Electromagnetic Transients (EMT) Model Design based on Modular Multilevel Converter Mockup

M.M. Belhaouane, H. Zhang, F. Colas, Riad Kadri, Taoufik Qoria, F. Gruson, P. Rault, S. Dennetiere and X. Guillaud

***Abstract*-- This paper deals with the conception and the development of a detailed EMT Model for MMC based on experimental results obtained from a mock-up. The main purpose is to illustrate how to exploit the performances of EMT simulation tools to develop a detailed model that represents accurately the behaviour of a physical MMC. According to step-by-step identification of the MMC element parameters, the idea is to perform a systematic method, which allows expanding an accurate EMT model considering the behaviour of the prototype and its environment. The first part depicts the MMC topology and the modelling approach of the Half-bridge Sub-Module (SM) using a detailed IGBT-based model. The second part of the simulation model conception concerns both control levels such as high-level and low-level controllers. The last part of the EMT model conception involves the modelling of measurement process, ADC (Analogue Digital Converter), sensors dynamics, the communication delays and especially the quantization effect. Finally, the obtained results from the final detailed EMT model is compared to the experimental behaviour for different active and reactive powers operating points in order to prove the effectiveness and the capability of the EMT modelling to reach a detailed and accurate model.**

***Keywords*: Modular Multilevel Converter (MMC), MMC Mock-up, Electromagnetic Transients (EMT) simulation Model, experimental test, Model conception and development.**

I. Introduction

To attempt to massively integrate renewable energy sources leads to increase the power transfer capacity of the electric power system, which can partly be achieved thanks to High Voltage DC systems (HVDC). The Modular Multilevel Converter (MMC) is an AC/DC converter topology used for high voltage adjustable speed drives and power transmission applications [1]. This topology shown in Fig.1 holds out many advantages such as modularity, scalability, lower switching frequency, better power quality and especially lower losses compared to 2 or 3 level converter topologies. Therefore, these topologies can replace thyristors based HVDC link (e.g. INELFE between France and Spain [2]) and are seen as good candidate future MTDC grids thanks to its power reversal capability. The main European and Asiatic HVDC manufacturers provide such technology [3, 4]. For academics and industrials, it is important to implement some control strategies on scale down MMC mock-up in order to challenge the offline simulation results with real hardware. The deep investigation of differences helps to improve the robustness of the control software as well as the accuracy of offline models. To be relevant, such mock-up must be as representative as possible of a full scale MMC, which has a large number of sub-modules (e.g. 401 levels for a 640 kV 1 GW HVDC MMC) [5]. Regarding the academic MMC mock-up, only a dozen converters are referenced in the literature. Apart one very low power converter (800 W) operating with 40 SM (Sub-Module) per arm [6], the other prototypes have only a very low number of SMs [7]. This type of mock-up requires a Pulse Width Modulation (PWM) control and thus generates a high switching frequency, which is not representative of an MMC converter for the HVDC but rather valid for electrical machine adjustable speed drives applications [8, 9]. Moreover, some of them are designed with a non-negligible capacitor on the DC bus. In addition, most of them are controlled by a single control hardware, which is different as industrial systems, which has different controllers according to the level of control. This kind of architecture would affect the general behaviour due to the communication time delays, the different time steps etc.

This article deals with offline MMC model improvement based on comparisons between physical experimental results obtained with a MMC mock-up and detailed EMT offline model of such system. The purpose of this research work is to define a systematic methodology for obtaining the important system parameters and find out the subtle details relating to the physical implementations to get accurate EMT model which matches the static and dynamic behaviours of the physical MMC prototype. Once the system is identified, the methodology would be applicable to high voltage MMC. Thus, this works would first consider a step by step component identification based on dedicated tests, then investigate the modelling of the control system and present a methodology based on the development tools to generate libraries which can be implemented into the simulation platform and thus guaranty the same software update is used for both offline model and in physical controllers.

The design of the mock-up considered in this article is detailed in [9], it corresponds to the scale down of a 640 kV and 1 GW MMC HVDC station. This mock-up operates at 50 Hz, 200 V phase-to-phase AC voltage, 400 V pole-to-pole DC bus voltage with a rated power of 5 kW and 1.5 kVAR. The

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converter control is dispatched on several hardware controllers, including distributed processors (one for each arm) and a master control.

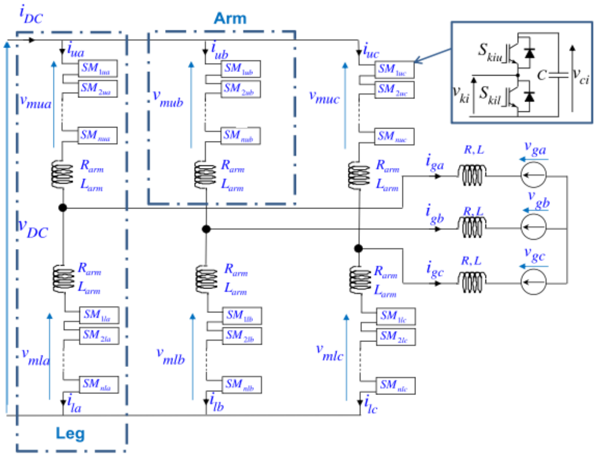

Fig. 1. Modular Multilevel Converter structure.

This paper is organized as follows: Section II presents the description of the MMC prototype and the identification procedure to get the different parameters of the mock-up and its environment. In section III, the systematic EMT model development of MMC mock-up is detailed. Based on the developed EMT model, a comparative study between experimental and simulation results is given in the section IV to depict the performances of the EMT model design method. Finally, section V concludes this paper.

II. MMC MOCKUP IDENTIFICATION AND EXPERIMENTAL TEST

A. MMC Mockup Description

The MMC prototype depicted by Fig.2, has 20 sub-modules (SMs) per arm, carrying a nominal active power of 5 kW and a reactive power of 1.5 kVAR. The prototype supports a DC voltage around 400 V on the DC bus and phase to phase 200 V as AC voltage for a three-phase AC grid balanced at 50 Hz. As said above, in order to have a realistic behaviour as possible respect to a full scale MMC with a large number of SM (i.e. 640 kV on the DC side, a rated power of 1 GW and 400 sub-modules), the design of the power part of the converter was based on the Per-unit approach. The used full-scale parameters are summarized in [9], which come from a realistic value close to those of the INELFE link [2]. More details about the different design steps of MMC prototype are given in [9, 10]. A detailed material description is shown through Fig.3. According to the number of SMs (120 sub-modules for the prototype) a DSP (Digital Signal Process) hardware development kit solution is considered using the rapid prototyping tools [11].

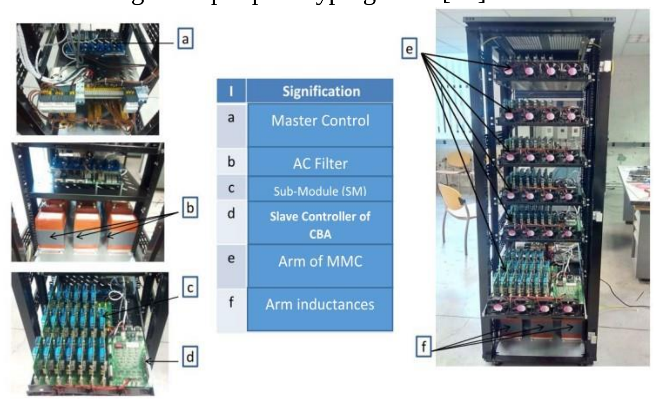

Fig. 2. Modular Multilevel Converter prototype.

As shown by Fig. 3, a distributed control structure has been performed. In the proposed architecture, the control system is divided between a master DSP and six slaves DSP. Each slave provides low-level control (switching function generation and SM arms control balancing algorithm (CBA)) of each arm while the Master provides the global control (high-level controller) with slower dynamics (control the power and the stored energy into the MMC). Therefore, for the high-level control (DSP Master), the well-known CCSC (Circulating Current Suppression Control) is considered [11], which involves suppressing the circulating component (i.e., 100 Hz component) of differential current (DC current) regulated in "dq0" reference. Thanks to this control strategy, the stored energy within the converter stabilizes naturally at their operating point (DC voltage equal to 400 V). The communication between the master and slaves DSP is done by optical links where required information are exchanged at 100 kHz. Each DSP slave provides to the master one the sum of the capacitor voltage of its arm while the master transmits to each slave, its reference of voltage that the associated arm must generate.

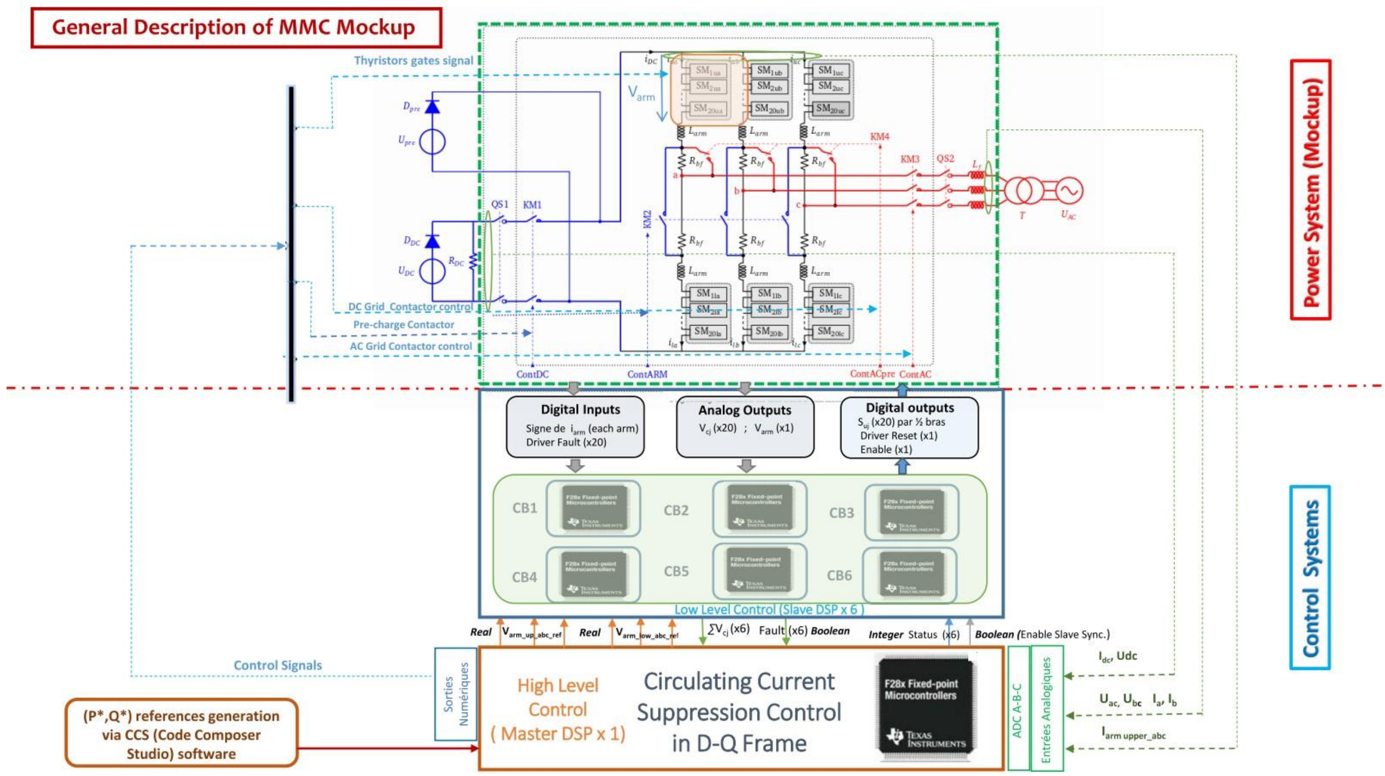

Fig. 3. Detailed material description of MMC Mockup

The chosen slaves DSP are the Texas TMS320F28377D as they have enough analog inputs (24 in total). The same reference has been selected for the master DSP for implementation simplicity. Note that the generation of active and reactive powers references, is provided via the console of CCS (Code Composer Studio) environment. Code Composer Studio software is an integrated development environment that allows you to program Texas Instruments embedded processors such as digital signal processors (DSP) of the TMS320 family [10].
Therefore, the main purpose of this study is to depict how to develop an EMTP simulation model of MMC based on the previous description of prototype. By the way, it is important to identify the parameters of the mock-up and its environment in order to integrate them in simulation model. This will be the subject of the next parts.

B. Parameters identification of MMC Mockup

In the aim of carrying out the identification task, experimental tools have been deployed. Indeed, in order to connect the MMC prototype to a balanced three-phase AC voltage, an ideal source has been used that represents the behaviour of the AC grid using a linear power amplifier where sinusoidal and balanced voltage references are generated through a dSPACE control desk [12]. In addition, a three-phase AC cable has been added over a length of 20 m, which links the output of the linear power amplifier to the primary of the transformer. A direct identification phase of the prototype parameters and its environment was performed using different measurement devices. The following Tables give the numerical values of the identified parameters of MMC mock-up for AC and DC side. A three-phase AC transformer with a unitary transformation ratio and Δ / Y coupling is used on the AC input of the MMC, which aims of galvanic isolation. The identification process of the transformer has been established using classic method such as short-circuit and open circuit tests.

TABLE I: AC FILTER PARAMETERS

Rf_a= 0.1184 Ω	Rf_b=0.0915 Ω	Rf_c=0.0976 Ω
Lf_a= 4.489 mH	Lf_c= 4.348 mH	Lf_c= 4.442 mH

TABLE II: UPPER AND LOWER ARM PARAMETERS

$Rarm_{ua}$= 0.169 Ω $Rarm_{la}$ = 0.164 Ω	$Rarm_{ub}$= 0.165 Ω $Rarm_{lb}$ = 0.162 Ω	$Rarm_{uc}$= 0.183 Ω $Rarm_{lc}$ = 0.151 Ω
$Larm_{ua}$= 8.72 mH $Larm_{la}$ = 9.01 mH	$Larm_{ua}$= 8.72 mH $Larm_{la}$ = 9.01 mH	$Larm_{ua}$= 9.09 mH $Larm_{la}$ = 8.89 mH

Tables III and IV give respectively the parameters of the AC transformer and cable. Only the resistive behavior of the AC cable is considered.

TABLE III: AC TRANSFORMER PARAMETERS

R_T = 0.388 Ω	L_T = 2.1 mH	R_{Magn} =4571 Ω

TABLE IV: AC CABLE PARAMETERS

Length = 20 m	Section=6 mm^2	R_{cable} =0.053 Ω

Table IV gives the parameters of the AC cable where only the resistive behaviour is considered. Regarding the identification of the MMC mock-up on the DC side, the 120-capacitance values of the submodules (SMs) were measured. To simplify the study, only the equivalent capacitors of each arm are depicted in the Table VI.

TABLE VI: EQUIVALENT CAPACITANCES VALUES

C_{armupA}= 7.16 mF	C_{armupA}= 7.18 mF	C_{armupA}= 7.18 mF
$C_{armlowA}$= 7.16 mF	C_{armupA}= 7.15 mF	C_{armupA}= 7.16 mF

Regarding the 120-measured capacitance values, the stored energy unbalance between upper and lower per phase is negligible, which is around 0.4%.

III. STEP BY STEP EMTP-RV MODEL DEVELOPMENT OF MMC MOCKUP

Based on the previous section, the fundamental purpose of this work is to develop an accurate EMT model, which will be able to describe accurately the behaviour of the mock-up identified above. The design of the EMT simulation model is based mainly on four steps:

- Modelling of the power part of the converter;
- Modelling of the high-level control given by CCSC-DQ ;
- Modelling of the low-level controller given by Capacitors Balancing Algorithm and Nearest Level Control (NLC);
- Modelling of measurement process, ADC (Analogue Digital Converter), quantization, sensors dynamics and the communication delays.

In the sequel, the steps mentioned above are stated to reach the detailed and accurate EMTP model.

A. MMC Topology and modelling based on Half–bridge Sub-Modules

The aim of this subsection is the detailed modelling of 20-level MMC using electromagnetic transient-type simulation. Seeing the three-phase configuration of the MMC mock-up topology in Fig. 3, the prototype is comprised of 20 SMs per arm, which results in a line-to-neutral voltage waveform of 21 levels. Each SM is a half-bridge converter and includes mainly a capacitor C and two IGBTs with antiparallel diodes (S1 and S2). There are many variables in an MMC. Different models can be used according to the type of study and required accuracy. MMC model evolution in decreasing complexity is detailed in [13]. For the proposed study, the detailed IGBT-based model called model#1 is used under EMTP to characterize the behaviour of each SM based on the datasheet of MOSFET component. As shown in Fig.4, this model considers a detailed representation of power switches and uses an ideal controlled switch, two nonlinear (series and anti-parallel) diodes, and two snubber circuits. As depicted by Fig.5, the non-ideal diodes are modelled with nonlinear resistances using the classical V-I curve of a diode and a snubber circuit to mimic the reverse recovery condition. The nonlinear characteristics is tuned based on manufacturer data sheets and introduced within EMTP model. This detailed model is able also to account for switching and conduction losses. Note that the resistances values RDson (i.e., 3.9 mΩ) are also identified and considered in the EMTP model. In addition, the SM circuits contain some measurement resistances, which are also taken in to account. The identified resistances of 1910 kΩ have been added in parallel to the SM capacitors in EMT model. In order to validate the power system part, a SM pre-charge tests without control under a DC-side perfect source were performed in experimental and EMT simulation. The aim is to check and validate that the charge cycle behaviour of SM capacitances in both static and dynamic areas lead to a quite similar responses. The performed experiment and simulation tests depict that the behaviours are close and the threshold voltage (V_0= 0.7 V) of the series diode is identified. Note that the snubber parameters (R_n and C_n) are sized based on the empiric method.

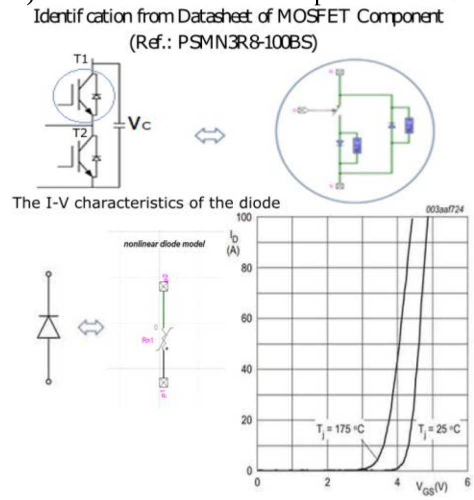

Fig. 4. Mockup EMTP Model – Detailed Model.

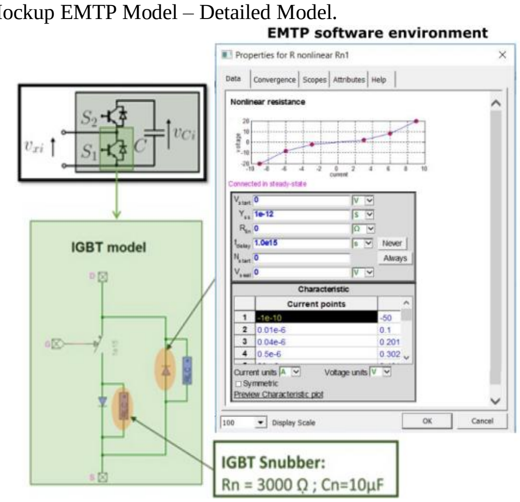

Fig. 5. Modelling strategy based on detailed IGBT characteristics.

B. Modeling of High level and low level controllers based on SimulinkDLL Toolbox

As mentioned above, the second step of EMT simulation model design concerns the high-level control provided by the classical CCSC-DQ strategy with uncompensated modulation and Synchronous Frame PLL (Phase-Lock-Loop). For more details concerning the control structure of CCSC-DQ, the reader can refer to [11].

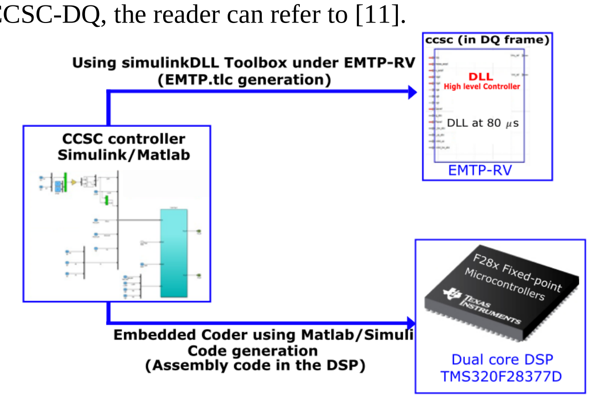

Fig. 6. Strategy of modelling and validation of high-level controller

In order to be sure that the same high-level controller used in the mock-up will be integrated in the simulation model, the SimulinkDLL Toolbox under EMTP is exploited. The toolbox allows importing Simulink models, regardless of its complexity. The Simulink DLL toolbox available in the EMTP library offers several advantages on the EMTP model conception. In fact, the use of the DLL gives the possibility to implement the same controller (high level and low level controllers) used in experimentation for the simulation by integrating the DLL in the EMT simulation model . Therefore, as shown in Fig.6, the main idea is to use the Simulink control model of CCSC-DQ used for assembly code generation and integrated inside the master Dual Core DSP for the DLL generation. Using the appropriate Matlab/Simulink toolboxes and a compiler, a DLL is automatically created for the global controller at 80 µs and used by this import tool to create the EMTP model with all the necessary connections (required measures and control signals). Thanks to that, exactly the same control is implemented on both sides (experimental and EMT simulation). The next part focuses on the modelling of low-level controller provided by Capacitors Balancing Algorithm (CBA) and Nearest Level Control (NLC). Like the high-level control, six DLL are generated for each CBA per phase running at 20 µs. The CBA implemented on each slave DSP is the reduced switching-frequency voltage-balancing algorithm. Since it is not possible to use the same DLL in simulation and experimentation for the CBA because the assembly code in DSP is optimized to minimize the computing time on CPU, a validation method based on real-time simulation is proposed. It consists to compare the CBA used on Mockup with those used in simulation for DLL generation and integrated thereafter in EMTP model. The idea is to verify that assembly code running on DSP and compiled Matlab code for DLL generation are similar and give identical results for the same input signals. Thus, as illustrated by the Fig.7, a dynamic comparative study has been performed using Real time simulation and HIL (Hardware in the Loop) concepts for a given operating point. Based on the obtained results given by Fig.8, the dynamic responses of 20-SM voltages are similar and even the chosen hysteresis range (i.e., 5%) for the CBA is the same for both Real time simulation and DSP environments.

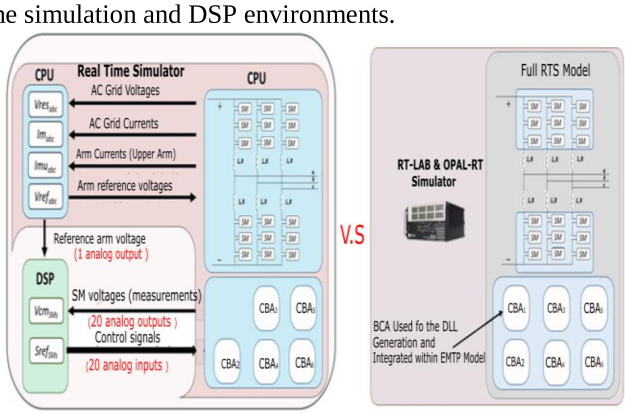

Fig. 7. Validation process of the CBA used for the DLL generation.

Until now, the power system part as well as both high level and Low-level control are modelled using electromagnetic transient-type simulation. However, it is important to take into account the interaction between the power and control system.

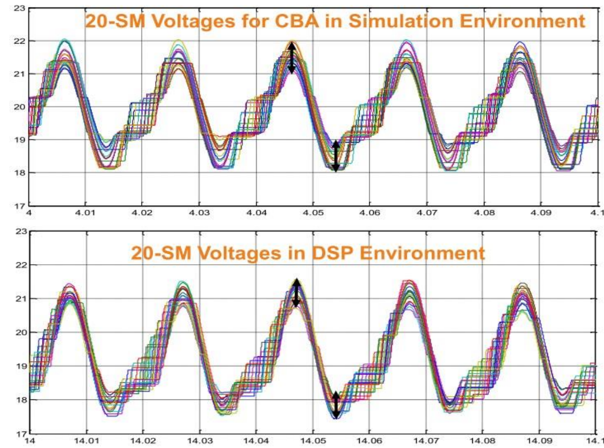

Fig. 8. Comparative results or the CBA.

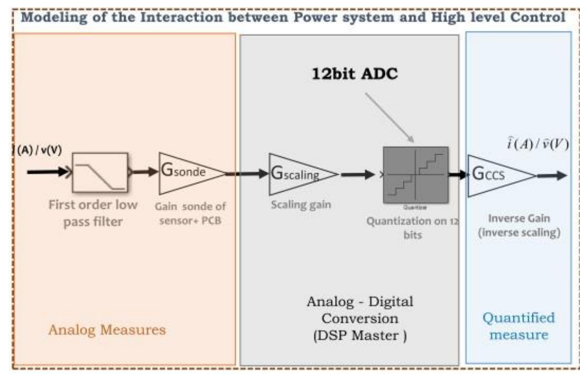

Fig. 9. Modelling of the ADC and quantization effect

C. Modeling of the ADC and quantization effect

Based on the EMTP libraries, the interface between the power system (Mockup model) and the high-level controller (DSP Master) is model taking into consideration the sensors dynamics using the datasheet of current voltage sensors, ADC (Analogue Digital Converter), and the communication delays. As shown by Fig. 9, a special attention on the modeling is given to the quantization process on 12 bits and its effect. In fact, the instrumentation part is not so perfect contrary to what is generally presented in the simulation models and it is important to model this part, which expresses the measurements noise and delays, the ADC conversion and the quantization effect. Based on current and voltage LEM transducers, the dynamics of the used sensors are very fast (i.e., in µs), which does not induce a significant effect contrary to the quantization operation. In digital signal processing, quantization is the process of approximating a continuous range of values by a relatively small set of discrete symbols or integer values. A common use of quantization is in the conversion of a discrete signal (a sampled continuous signal) into a digital signal by quantizing. Both of these steps (sampling and quantizing) are performed inside the DSP thanks to analog-to-digital converters with the quantization level specified in bits (e.g., 12 bits for Texas TMS320F28377D). By taking in to account the quantization process in the EMT model, quantization noise is also considered. It is a rounding error between the analog input voltage to the ADC and the output-digitized value. The noise is non-linear and signal-dependent. It can be modelled in several different ways. Therefore, by adding this part under EMTP, the model is improved and it became more accurate.

However, this concern is being investigated in order to increase the precision of the EMT model and an improvement of the results in terms of precision is expected.

IV. Comparative Study between experimental and simulation results

A comparative study has been performed between experimental and simulation results based on the designed detailed EMTP model through the modelling steps depicted above. Several tests have been made to evaluate the accuracy of the EMT model respect to the mock-up behaviour for different step changes of active reactive powers operating points. In the following, only one test will be presented which corresponds to Pacref=0.5 p.u (2500 W) and Qacref=0.0 p.u. For the comparative results, Figs. 10 and 11 depict the dynamic responses of the AC and DC currents.

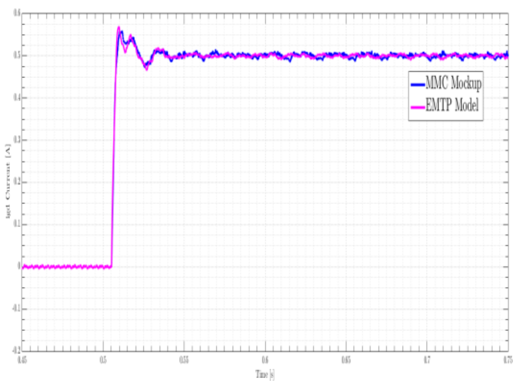

Fig. 10. AC-side current (d-component in d-q frame [A]). MMC Mockup in blue and EMTP simulation in magenta.

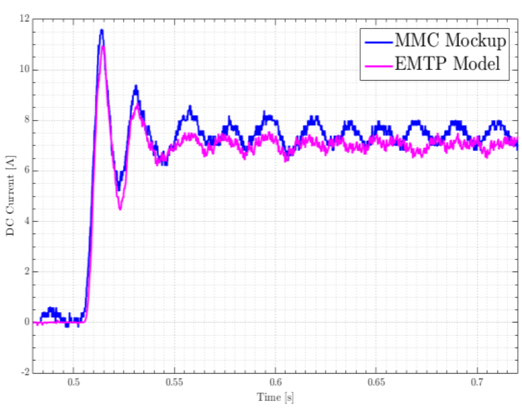

Fig. 11. DC current [A]. MMC Mockup in blue and EMTP simulation in magenta.

As shown by Figs. 10 and 11, the EMTP simulation model leads to similar results as experimental for the AC side variables. However, some differences remain for the DC side variables, specifically for the DC current where the simulation model does not reproduce exactly the behaviour of the experimental MMC mainly in transient. Moreover, oscillations at 50 Hz observed are observed in experimental results and reproduced in EMT simulation thanks to the modelling of the interaction between the high-level control (DSP in Master mode) and the power part of MMC. As perspectives, further works are in progress in order to improve the precision, like model validation without both high and low levels controllers based on precharge cycle of SMs capacitances, MMC operating on a resistive load in AC side to avoid the grid harmonic effect.

V. Conclusions

The purpose of this paper is to illustrate the conception and development of a detailed simulation model under EMTP to faithfully produce the behaviour of a small-scale 20-level MMC converter. Then, first, a parameter identification step is established in order to integrate them in the developed simulation model. Based on the identified parameters of the prototype, a detailed EMT simulation model is designed and developed starting from the power part, then the high-level controller and finally the low-level controller. The material part of the mock-up and its external environment was taken also into consideration in the design and development phases of the EMT simulation model. Based on the experimental results under CCSC as global controller, steady-state oscillations at 50 Hz have been identified in experimental and produced in EMT simulation thanks to the modelling of the quantization effect. The performance of the simulation under EMTP allowed modelling in detail the static and dynamic behaviours of the mock-up. Therefore, the comparative study between experimental and simulation results leads to a quite similar behaviour on the AC side. However, small differences remain on the DC side variables mainly in transient. Additional work are in progress to improve EMT model accuracy.

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