Center for Advanced Power Systems
Florida State University

Model Design Document

Modular Multi-Level Converter Average Value Model

Document for ESRDC Project

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Version 1.0

Prepared by

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REVISION HISTORY

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VERSION NUMBER	DATE	COMMENTS
1.0	November 8, 2019	Initial version.

Contents

Glossary

AC Alternating Current

CHIL Controller Hardware in the Loop

CSM Current Source Mode

DC Direct Current

FSU-CAPS Center for Advanced Power Systems, Florida State University

MATLAB® MATrix LABoratory, a registered trademark by MathWorks Inc.

MDD Model Design Document

MMC Modular Multi-Level Converter

PI Controller Proportional Integral Controller

PLECS® Piece-wise Linear Electrical Circuit Simulator, a registered trademark by Plexim Gmbh.

RTDS® Real Time Digital Simulator

VSM Voltage Source Mode

1 Introduction

This Model Design Document (MDD) describes the implementation of an Averaged Value Model (AVM) of a Modular Multi-Level Converter (MMC) for the MATLAB/Simulink/PLECS computing environment. The details of the model development is described in [1]. Unlike the conventional white box method to build up the AVM with all the control information available, this AVM is built from a black box with only the measured MMC impedance results. The method in this report is much simpler than the conventional method, and does not expose the internal control information. The control algorithm and control methods are modeled based on the impedance shaping results. The saturation limitations in the controller are designed based on the system transient.

1.1 Purpose

The purpose of the MMC is to convert electric power from high voltage alternating current (ac) to high-voltage direct current (dc), or vice-versa, while maintaining either a constant voltage or current at the output of its terminals. The purpose of this AVM is to achieve less complexity and faster time domain simulation studies of the MMCs available at CAPS while still maintaining sufficient converter dynamic accuracy. The method applies equivalent circuit models of the power stage and the duty-cycle generation circuitry to describe the low frequency behavior of switching model systems.

1.1.1 Model Description

This MMC AVM uses controlled voltage- and current sources to simulate the average-value performance of the MMCs available at CAPS' PHIL MVDC test facility. This model is implemented in the MATLAB/Simulink/PLECS computing environment.

1.1.2 Requirements

The MMC AVM is required to accurately represent the average-value performance of CAPS' MMCs in both voltage-source mode (VSM) and current-source mode (CSM). In VSM mode, the MMC is controlled to provide the desired output dc-link voltage, and in CSM mode it is controlled to provide the desired output dc-link current.

1.1.3 Model Components

The model components include:

- MMC ac power circuit: Controllable voltage sources, ac inductor, and ac grid; and
- MMC dc power circuit: Controllable voltage/current sources, dc inductor, dc filters, and dc load; and
- MMC controls: Current loop for ac side, current and voltage loop for dc side.

1.2 Identification

The model of the MMC AVM implemented here is identified as MMC AVM version 1.0. This version of the model was completed within the MATLAB/Simulink (2018b) and PLECs (4.2.4) environment while ensuring consistent use of the model variable naming conventions described in Section 5.1. The file set for this model includes Simulink files (".slx" extension) and MATLAB files (".m" extension).

1.3 Hierarchy

This model can be operated autonomously by running the .m files. The MMC AVM model can also be used as a component of a larger system model by replacing the ac grid and dc load with other system components.

2 Applicable Documents

2.1 Inventory of materials released

The inventory of materials released includes

- AVM for CSM MMC: *Run_I.m*, *MMC_AVM_I.slx*;
- AVM for VSM MMC: *Run_V.m*, *MMC_AVM_V.slx*;
- AVM for VSM short circuit: *Run_V_SC.m*, *MMC_AVM_sc.slx*

The .slx file is the MMC AVM Simulink/PLECS model, and the .m file is the MMC parameters setup and example cases execution.

2.2 Information Assurance

N/A

2.3 Changes

N/A

3 Functionality

3.1 Model Capabilities

Technical Report [1] provides the functionality and mathematical implementation of the MMC AVM. A summary is provided here.

3.1.1 Functional description

This model uses a mathematical formulation based on the AVM as described [1]. In this model, the power electronic switching devices are not explicitly represented. The MMC behavior is modeled using controlled voltage sources. This AVM assumes that all internal variables in the MMC are perfectly controlled, all capacitor voltages are perfectly balanced and second harmonic circulating currents in each phase are suppressed by the corresponding controls.

Figure 3.1 shows the MMC AVM electrical circuit configuration. The input of the model is the dc modulation index d and the ac modulation index m. The ac loop and the dc loop are modeled separately. The dc loop is fully decoupled from the ac loop in this model. In the ac loop, there is a controlled ac voltage source, ac inductors, and the ac grid. In the dc loop, there is controlled dc voltage source, dc inductors, and a resistive load. This model contains no switching related components.

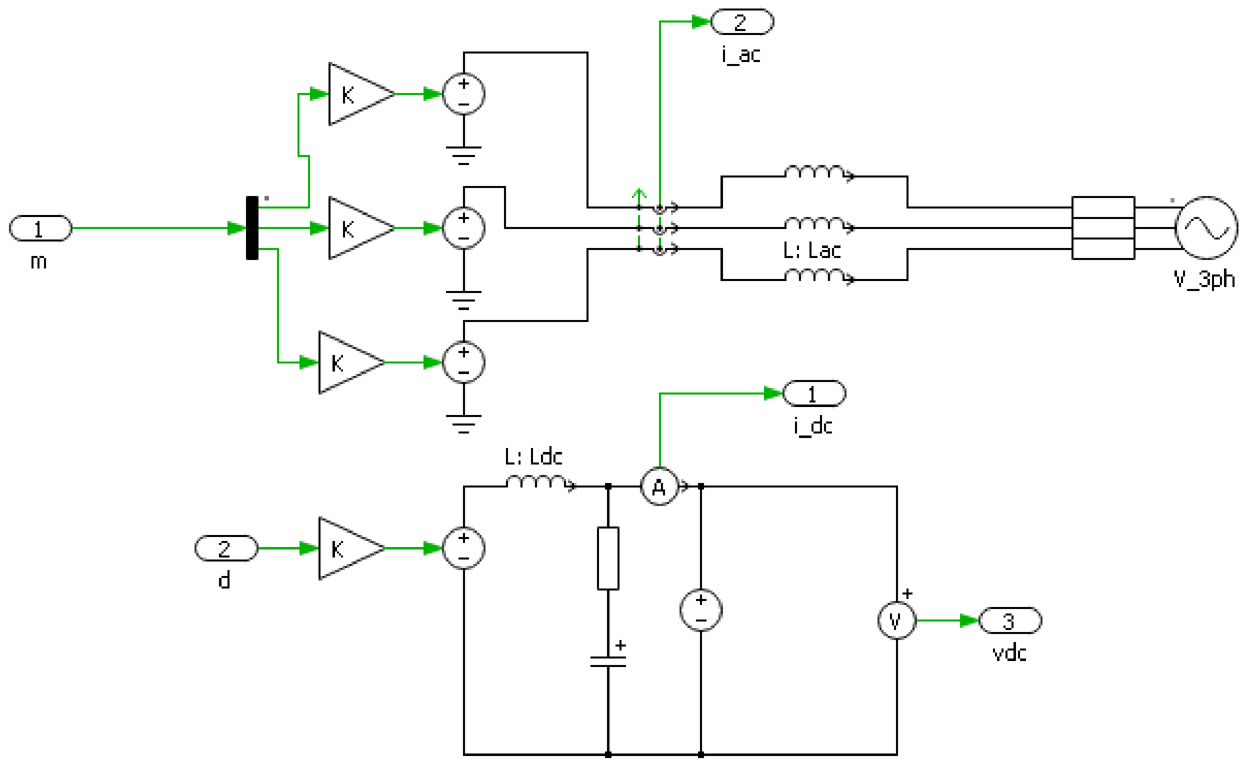

Figure 3.1: MMC AVM ac-side and dc-side circuit representation

3.1.2 Control flow

The control structures are based on impedance shaping and are described in [1]. The corresponding controllers implemented in the simulation are shown here in Fig. 3.2, Fig. 3.3, and Fig. 3.4.

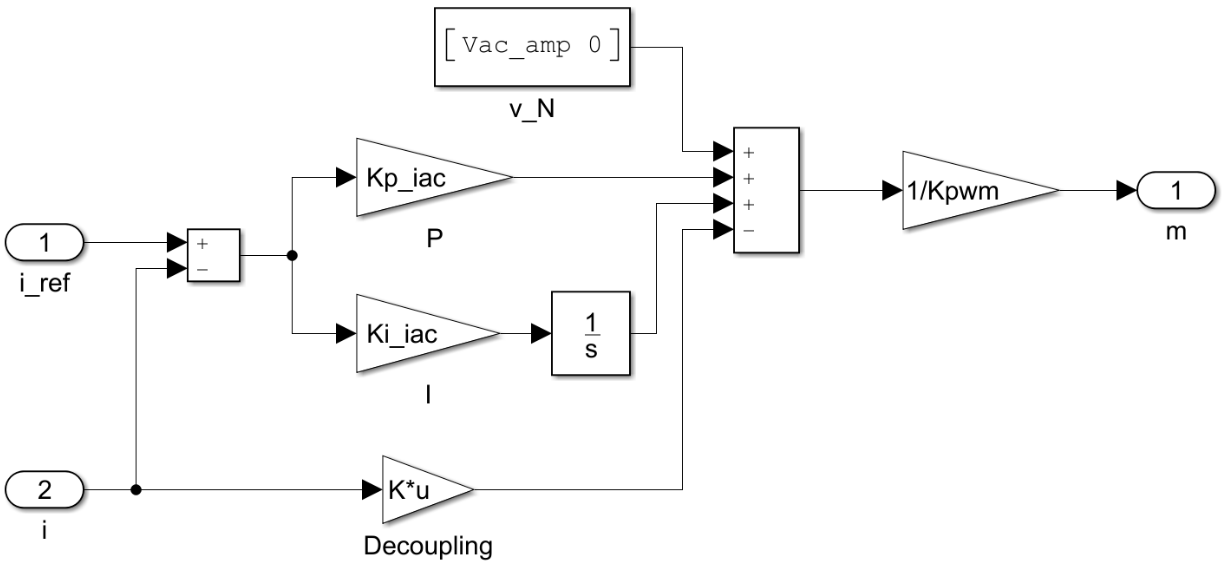

Figure 3.2: AC current controller

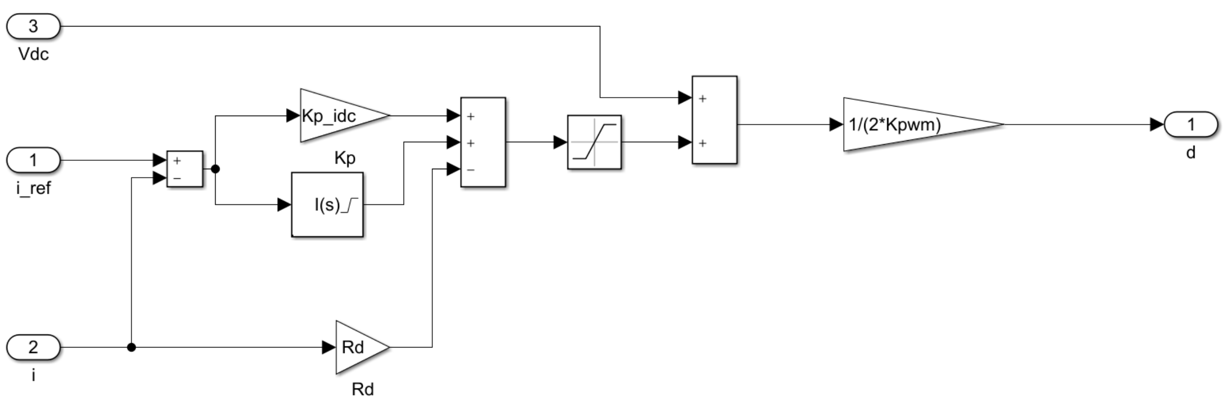

Figure 3.3: DC current controller

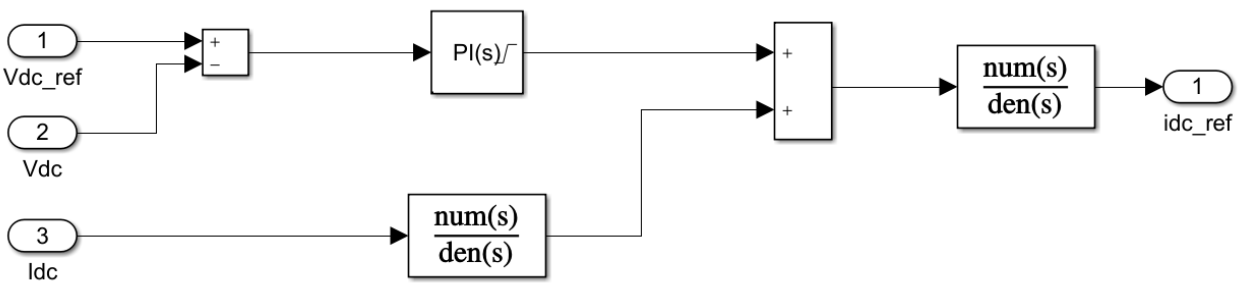

Figure 3.4: DC voltage controller

3.1.3 Mode transitions

Both the CSM and VSM AVM have two modes, by setting the Step_Response variable, where '1' is for time domain simulation and '0' is for impedance measurement. This parameter is listed in Table 5.1 (inputs). The impedance measurement is based on the single tone small signal injections [2].

3.1.4 Operating range limitations

The MMC AVM model performance is limited in operation, in the range of positive output dc voltages from 0 to 6000 V, and the range of dc current from 0 to 200 A.

3.2 Assumptions

This model assumes that variables in the MMC are perfectly controlled, all capacitor voltages are perfectly balanced and second harmonic circulating currents in each phase are suppressed.

3.2.1 Manufacturing variance/tolerance

N/A

3.3 Boundaries

N/A

3.3.1 Environmental criteria

N/A

3.3.2 Model interfaces

The MMC AVM can be connected to other models/subsystems by replacing the ac grid and the dc load in Fig. 3.1. The control interfaces of the model (input and outputs) are listed in Table 5.1 (inputs) and Table 5.2 (outputs).

3.4 Component Description

See section 3.1.1.

3.5 Fault Modeling

N/A

3.6 Error Analysis

N/A

4 Analytical Methods

The MMC AVM was developed from impedance shaping as described in [1].

4.1 General Algorithms

The model runs with a automatic solver selection, with variable time-step.

4.2 Discontinuity Management

N/A

4.3 Analytical Capabilities

N/A

5 Data

5.1 Naming Convention

N/A

5.2 Intrinsic Properties

N/A

5.3 Input Variables/Parameters

Table 5.1: Input Variables/Parameters

Symbol	Description	Default Value	Type
Step_Response	Operation modes (1: step response; 0: impedance measurement)	1	Constant
Vdc_base	DC voltage base value	6 kV	Constant
Idc_base	DC current base value	200 A	Constant
Vdc_initial	DC voltage initial value before the transient	0	Constant
Idc_initial	DC current initial value before the transient	0	Constant
Vac_amp	AC voltage base value	3.3 kV	Constant

5.4 Output Variables/Parameters

Table 5.2: Output Variables/Parameters

Symbol	Description	Type
y.Vdc	Output DC voltage (V)	Measurement
y.Idc	Output DC current (A)	Measurement
Z	Impedance (magnitude and phase)	Calculation

5.5 Internal Variables/Parameters

Table 5.3: Internal Variables/Parameters

Symbol	Description	Default value	Type
P_base	Base active power	1.25 MW	Constant
Rdc_base	DC load base value	3 Ω	Constant

Table 5.3: Internal Variables/Parameters

Symbol	Description	Default value	Type
Iac_amp	AC phase current magnitude	309 A	Constant
Vcell	MMC cell voltage	1020 V	Constant
num_sm	MMC cell number in one arm	6	Constant
Kpwm	MMC Modulation gain	3060 V	Constant
Rf	DC side RC filter resistance	5 Ω	Constant
Cf	DC side RC filter capacitance	20 µF	Constant
Lac	Inductance in the AC loop	0.75 mH	Constant
Ldc	Inductance in the DC loop	2.5 mH	Constant
Kp_iac	AC current control proportional gain	4.7 A	Constant
Ki_iac	AC current control integral gain	465 A.s	Constant
Kp_idc	DC current control proportional gain	4 A	Constant
Ki_idc	DC current control integral gain	2960 A.s	Constant
Rd	DC current control active damping coefficient	1 A	Constant
Kpv	DC voltage control proportional gain	1 V	Constant
Kiv	DC voltage control integral gain	40 V.s	Constant
Vpt	DC voltage perturbation percentage	0.05	Constant
Ipt	DC current perturbation percentage	0.05	Constant
Freq	Impedance measurement perturbation frequency	1-3 kHz	Array

5.6 States

N/A

5.6.1 Initial Conditions

N/A

5.7 Key Variables and Signals

See sections 5.3, 5.4, and 5.5.

5.7.1 Scalable Parameters

See sections 5.3, 5.4, and 5.5. All variables/parameters described as type "array" must be defined prior to the running of the simulation, but can be defined as time varying parameters which allows them to vary during the simulation. All variables/parameters described as type "Constant" must be defined prior to the simulation and cannot be defined as time varying parameters as they are not allowed to vary during the simulation.

5.7.2 Interface Signals

The interfaced signals of the MMC AVM are the ac and dc terminals shown in Fig. 3.1 and the input values are listed in Table 5.1

5.7.3 Data Acquisition Signals

N/A

6 User Guidelines

6.1 Target Modeling Environment

Version 1.0 of the model was created in the MATLAB/Simulink environment (2018b) and PLECS Blockset (version 4.2.4).

6.2 Key Variables

See sections 5.3, 5.4, and 5.5.

6.3 Model Integration

When integrating the model into other systems, connections should be made at the ac and/or dc terminals shown in Figure 3.1.

6.4 Model Performance

N/A

6.5 Test Cases

The single tone impedance measurement and several cases have been tested in the MMC AVM, the details are described in [1].

The test cases include

- CSM MMC impedance measurement;
- VSM MMC impedance measurement;
- CSM MMC current 0-150 A step response at 5 kV;
- VSM MMC voltage 0-5 kV step response at 200 A;
- VSM MMC short circuit at 5 kV open circuit.

6.6 Installation Instructions

In order to install and use the models the following steps should be followed

1. Ensure that your computer has the software configuration as described in Section 6.1.
2. The MATLAB scripts and Simulink/PLECS model can be used from within any folder and have no additional dependencies.

6.7 Operating Instructions

To operate the MMC AVM model:

1. Run either *Run_MMC_V.m*, *Run_MMC_I.m* or *Run_MMC_V_SC.m* m-file to set the input variables.
2. The m-file will setup the scenario and execute the Simulink/PLECS-model (*MMCAVM_V.slx*, *MMCAVM_I.slx* or *MMCAVM_sc.slx*).
3. The figures will be automatically generated.

6.8 Validation

Please refer to [1] for the validation results.

7 Error Management

7.1 Known Discrepancies

N/A

7.2 Error Trapping

N/A

7.3 Message Description

N/A

8 Data Sources

N/A

References

[1] L. Wang, Y. Shi, D. Soto, J. Langston, K. Schoder, and M. Steurer. Average model research for caps mmc. Technical report, The Electric Ship Research and Development Consortium, October 2019.

[2] Gunnar Chauncey. Impedance measurement techniques in noisy medium voltage power hardware-in-the-loop environments. Master's thesis, Florida State University, 2018.