study case

III. MULTISTEPS VALIDATION PROCEDURE

A. Static simulation

In this step, only discrete actions from algorithms outputs are observed. In this step, microgrid components are simple models with only power limitations for generation and consumption assets, with in addition State of Charge (SOC) limitation for storage assets. Algorithm effects are drawn as suite of iterations, each of them considered as a steady-states of the microgrid due to the actions taken from the previous iteration. Power limitation check up is an additional validation element while time-related dynamic is not represented in this step. In addition, a dedicated module to

generate various scenarios has been developed in order to strengthen this validation step.

Fig. 3 illustrates a black start operation of the microgrid example. A state-of-the-art black start procedure [4] is used here as example. In this case, algorithms deal with the activation of each asset, their connection to the system and finally their power dispatching. Observation of taken actions in each iteration permits to ensure the black start order follow-up according to the asset capacity and limitation, from initial state with all component OFF (top figure) to final state (bottom figure) where all components are ON. The dark coloured part of each asset bar shows the power level, allowing to verify different dispatching constraints such as the respect of power limitations (min and max) and their priority. In this example, GE units with self-starting are activated and connected first to the grid line, followed by battery storage as it is controllable source, then critical loads according to their priority order, PV inverter and lastly the uncritical loads. Once connected, dispatching priority is applied, in such a manner that PV power is fully used as it has higher priority than GE which are running at their minimum level.

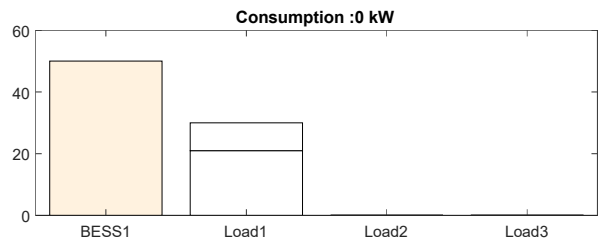
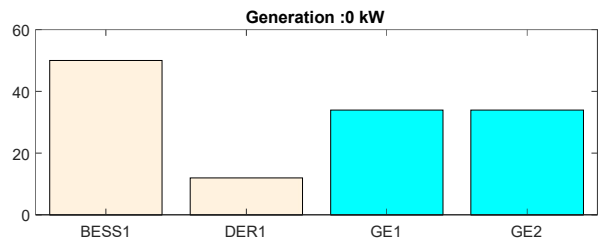
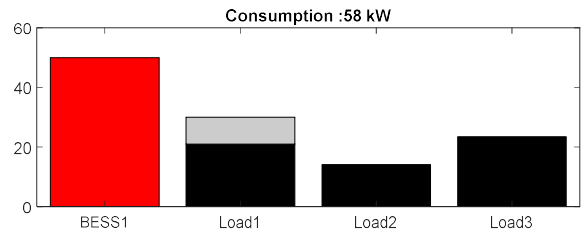
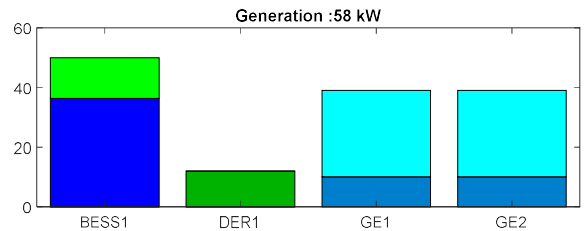


Figure 3 Representation of two states during a black start procedure

B. Dynamic simulation

In this step, the same control functions are implemented in another simulation environment where microgrid is modelled with detail models based on Matlab Simulink library. Setting parameters of each model have been tuned to correspond to the devices that will be used in the next test. The microgrid time-related dynamic is observed.

The discrete iteration suite in static simulation is transformed to a continuous operation where execution time of each action can be seen. Fig. 4 shows the connection order of the microgrid assets allowing the black start procedure. The connection order is obviously the same as seen in the static simulation, with specific delays related to control time constants and/or physical delay of the components. These delays are visualized by the gap between the connection commands (continuous lines) and the corresponding “measured” (dotted lines). As an example, the first diesel generator (GE1) connection activation is given at $t = 5$ second (connection command value set point goes from 0 to 0.5), but its effective connection is performed at around $t = 7$ second (measured connection value is 1). The delay of 2 seconds is mainly due to physical starting duration of the genset which is the addition of machine’s thermal starting delay and regulation delay to reach voltage and frequency nominal values. Within the two instants, GE1 connection set point remains at 0.5, meaning ongoing activation of the generator before reaching synchronisation conditions to be connected. It can be observed that this delay is longer for the second generators GE2, as it takes almost 6 seconds, due to synchronisation procedure. Indeed, once a first generator is active and regulates microgrid frequency and voltage, in order to be connected to the microgrid, other generator is called to be synchronized in terms of frequency, voltage and angle to the first one. This is normally performed by a synchronizer, which monitors frequency, voltage and angle on both sides and allows the connection. As the synchronizer has its own operation frequency, it may take several periods to have synchronization conditions satisfied.

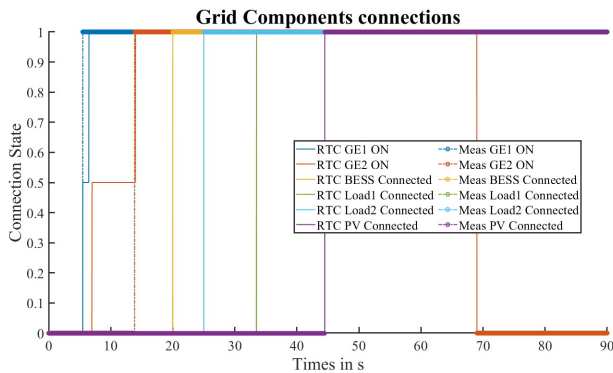


Figure 4 Microgrid assets connection states during black start

In addition to the asset connection state and power values, electrical indicators such as frequency and voltage are

monitored, aiming to indicate microgrid stability condition. Criteria based on these stability indicators are used to validate the end of each step allowing the start of the following one.

As observed in Fig. 5, frequency and voltage are maintained around their nominal values (50Hz for frequency and 1p.u for voltage) during the black start procedure. Each additional asset connection creates one new frequency and voltage variation but the grid forming units (in this case the two diesel generators) manage to stabilize microgrid frequency and voltage. Increasing power production leads to positive power unbalance and reversely.

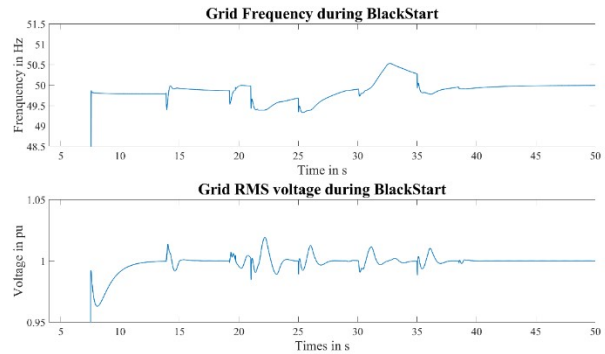


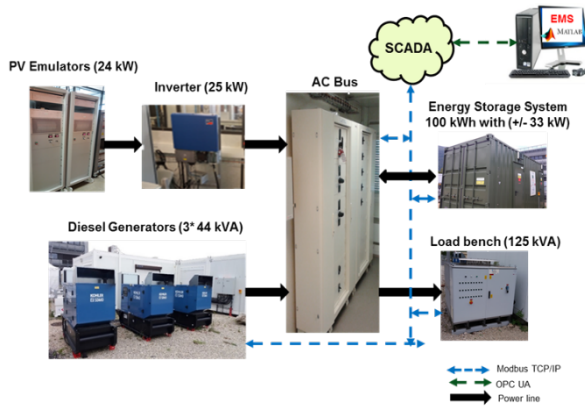
Figure 5 Microgrid frequency (top) and voltage (bottom) during black start

Most of existing models from Matlab/ Simulink Simscape library do not cover the starting mode. They are designed to work in active operating state. In order to get model covering both the starting phase and operation phase, some adaption on asset models have been carried out.

C. Experimental testing

In CEA-INES platform, microgrid experimentation with real devices or emulated devices can be performed. The same microgrid described in previous sections have been built with: two diesel generators of 44kVA, 1 SMA inverter of 25kVA and a DC amplifier for PV system representation, 1 AC amplifier for 30kVA BESS emulation and three loads with respective values of 100 kVA, 50kVA and 33 kVA. Communication within control algorithm and microgrid assets are based on the combination of Matlab OPC UA toolbox allowing the communication between controller PC (where algorithms are implemented) and the SCADA which handles the control and the monitoring of all equipment within the lab platform.

Figure 6 Microgrid experimentation in CEA-INES platform



Similar to dynamic simulation, indicators such as components connections (Fig. 7), powers (Fig. 8); frequency and voltage have been monitored during experimentation validation. At first, asset connection order, which is identical to simulation

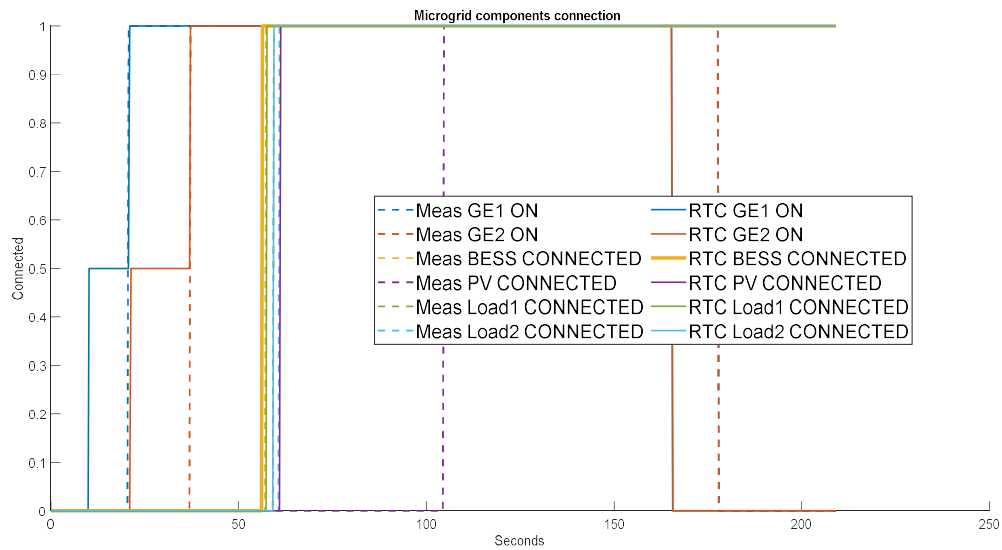


Figure 7 Connection states of microgrid assets during black start

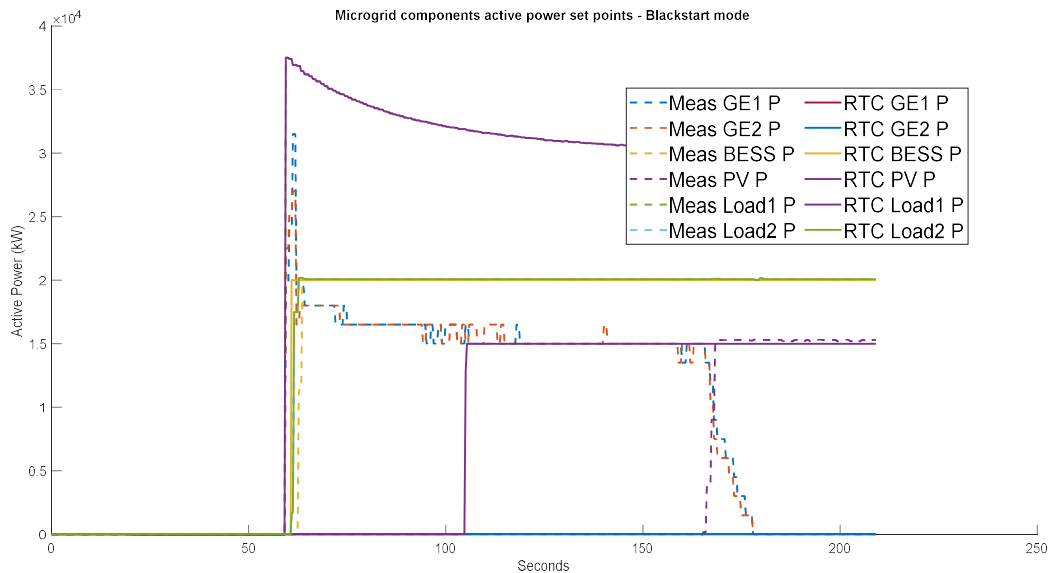


Figure 8 Microgrid assets active power during black start

validations, confirms black start algorithm performance. Furthermore, it can be observed that in some cases, time delays may be different from dynamic simulation, such as PV inverter connection, which is ordered at $t = 60$ seconds but performed only at $t = 110$ seconds. They can be explained by real device characteristic. Indeed, in simulation, it is assumed as an immediate connection while in experimental platform, PV system is built based on a SMA inverter and an DC power supply. The latter needs to be triggered for the starting and the delay observed for PV connection to the microgrid corresponds mostly to this feature.

In Fig.8, it is noticed that there are some oscillations concerning the generators power curves (diesel generator 1 and 2 active powers, namely *MeasGE1P* and *MeasGE2P*). It can be explained by generators' power meter uncertainty, which is around 1kW.

A filter was added also to the frequency and voltage monitoring functions, in order the better observe these indicators according to the experimental metering.

IV. CONCLUSIONS AND PERSPECTIVES

Microgrid configuration and functionalities become more and more complex, with an increasing ratio of renewable production and storage. Control algorithms' development for such microgrid requires robust evaluation and validation procedure. In this paper, the authors present a framework aiming to improve the efficiency of microgrid controller development and implementation process and benchmarking between different controllers. The framework is composed of three evaluation steps: two through simulation and one through experimentation. From one step to another, new analysis from algorithms' performance are observed, which help to either confirm the algorithms' effect, or to improve them. This framework is designed to fit to various microgrid configuration without consequent effort from developer. In the future, more test case can be used with both CEA-INES control algorithms and external ones in order to further consolidate this validation framework and benchmark microgrid control solutions. Different aspects can be considered, both in terms of microgrid controller architecture

and their communication. The last point represent a real challenge for microgrid controller developers [6], which has to deal with different assets and sometime main grid operator devices that implement various communication protocols. The framework tend to include the most used communication standards, such as MQTT, IEC 61850, Mod bus, DNP3 in order to cover a large number of microgrid and controller configurations.

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ACKNOWLEDGMENT

This work has been realized with the participation from members of INES.2S and received funding from the French State under its investment for the future program with the reference ANR-10-IEED-0014-01.