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COMPARATIVE ANALYSIS OF GRID FORMING INVERTERS BASED POWER SYSTEMS IN PHASOR DOMAIN AND ELECTROMAGNETIC TRANSIENT DOMAIN

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ABSTRACT

As the number of inverter-based resources (IBRs) increases and the number of synchronous generators decreases in the power systems, new challenges have emerged in terms of power system stability and reliability. To assess this stability, phasor-based time-domain simulation is one of the classic methods, however, with more IBRs; their fast dynamics can affect the system. Thus more detailed simulations, such as EMT, may be required. In this paper, the phasor simulation will be compared to EMT simulations, in the case of a Grid Forming inverter (GFM) based microgrid. A brief discussion of the simulation tools is provided and the results of the comparative analysis results are discussed.

INTRODUCTION

Microgrids based on Distributed Energy Resources (DERs) based have become more popular together with the development of power inverters in terms of costs, performance and power rates. New challenges are arising with fewer synchronous generators and more inverters based resources (IBRs) mainly due the impacts of these latter on power system's reliability and stability.

As a solution, the Grid Forming (GFM) [1] structure was proposed to deliver more supporting services to the grid and improve the participation of IBRs in the reliability of power system [1], [2].

The dynamic behavior and stability problem in a microgrid is different from those of a conventional power system [3], since the size and nature of equipment are different. The main objective of the GFM inverters is to maintain stable voltage and frequency in a microgrid.

There are more than one method to assess stability of microgrids such as small-signal analysis, Lyapunov methods [4], real time Hardware-In-the-Loop (HIL) simulations [3], and time-domain simulations, which are based on modelling the system components and their controls. Phasor-based, known also as RMS, and EMT (Electromagnetic Transients) tools are both types of time domain simulations that can be used to assess transient stability. The work in [5], conducted a comparative study between RMS and EMT models of typical Grid following (GFL) inverters. In [6], a comparison of EMT and RMS models of GFM and GFL based microgrids have been realized. The efforts made to clarify the differences between these two types of models are still lacking. In the present paper, the characteristics and differences between these two types of simulations will be investigated in the case of a microgrid composed of a Grid Forming inverter in standalone mode feeding a set of loads.

The remaining sections of this document are divided as follows: in the Section 1, a review of stability in microgrids will be introduced. The Section 2 provides a brief discussion of the simulation tools such as EMT and Phasor used to assess large disturbance stability in microgrids. Section 3 presents and discusses the results of a comparative analysis between Phasor and EMT simulations for a case study, which will be detailed in the same section. The Section 4 presents some conclusions and draw up perspectives of the future work.

I. STABILITY IN MICROGRIDS

In the context of a microgrid, large and small signal stability are important to be studied to ensure a reliable operation of the system. Small signal stability concerns events with less impact on the microgrid as a small step of load. On other hand, large signal stability studies the impacts of large disturbances such as faults, unplanned transitions from Ongrid to Offgrid modes of operation, and many other severe events that can cause large deviations of frequency and voltage [3], which can damage equipment and disrupt power supply to loads.

In this study, the both types of stability will be assessed using the time-domain simulation tools, and two events will be applied to the proposed microgrid. A load change event, which can be considered as a small signal disturbance, and a fault, which can be seen as a large signal disturbance.

In the next section, the time-domain simulation tools, used in this study, will be briefly discussed.

II. TIME-DOMAIN SIMULATION TOOLS

Phasor-based model:

A Phasor-based model, also called RMS, is a time-domain model in which the system frequency is assumed to be close to its nominal value. Electrical systems are represented, using this method, by phasors, complex vectors of current and voltage, split into different frequency sequences: positive, negative and zero. These phasors are assumed to rotate with the nominal angular speed.

With more decentralised generations (DERs), the stability of power grids is impacted by rapid dynamics. However, in the classic Phasor models of conventional systems, the rapid dynamics in general are neglected. This is justified by the fact that the stability of conventional systems is mainly influenced by the electromechanical states of synchronous generators.

Thus, the question of whether the use of time-domain simulations based on the Phasor model is still compatible

in case of systems with high rate of CIGs, must be explored.

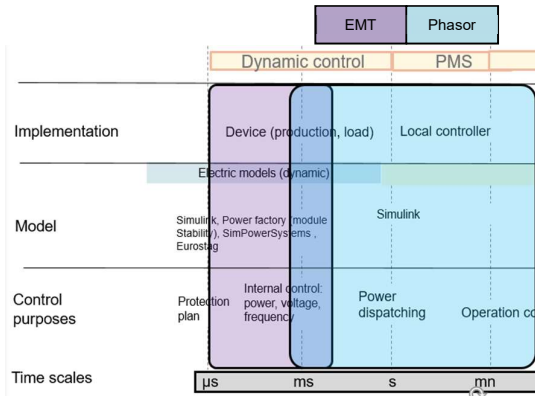


Figure 1 Time scales of the study

Electromagnetic Transient (EMT) model:

In an EMT model, the power system is solved in differential equations for each voltage and current phase. Thus, this method can represent the system at the circuit scale of all lines and components taking into account non-linear and discrete aspects. The level of detail in the EMT simulations allows a better observation of the transient dynamics in the system. However, this comes with higher numerical cost, modelling complexity and data requirements.

Time scales of Phasor and EMT simulations:

EMT simulations are concerned with transient phenomena of instantaneous current and voltage quantities. This requires a large number of computational points over a fundamental period, making the time step approximately several microseconds (μs) to several milliseconds (ms). The Phasor simulations use larger simulation steps. This implies a steady state representation of the passive elements of the network. A few milliseconds (ms) to few minutes (mn) is referred to as a time scale. Figure 1 depicts the range of time scales studied in this paper. They are between several microseconds to several milliseconds for both EMT and Phasor (RMS) simulations. The choice of appropriate model/ simulation domain for microgrid stability analysis depend often on the compromise between computation time cost and accuracy. It has been well known in the literature the EMT simulations is better accurate but require longer computation time. On the other hand, RMS or Phasor simulations make some assumptions that could simplify the models and make it possible to reduce the computation time. In this work, the authors aim to quantify the differences between the both simulations, EMT and Phasor, for a typical model of a microgrid with CIGs. A first step is to study GFM model that is potentially one of the present component in new microgrids with major renewable production part. Secondly, the comparison between EMT and Phasor simulations is made according to physical and

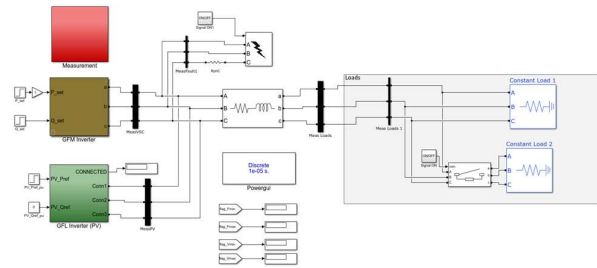
numerical criteria, which will be detailed later in the paper.

III. COMPARISON BETWEEN EMT AND PHASOR-BASED MODELS OF A GRID FORMING INVERTER BASED MICROGRID:

Case study:

In order to highlight the main differences between EMT and Phasor tools in assessing the stability in microgrids. A microgrid is modelled in Matlab/SIMULINK comprising a series of components including: a grid forming inverter, fixed and variable loads and a grid following inverter representing a PV plant. The figure 2 represents the studied system. The DC side of both inverters is supposed to be sufficiently stable and it is not in the scope of the study. The comparison between EMT and Phasor is conducted based on two main disturbances events: load variation and a short-circuit fault.

Figure 2 A presentation of the studied microgrid



Modelling approach:

GFM inverter:

Grid forming inverters work as ideal ac voltage sources representing low output impedance. A control block diagram for the studied GFM inverter is presented in the figure 3 [2]. It consists of a droop control that adjusts the

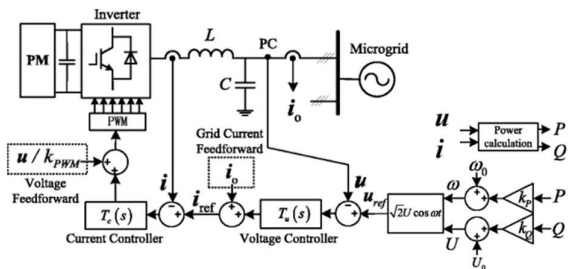


Figure 3 Control block diagram of the GFM inverter

grid voltage and frequency at the PC point according to the output power variation of the inverter. Then a cascade structure of internal control of voltage and current respectively was designed. The objective of the GFM inverter control is to keep the voltage across the LC filter capacitor close to its reference value regardless of the load demand or the state of the microgrid. The control part of the GFM inverter generates reference voltages that will be used depending on the inverter model chosen. In this study, three GFM models are compared:

EMT_{sw}: The GFM inverter is modelled with IGBT/Diode models driven by pulses produced by PWM strategy. This model is simulated using a discrete solver and used as a reference of comparison with other models described below. By using this detailed model, it is possible to simulate the inverter fast switching and catch the voltage and current transients in the system.

EMT_{avg}: The GFM inverter is modelled using switching functions directly controlled by the reference voltage. PWM strategy is not required in this case. In the absence of semiconductors, high frequency harmonics related to the switching frequency are not taken into account. By using this model, the solver step size can be significantly reduced without losing accuracy compared to EMT_{sw}.

Phasor-based: The GFM inverter is replaced by an ideal three-phase voltage source controlled by the output reference voltages of the control stage. The model is simulated using the discrete phasor mode available in the ‘‘Powergui’’ block in Matlab/SIMULINK. It allows the use of simplified algebraic equations instead of the differential equations that are used in EMT models

The control part of the inverter remains the same for all models. However, for the Phasor-based model, which only takes into account complex values in the form of phasors, adaptations of the Park transformations and input-output types, used in the control blocks, have been made.

GFL inverter:

The model chosen for the representation of the PV system is a behavioural model. It estimates, due to a Phase Locked Loop (PLL), the frequency and the voltage at the output of the GFL inverter, and synthesizes, by knowing the active and reactive power set points, the value of the positive sequence current, which is injected to the microgrid via a controlled three phase current source. The same model is used to simulate all the three models of GFM inverter in the comparative analysis section.

Loads:

The loads used are fixed loads, notably resistive and inductive, which are used to simulate and study the impact of load variation events on the microgrid. Same as the GFL inverter, the loads models are used to do both EMT and Phasor simulations.

Criteria of comparison:

In order to verify the statements made in the Section II, about the differences between the EMT and Phasor models, this comparative study will examine the following points for each model:

Accuracy:

As this criterion requires results from a reference model, the most detailed EMT_{sw} model is considered as reference. A time step of 5 μ s is used to simulate the latter in order to observe any transients in the system. The two other models EMT_{avg} and Phasor are compared to this reference model (EMT_{sw}) based on numerical values of

voltage, current and frequency.

Execution time:

This is recorded for each simulation, including the reference model. This criterion is important to qualify the numerical cost of the simulations and gives an idea on what type of simulation should be used to simulate which event or system.

Voltage and frequency stability:

The ability of the model to recover its stability in voltage and frequency after being disturbed will also be of interest. To qualify the transient stability of the simulated models, frequency and voltage thresholds must be chosen. This is done based on operating values described in the table 1 below.

Table 1 Acceptable operating values for the studied microgrid

Acceptable value excursion around the reference	Voltage (% p.u.)	Frequency (% p.u.)
Static : when the microgrid is in a steady state similar to a static regime	+/- 20 %	+/- 4 %
Dynamic : when the grid is still under the impact of a disturbance phenomenon (< 2 s)	+/- 50 %	+/- 10 %

Results of the comparative analysis:

Table 2, describes some of the characteristic parameters of the studied microgrid. Two main events are observed: a load variation (event A) and a three phase symmetrical fault at the output of the GFM inverter (event C3).

For every event applied to the microgrid, the performances of the three models EMT_{sw}, EMT_{avg} and Phasor will be shown. The comparison will be conducted based on the criteria cited in the previous paragraph.

The three models are simulated with different optimal step sizes based on the nature of blocks implemented and the type of event applied. The objective of this step is to simulate each model with the largest possible time step without invoking inconsistencies or solver errors. Thus, for each event, the time step will be determined.

Event A: Load variation:

Event A is based on a change in the active power demand. The simulation starts with an initial active power demand of (0.227p.u), equivalent to 15 kW, represented by Load1.

Table 2 Characteristic parameters of the studied microgrid

Type	Parameters	Values
Physical	Snom	66 kVA
	Vnom(ph-ph)	400 V
	Fnom	50 Hz
	Udc (GFM inverter)	800 V
	Switching frequency for EMT _{sw} model	10 kHz
Simulation	Simulation time span	10 s
	Event time (T _{event})	5 s
Events	C3 : Fault impedance	0,001 Ohm
	C3 Ground impedance	1e6 Ohm
	C3: Fault Clearing time	200 ms
	A: initial power demand	0.227 p.u
	A: active power variation	0.455 p.u

The GFL is considered connected by the beginning of the

simulation with an input of power fixed at 0.16 p.u, equivalent to 10 kW. The event is caused by the connection of the Load2 (0.455 p.u), equivalent to 30 kW, by closing the three phase breaker shown in the figure 2.

This event represents a signal disturbance in the microgrid, as it only changes the load set point, which remains below the nominal power of the GFM inverter.

The step sizes of different models are given below:

Model	Step size in μ s
EMTsw	5
EMTavg	100
Phasor	1000

Models accuracy:

The figure 4 shows the active power produced by the GFM inverter before and after the load variation event for the three models. In general, the EMTavg and Phasor models show similar behaviour to the reference EMTsw. However, A 13% overshoot of the final value is noticed for the Phasor-model.

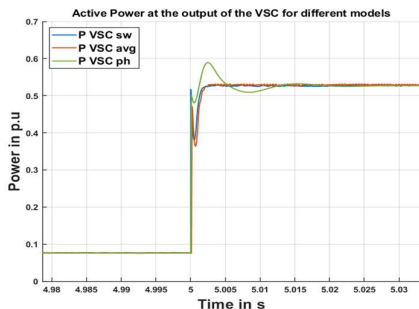


Figure 4 Active power of the GFM inverter

The figures 5 and 6 below show the voltage and frequency behaviour of the system for the three models.

Thanks to the implemented control of the GFM inverter, the voltage at its output is practically the same and is stable

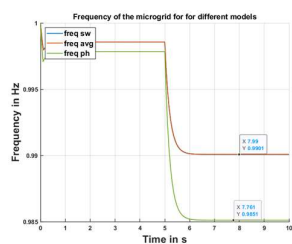


Figure 5 Frequency of the microgrid

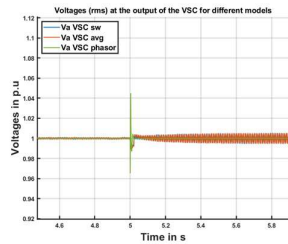


Figure 6 Voltage (rms) at the terminals of the GFM inverter

around 1 p.u, for all the three models. Contrary to the EMTavg and EMTsw models, the Phasor model estimates a more significant drop in frequency, particularly after event A, where it reaches 0.9851 p.u instead of 0.9901 p.u for the first two models. On the other hand, the response time of the Droop Control remains visibly the same for the three models.

In general, the performance of the EMTavg and Phasor models is close to the reference model, except that the Phasor model shows a power peak at the time of the event followed by a slight damping that does not affect the

steady state values of the active power.

Computation time: The computation time of the EMTavg and Phasor models is calculated for 10 s simulation of the microgrid. The computation time of the Phasor model, for a 1000 μ s step size, is 5 s, which is 100 times smaller than the time of EMTavg for a step size of 5 μ s (556 s), as shown in the table 3 below.

Table 3 Computation time for EMTavg and Phasor simulations for event A

Step size (μ s)	Computation time in s	
	Phasor	EMTavg
5	311	556
100	27	39
1000	5	-

Voltage and frequency stability:

The behaviour of the EMTavg and Phasor models remains stable as shown in their accuracy analysis. The frequency and voltage limits are respected throughout the simulation with respect to the acceptable operation values depicted in the Table 1.

Given the numerical and physical criteria observed, the Phasor model can be adapted to small signal stability assessment, as it allows accurate simulations to be carried out with a computation time 100 times smaller than the EMTavg model.

Event C3: Three-phase short-circuit:

Event C3 causes a short circuit between the three phases A, B and C at the output of the GFM inverter. It represents a large signal disturbance that calls into question the ability of the GFM inverter to recover the microgrid stability.

The fault is assumed to be cleared after 200 ms from the time of the event (5s).

The step sizes of different models are given below:

Model	Step size in μ s
EMTsw	5
EMTavg	100
Phasor	1000

Models accuracy:

As shown in figures 7 and 8, it is clear that the Phasor model overestimates the model response and estimates that the short circuit current at the output of the GFM inverter exceeds 8 p.u and the voltage 2 p.u after the clearing fault time. This can be justified by the fact that Phasor model cannot take into account the very fast dynamics occurred in the event, as phasor simulation is based on mean values of currents and voltages. However, the Phasor model has shown a stable behavior in the steady state after 5.5 s.

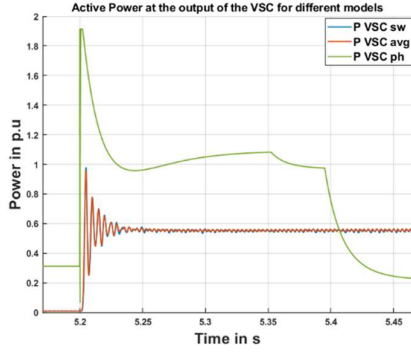


Figure 7 Active power of the GFM for the three models

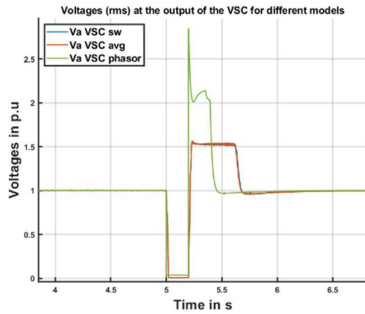


Figure 8 Voltages (rms) of the GFM for the three models

The EMTavg model has successfully follow the same behavior as in the reference model as shown above.

Computation time:

As for the event A; the computation time of the models is illustrated in the table 4. The Phasor model is not taken into account as it shows a non-accurate behavior compared to the EMTsw model.

Voltage and frequency stability:

The behaviour of Phasor model is not stable based on the accepted operation values of the table 1, contrarily to the EMTavg, which remains stable during and after the fault. Based on the analysis above, the Phasor model seems to not be adapted to very fast dynamic event as faults. It would be then mandatory to use an EMT simulation to catch all the dynamics that occur during the fault.

Table 4 Computation times for EMTavg and EMTsw (event C3)

Step size (μ s)	EMTavg	EMTsw
5	515	584
100	34	-
1000	-	-

IV. CONCLUSION AND PERSPECTIVES:

In this paper, a state of the art of some simulation tools used to assess the large disturbance stability in microgrid is presented. A comparative analysis on a typical microgrid composed of a GFM, GFL and loads, is then conducted. The results showed that the Phasor model might be accurate in small signal stability analysis; however, they cannot represent the behaviour of the system in case of large-signal disturbances where EMT

simulations might be required. In the next steps of this work, HIL tests with the model of the GFM inverter will be conducted to validate the simulation results of the EMTsw ref. Moreover, more events and components will be added to the microgrid to allow more advanced analysis of the stability.

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