Efficient Real-Time Testing of 51 Level MMC Converter in Hardware in Loop (HIL) Setup for HVDC Applications

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***Abstract*—With the recent development in power semiconductor devices, the high voltage direct current (HVDC) transmission system becomes the most dominant technology for future power systems. Modular multi-level converter (MMC) has been recognized as the most prominent topology in building HVDC systems due to its numerous advantages over other converter topologies due to its salient features. Today many solutions are proposed for the issues related to the operation, control, and protection of MMCs using different simulation platforms and small prototypes. In this research work, the MMC and its controller are designed and tested under a real-time simulation environment using a hardware in loop (HIL) setup. The three-phase MMC circuit designed in MATLAB is loaded in NI PXI. The NLM controller designed in LabVIEW is then loaded on an FPGA-based Compact RIO controller to control the circuit running in PXI. The real-time simulation environment enables engineers and researchers to develop and test their proposed controllers without involving and damaging the costly hardware equipment. The results obtained using real-time simulation mimic the actual behavior of the controller. The developed MMC possesses an improved power quality and a very low total harmonic distortion (THD) maintaining a modulation index of 0.8. The proposed method is simpler to implement and produces a pure sinusoidal AC output waveform, tracking the reference signal.**

Keywords—Modular Multi-level Converter (MMC), Multi-terminal direct current (MTDC), Droop control, Hardware-in-the-Loop, Real-time Simulation (RTS)

I. Introduction

The AC transmission system of bulk power along long distance possess limitation of high capacitance and huge power losses. High voltage direct current (HVDC) technology has been recognized as the most proven and economical solution for future power systems [1]. HVDC transmission based on LCC has been used for many years as an effective solution for bulk power transmission [2]. However, such systems require external reactive power for semiconductor switching and are not suitable for isolated systems [3]. The voltage source converter (VSC) based on insulated bipolar transistors (IGBT) overcomes all the limitations imposed by LCCs [4]. A VSC-based HVDC system provides independent control of active and reactive power and allows bidirectional power flows [5]. However, a VSC imposes high di/dt on arms of converter and semiconductor, which causes high stress and overvoltage in semiconductors. Moreover, DC short circuits are difficult to limit in VSC-based HVDC systems [6]. A modular multi-level converter (MMC) has been identified as the most attractive topology in recent years [7]. MMC is considered as the basic building block of HVDC and multi-terminal direct current (MTDC) grids due to its salient features such as modularity, fault blocking capacity, inherent energy storage capability, reduced dv/dt and di/dt stress, improved power quality. The leading entrepreneurs of MMC are Siemens, EPRI, ALSTOM, and ABB [8].

A lot of research work has been presented on the modeling and control of MMCs. Traditionally, offline simulations have been extensively carried out to analyze the performance of MMCs with different modeling and control approaches. However, the precision of such offline simulations in contrast to the real-time behavior of MMC is quite low [11]. Hardware in loop (HIL) real-time simulation has been recognized as a competent solution to prototype the industrial controllers [12]. The digital real-time simulators replicate the output voltage and current signals of an electrical system with accurate precision [13]. Engineers are researchers are progressively working on modeling and control of MMCs using real-time simulation, which enables them to accurately replicate the behavior of actual MMC without causing any damage to expensive equipment. HIL setup enables engineers and researchers to test and investigate different control strategies applied to MMC under steady-state and transient conditions [14].

This study presents a platform for developing MMC using real-time simulation environment. Where the control algorithm is developed in a graphical-based LabVIEW platform, which is used to control the MMC implemented in an NI PXI system. In this research work, a 51 level MMC has been developed in a real-time simulation environment using the HIL setup. The developed MMC consists 50 half-bridge submodules (HBSMs) using average value model (AVM). The control algorithm of MMC is based on NLM with an N+1 modulation strategy. The circuit of MMC is designed in MATLAB and its controller is developed in LabVIEW. The designed MMC circuit is loaded in NI PXI and its controller is implemented in FPGA-based compact reconfigurable input/output (CRIO) controller for real-time testing. The developed real-time controller for MMC saves time and human effort by replicating the actual behavior of the hardware system. The real-time results obtained envision the robust performance of MMC with reduced ripple in submodule voltages, reduced circulating current, and a low total harmonic distortion.

The rest of the paper is organized as follows: Section II presents the architecture of the HIL setup. In Section III, the development of MMC has been discussed. In section IV, the implementation of the control algorithm is discussed in detail. Section V presents the real-time simulation results. Finally, section VI concludes the outcomes of the paper.

II. Real-Time HIL Setup

The real-time HIL setup helps researchers to convert their ideas into reality. In contrast to the offline simulations, the real-time HIL simulation provides the output result of a controller more closure to reality. HIL setup allows engineers and researchers to develop and test their systems in a secure environment without any damage to hardware equipment [19-20].

HIL laboratories utilize an open electrical hardware solver (EHS) for real-time simulation which is developed by OPAL-RT Technologies [19, 20]. The EHS simulates the electrical circuits on the NI PXI platform without performing any programming or mathematical calculations [21]. It provides a platform to researchers to build their models using MATLAB, NI Multisim, PLECS, or PSIM, which is then directly loaded in NI PXIe with a time step of nanoseconds. The setup for the real-time HIL laboratory available at our university is shown in fig. 1.

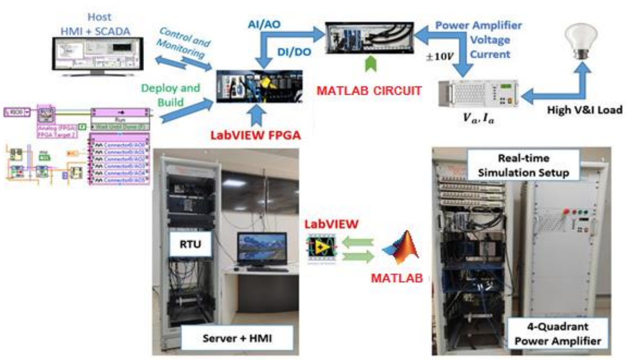

Fig. 1. Real-time HIL laboratory facility.

III. Design of MMC

A huge number of power semiconductor devices in an MMC produces heavy computational burden and technical challenges when they are modeled in electromagnetic transient (EMT) type software. Detailed models (DM) of MMC use thousands of semiconductor devices and require small numerical integration steps to accurately simulate the behaviour of an MMC, which produces heavy computational burden. However, the Average value model (AVM) requires less computational resources and uses larger integration time steps which leads them towards reduced computational burden [9, 10]. An AVM reproduces DC and AC side converter dynamics for voltages and currents. Such models are extensively used for an accurate representation of terminal dynamics, external faults system-level studies [9]. Similar to DM an AVM provides independent control of magnitude and phase angle of the voltage of an MMC [10]. Moreover, an AVM reproduces DC and AC side converter dynamics for voltages and currents. In an AVM, the distributed arm capacitors of MMC are represented by a lumped capacitor. Hence, AVM does not capture the internal dynamics of the converter. Such models are extensively used for an accurate representation of terminal dynamics, external faults and system-level studies. They are suitable for converter control design and arm modulation techniques [15]. In this research work, a 51 level MMC has been realized. Each MMC consists 50 half bridge submodules (HBSMs) using AVM. Fig. 2 [10] shows the schematic diagram of the MMC topology used in this research work. An arm reactor L_{arm} has been placed with each arm of MMC, which controls the circulating currents and reduces fault currents in an arm.

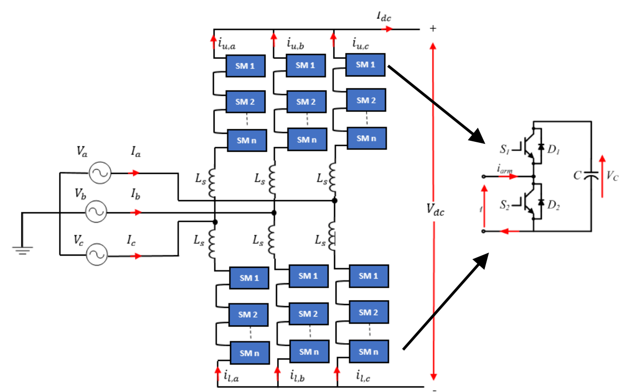

Fig. 2. Schematic diagram of three phase MMC [10].

Referring to the schematic diagram of MMC shown in figure 1, the AC equivalent of the MMC is given as [10]

$$V_j = -V_{uj} + \frac{V_{dc}}{2} = V_{lj} - \frac{V_{dc}}{2} \quad (1)$$

Where the reference voltages for the upper and lower arm are given as

$$V_{uj}^{SM} = -V_j + L_s \frac{di_{uj}}{dt} + \frac{V_{dc}}{2} \quad (2)$$

$$V_{lj}^{SM} = V_j + L_s \frac{di_{lj}}{dt} + \frac{V_{dc}}{2} \quad (3)$$

where V_{uj} is the total upper arm voltage on each phase including the voltage of reactor , the voltage V_{uj}^{SM} is the total voltage of all upper SMs. Similar holds for lower arms. For arm currents in each phase [10, 16]

$$i_{uj} = \frac{i_j}{2} + \frac{I_{dc}}{3} + i_{zj} \quad (4)$$

$$i_{lj} = -\frac{i_j}{2} + \frac{I_{dc}}{3} + i_{zj} \quad (5)$$

Where the circulating current is represented by

$$i_{zj} = \frac{i_{uj}+i_{lj}}{2} - \frac{I_{dc}}{3} \quad (6)$$

Subtracting equation 2 from equation 3

$$V_j = \frac{L_s}{2}\frac{di_j}{dt} + e_j \quad (7)$$

here V_j is the phase voltage of each phase of MMC, where j = a,b,c, the reference voltage for each phase e_j is give by:

$$e_j = \frac{V_{lj}^{SM} - V_{uj}^{SM}}{2} \quad (8)$$

Replacing equation 7 and equation 8 into equation 2 will give upper arm voltage equation

$$V_{uj}^{SM} = -\left(V_j - \frac{L_s}{2}\frac{di_j}{dt}\right) + \frac{V_{dc}}{2} = -e_j + \frac{V_{dc}}{2} \quad (9)$$

Similarly for lower arm

$$V_{lj}^{SM} = \left(V_j - \frac{L_s}{2}\frac{di_j}{dt}\right) + \frac{V_{dc}}{2} = e_j + \frac{V_{dc}}{2} \quad (10)$$

Equation 9 and 10 is used to calculate upper arm and lower arm voltages of the MMC respectively. The modulation index is calculated using equation 11

$$m_j = 2\frac{e_j}{V_{dc}} \quad (11)$$

Where e_j is given by

$$e_j = \frac{m_j V_{dc}}{2} \quad (12)$$

IV. Development of NLM Control Algorithm in LabVIEW

LabVIEW is the graphical-based programming language that enables us to program the FPGA without using VHDL or Verilog. A nearest level modulation (NLM) algorithm with N+1 modulation strategy is programmed in LabVIEW to control the MMC operation, which is deployed in in real-time NI controller i.e., compact reconfigurable input/output (CRIO). NLM is the most common strategy applied for MMC operating at high voltage levels. As compared to other modulation techniques, the switching frequency of an NLM is equal to fundamental frequency, as a result the overall losses of converter are reduced [11, 12]. The MMCs are employed using AVM, hence no capacitor voltage-balancing algorithm has been implemented modulation strategy. Equations (13) and (14) are used to implement the NLM algorithm.

$$N_U = round_{0.5}\frac{V_{dc}}{2V_d}(1 + m\cos(\omega t)) \quad (13)$$

$$N_L = round_{0.5}\frac{V_{dc}}{2V_d}(1 - m\cos(\omega t)) \quad (14)$$

For a closed loop MMC, it is necessary to control and vary the modulation signals wr.t change in active and reactive power [19, 20]. In this research work, a vector current control scheme has been adopted to provide the independent decoupled control of active and reactive power [17]. The vector current control scheme finds core importance in the MMC control system. Following mathematical relationships are used to implement a vector current control [18]:

$$P_g = V_g^d I^d \quad (15)$$

$$Q_g = -V_g^d I^q \quad (16)$$

From equations (1) and (2), it is clear that the active power can be controlled using the d component of the current while the reactive power can be controlled using the q component of the current. This provides an independent decoupled control in an MMC. In LabVIEW DQ frame is used to achieve zero steady-state error using a PI controller The block diagram for the closed-loop algorithm developed in LabVIEW is shown in figure 3 and the NLM controller developed in LabVIEW is shown in figure 4.

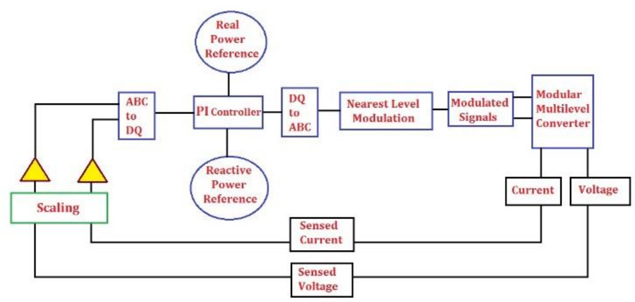

Fig. 3. Closed loop control diagram.

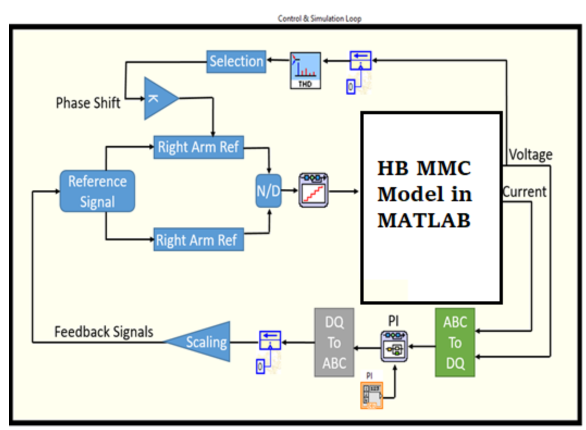

Fig. 4. NLM algorithm in LabVIEW.

V. Real Time Simulation Results

The setup for real-time simulation is shown in Figure 5. The parameters of MMC are shown in Table I. The control algorithm for NLM, which is designed in LabVIEW is compiled through NI cloud servers and then loaded into FPGA based CRIO. The control signals generated from CRIO are sent to FPGA based PXI, where the real-time circuit of MMC is loaded. The real-time results obtained from PXI are shown in figures 6 to 11.

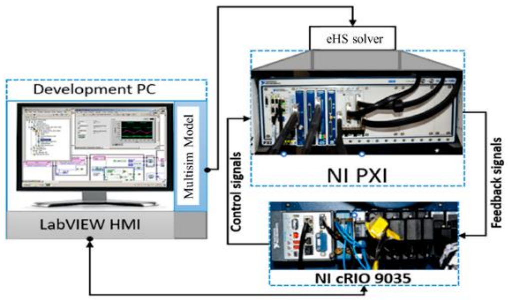

Fig. 5. Layout for experimental setup.

TABLE I. PARAMETERS OF MTDC SYSTEM

Quantity	Value
Arm Inductance	0.15 p.u
Arm Resistance	0.03 ohm
Submodule Capacitance	10.4 mF
DC Bus Voltage	135 kV
Frequency	50 Hz
X/R	14.28
MMC Station	220 MVA

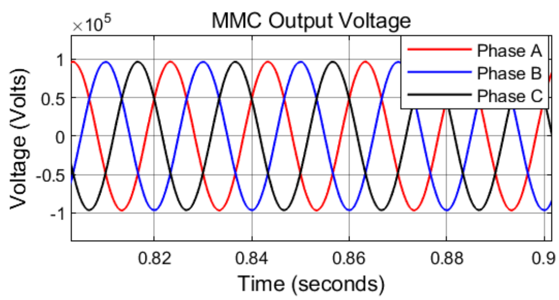

Fig. 6. Three-phase output voltage of MMC.

The three-phase output voltage and current waveforms of MMC are shown in figures 6 and 7. It can be observed that the output AC waveforms are tracking the sinusoidal reference properly. It can be witnessed that by increasing the level of MMC, the power quality of AC output waveforms is improved. The submodule voltages and arm currents are obtained using equations 2 to 5, which are shown in figures 8 and 9. It can be witnessed that the submodule voltages contain a very small ripple, which is less than 10%. All capacitors can handle this quantity very well. The arms currents are also balanced. This shows that capacitors inside the submodules of MMC are properly dimensioned. The result for the circulating current flowing through each phase of MMC is obtained using equation 6, which is shown in figure 10. It can be observed that the amount of circulating current is very small, which is less than 0.1 p.u. The modulation index of MMC is obtained using equation 11, which is shown in figure 11. It can be witnessed that the modulation index of the MMC station is 0.8, which follows the standard operational grid codes of HVDC systems.

The THD for the output voltage and current for MMC is calculated as 0.25% and 1.40 % respectively, which ensures IEEE standards for THD.

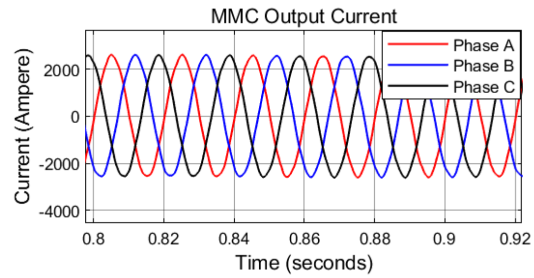

Fig. 7. Three phase output current of MMC.

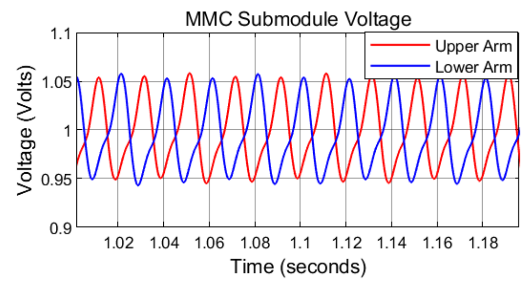

Fig. 8. Submodule voltages of MMC.

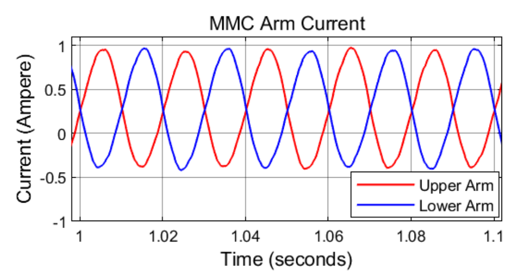

Fig. 9. Arm currents of MMC.

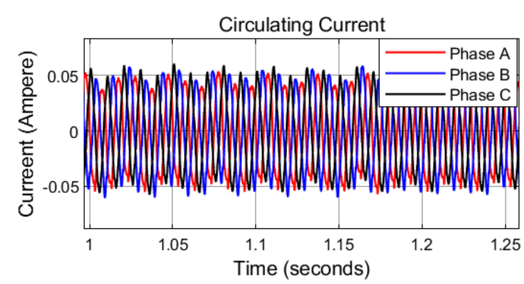

Fig. 10. The circulating current of MMC.

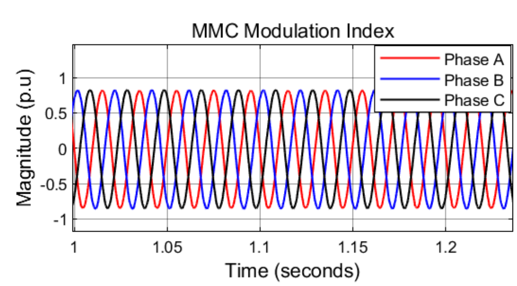

Fig. 11. The modulation index of MMC.

VI. CONCLUSIONS

In this research work, the real-time analysis of an MMC was performed using a HIL setup. Where the MMC circuit was designed in MATLAB and its controller was programmed in LabVIEW. Such analysis reduces the efforts of engineers and researchers and allows them to design and test their controllers in a real environment without causing any damage. The real-time simulation produces results with a time step of nanoseconds, which mimics the actual behavior of the controller. The designed MMC controller produces a pure sinusoidal output waveform maintaining a standard modulation index of 0.8 and a low THD for output voltage and current. Hence, such type of MMC can be easily recommended for its implementation in HVDC grids. In the future, the developed MMC will be tested in HVDC grids using a real-time simulation platform.

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