A Generic Point-to-Point MMC-VSC System for Real-Time and Off-Line Simulation Studies

S. Arunprasanth, U.D. Annakkage, C. Karawita and R. Kuffel

***Abstract*--The numerous advantages identified on Modular Multilevel Converter (MMC) type Voltage-Sourced Converter (VSC) have attracted researchers and industrial engineers to consider it for future HVDC implementations. During the design phase of HVDC projects, lots of simulation studies are conducted using Electromagnetic Transient (EMT) simulation tools. In particular, real-time simulators that combine EMT simulation technique with parallel processing not only offer the speed of simulation enabling large number of simulations to be done at the design stage but also allow the real-time hardware in the loop testing of designed controllers. This paper presents a detailed model of a point-to-point MMC-VSC system on the Real-Time Digital Simulator (RTDS), suitable for real-time and off-line simulation studies. This paper discusses typical behaviors of an MMC-VSC system simulated for disturbances such as power order change, power reversal, AC system change, and AC faults. The paper also discusses transient responses such as oscillations after a disturbance. The oscillations associated with the MMC-VSC system are investigated using small-signal stability analysis technique and the contributions of physical systems and controllers to oscillations are identified.**

***Keywords*: Modular multilevel converter, real-time digital simulator, electro-magnetic transient, AC system strength, small-signal stability.**

I. INTRODUCTION

THE HVDC technology was introduced to interconnect asynchronous power systems and also to facilitate the long distance power transmission. Recently, the HVDC is being widely used to integrate renewable generations such as offshore wind farms to power grids. In this context the VSC based HVDC system provides many advantages compared to the conventional Line Commutated Converter (LCC) based HVDC system, including independent control of active and reactive powers, interconnection with weak or dead (passive) AC networks, quick power reversal, black start capability, and stability improvement of AC networks [1]-[3]. The DC current based power reversal capability of VSC is the key advantage for considering it to implement multi-terminal DC systems, which are also referred as DC grids. The latest VSC technology known as the MMC is constructed by cascading several chopper cell sub-modules to generate AC voltages closer to sinusoidal waveforms. MMC adds more advantages to the VSC advantage list, together with high voltage rating capability, less or no harmonic filter requirement, and lower switching losses compared to two-level and three-level VSCs. Therefore MMC technology is preferred for future implementations.

The vector control method [4] is the commonly adopted VSC control technique and it is now referred as the d-q decoupled control method. This control scheme consists of cascaded PI-control loops known as outer-loop voltage controllers and inner-loop current controllers. Performance of an MMC-VSC system depends on control system parameters and the AC system strength. The AC system strength is used to represent the interaction between AC and DC systems and it is quantified using Short Circuit Ratio (SCR).

EMT simulation tools are preferred to conduct power system simulation studies in detail as they capture nonlinearities and switching transients of power systems. Therefore in HVDC projects the usual practice is to model the system using an EMT simulation tool and analyze the behavior under different disturbances and possible operating conditions. Many of the planned HVDC projects are IGBT based point-to-point links [5]. The point-to-point link is the basic structure that can be used to investigate the performance of an MMC-VSC system. There are a few published articles in literature on EMT modelling and simulation of MMC-VSC systems. Reference [6] models the AC system using an ideal voltage source, which does not represent the AC system strength information. In [7], some general conclusions are drawn based on the analysis done by modelling the DC system using an ideal DC voltage source. This approach is not acceptable as the DC system dynamics are very important to be considered as they impact the transient stability of the system. VSC HVDC system modelled in [8] simplifies the control system by removing the outer-loop voltage controllers in order to reduce the modelling complexity. This approach disables the flexibility of controlling current magnitudes and therefore it is not recommended.

This paper presents the modelling of a point-to-point MMC-VSC system on RTDS simulators, to be used for real-time and off-line simulation studies. This test system consists of both the physical system and the control system. The

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physical system includes AC network represented using its Thevenin equivalent, DC network modelled using an overhead transmission line, MMCs modelled using half-bridge chopper cell sub-modules, converter transformers and arm inductors. The control system consists of the complete d-q decoupled control and the circulation current suppression control.

The rest of the paper is organized as follows. Section II describes the EMT modelling of the system. Brief explanations on small-signal stability modelling and analysis are presented in sections III and IV. Section V explains the time domain simulation results. Finally conclusions are drawn in section VI.

II. Electromagnetic Transient (EMT) Modelling of the MMC-VSC System

EMT modelling of the test system is done using the RSCAD software, which is the user interface of the RTDS simulator. Many power system operators are now interested in modelling their utility network on a real-time simulation tool as these are faster than commercially available off-line EMT simulation tools. The motivation behind this work is to develop a generic MMC-VSC test system with typical controls to be used for both real-time and off-line simulation studies. A point-to-point MMC-VSC system is shown in fig. 1, in which AC power systems connected to the HVDC network terminals are represented using their Thèvenin equivalent models.

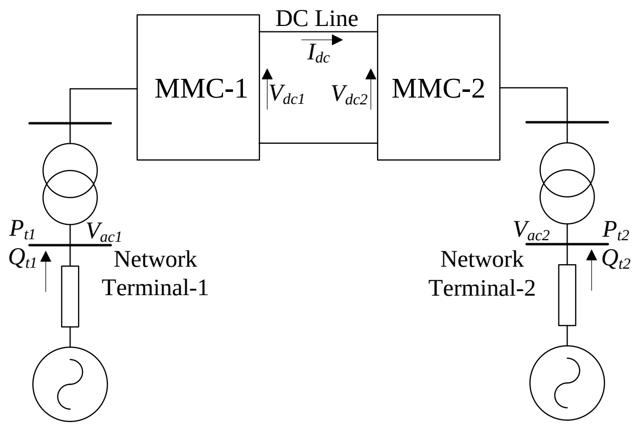

Fig. 1. A point-to-point MMC-VSC system with AC network connections

A. An Overview to the RTDS Simulators

RTDS simulators are made of specially designed high performance processors to perform real time digital simulation studies of power systems, based on Dommel's EMT simulation algorithm [9]. Large power systems are simulated as multiple subsystem cases, where each subsystem is simulated on individual RTDS racks. An RTDS rack comprises a Giga Transceiver Workstation Interface (GTWIF) card to support the communication between the RTDS hardware and workstations and a number of processor cards to compute the system behavior. RSCAD software is the graphical user interface used for the RTDS simulator. Simulation cases are constructed on RSCAD draft module using the generic components available in RSCAD master library. Transmission lines and cables are created using two different modules known as T-Line module and cable module. As an added feature, the C-Builder module allows user to create user defined control or power system components. Compiled simulation case is run using the RunTime module through which users interact with their simulation case by altering switch states and slider values. Meters and scopes in RunTime are assets to capture important events in power system and also for continuous monitoring. A special feature of RSCAD is the conversion module that allows the conversion of cases from PSS/E to RSCAD and also from MATLAB Simulink to RSCAD [10]-[11].

The MMC-VSC test system is modelled as a single subsystem case that requires four GPC or PB5 processor cards and a GT fibre cable connection between any two of those four cards to establish the DC link. The physical system and control system parameters are given in the APPENDIX. The following subsections explain the modelling of various components of the system.

B. AC power system

AC power systems are represented using Thèvenin equivalent models. A three-phase balanced AC source with R-R//L type impedance is used to construct the Thèvenin equivalent model. RTDS source model has typical source impedance types as R, L, R//L, R-R//L, and $Z\angle\theta$. But in HVDC studies, the Thèvenin source impedance is always defined in-terms of the Short Circuit Ratio (SCR). Therefore to facilitate HVDC simulations in RTDS, a user defined control component is created to convert the SCR information to the corresponding R-R//L values.

C. VSC Interface Transformer

RTDS allows simulation of a case using two different time-steps to keep the accuracy at a higher level while performing the real-time simulation. MMC converters and the DC system are simulated using a small integration time-step to achieve high accuracy and the AC systems are solved using a larger integration time-step. VSC interface transformers are used to interface the two different time-steps and also to function as the converter transformers.

D. Modular Multilevel Converter

An MMC station is modelled using six MMC5 modules, each of which models a single arm of the converter. The sub-module capacitor voltage balancing is done internally in this component. Each MMC is simulated on a separate GPC or PB5 processor card.

E. DC Transmission Line

The point-to-point connection between MMC stations is made using a DC overhead transmission line. This line is modelled as a "Bergeron" type ideally transposed transmission line.

F. MMC Controls

The commonly used d-q decoupled control system is adopted in this test system. Since the control system of each

MMC converter is equipped with both DC voltage (V_{dc}) and real power (P_t) controllers, the power reversal operation can be studied using this test system and also this allows the MMC-VSC system to operate in all four quadrants of the PQ-plane. Limits for reference current and control voltage magnitudes are also modelled to prevent any undesirable operation outside of the converter and transformer ratings. In addition the circulation current suppression control is modelled to suppress the circulation currents present in converter arms. Fig. 2 shows the d-q decoupled control system with both inner-loop and outer-loop PI-controllers.

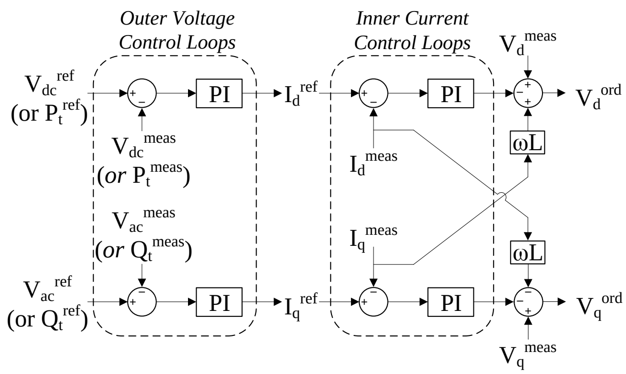

Fig. 2. d-q decoupled control system (ref-reference, meas-measured, ord-order)

PI-controller gains and the integrator limits used for this test system are determined by the trial and error approach and the parameter values are given in APPENDIX.

III. Linearized Model of the MMC-VSC System

A linearized state-space model of the aforementioned MMC-VSC system is modelled by writing system dynamic equations from first principles. The linearized system includes MMC converters, DC transmission system, d-q decoupled control system (inner-loop and outer-loop) as depicted in Fig. 2, converter transformers and phase reactors. The AC network is modelled using dynamic phasors as explained in [12], to increase the reliable frequency band up to the AC system fundamental frequency. System parameters used in modelling are given in APPENDIX. The small-signal model of the point-to-point MMC-VSC system consists of 27 State Variables (S-V) and 8 Control Inputs (C-I) in total, including AC systems (8 S-V, 4 C-I), DC system (3 S-V), converter controls (12 S-V, 4 C-I), and PLL (4 S-V). The adequacy of the linearized model is evaluated using time domain simulations. Simulation results obtained using both small-signal and EMT models for a small disturbance, are compared.

A small pulse with a magnitude of 0.03 pu and a duration of 100 ms was applied to the DC voltage reference. Fig. 3 shows simulation results of changes in rectifier side DC voltage, inverter side DC voltage, and the DC current obtained using both Small-Signal (SS) and RTDS EMT simulation. Small-signal results show a close match with RTDS simulation results. Therefore it can be concluded that the small-signal model developed in this study is adequate to be used to analyze the system dynamics.

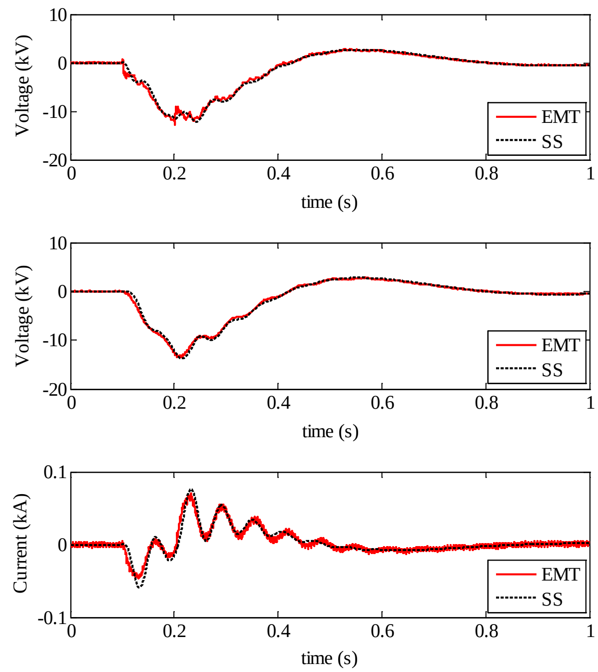

Fig. 3. Changes in (a) Rectifier side DC voltage, (b) Inverter side DC voltage, and (c) DC current for a 0.03 pu, 100 ms pulse applied to the DC voltage reference

IV. Small-Signal Stability Analysis

The validated small-signal model is used to analyze the dynamic behavior of the system around the steady state operating point, which delivers the rated power to the terminal-2 AC power system at rated AC and DC voltages. Eigenvalue and the participation factor analysis are used to determine both physical and control modes of the system and the corresponding participation factors. Out of 27 eigenvalues of the system, dominating modes are stored in table I and other modes showed damping values greater than 80 % for this particular operating point.

TABLE I
Dominating Modes of the System and Participating States

Modes (Hz)	Damping (%)	Participating States
15.34	10.94	DC voltages, DC current
1.27	46.65	DC voltages, DC and AC voltage controllers

The DC resonance (15.34 Hz mode) between the DC transmission line inductor and the MMC sub-module capacitors is the critical mode present in the system. DC voltages and the DC current highly participate in this mode. It can also be observed that the results presented in fig. 3 shows the presence of this electrical DC resonance mode. Fig. 4 shows the participation factors of all states to this mode. Interestingly the low frequency controller mode (1.27 Hz) gets excited after clearing AC system faults as shown in the following section.

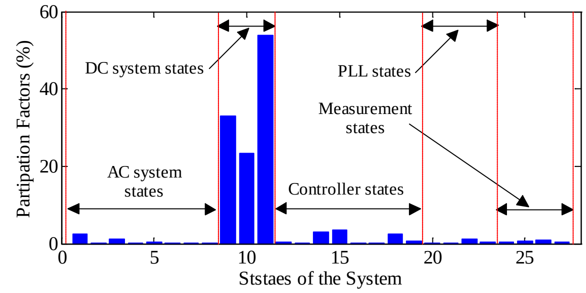

Fig. 4. Participation factors of all states in the DC resonance mode

V. Time Domain Simulation Results and Discussions

MMC-1 is selected to operate in rectifier mode and MMC-2 operates in inverter mode. HVDC systems are operated with a start-up sequence to smoothly bring the system to the desired operating point. Start-up sequence used in this study is given below.

Step-1: Enable the DC voltage controlling converter (MMC-1) to allow sub-module capacitors to charge and establish the rated DC voltage.

Step-2: Enable the power controlling converter (MMC-2) and ramp the power reference at a suitable rate to reach the required power transfer.

A number of disturbances were applied to the test system while it operates at the rated operating conditions and the following subsections explain the simulation results obtained for each disturbance.

A. Power Order Change

Depending on system requirements, the power order of the HVDC system is changed at a suitable rate, while maintaining AC and DC voltages at rated values. To study this operation the reference power order of MMC-2 was changed from full power to 0.5 pu at 1.0 sec and then to 0 pu at 2 sec and finally back to the full power at 3.0 sec. The rate of change was set to 5 pu/s. Fig. 5 show the RTDS simulation results obtained for this power order change.

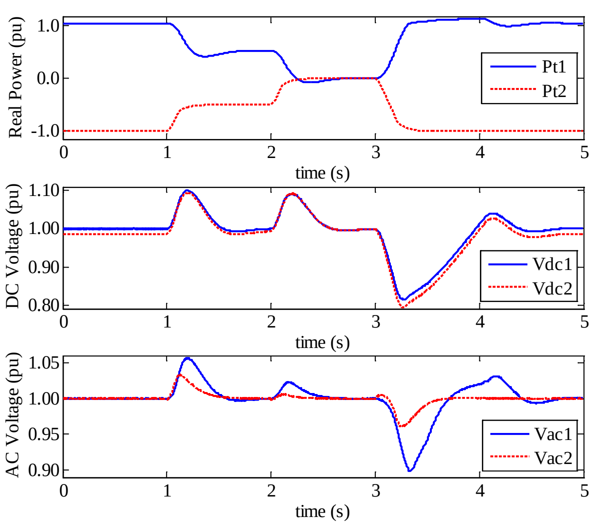

Fig. 5. Simulation results for power order change (a) terminal real powers, (b) DC voltages, and (c) terminal AC voltages

It can be observed that power order change immediately reflects in terminal-2 real power (P_{t2}) and the sending end power (P_{t1}) changes accordingly to cater the receiving end requirement. DC voltages (V_{dc1} and V_{dc2}) increase when the power order is reduced and drop below the rated value, when the power order is increased. The strong relationship between the DC voltage and the AC voltage makes terminal AC voltages (V_{ac1} and V_{ac2}) to follow corresponding DC voltages.

B. Power Reversal

Power reversal operations are rare in point-to-point HVDC links as the power transfer will mostly be in one direction. But when offshore wind farm integrations and DC grids are considered, the bidirectional power controlling capability is a mandatory requirement. To investigate the power reversal operation, the real power order to the MMC-2 was varied from 1.0 pu to -1.0 pu at 1.0 sec and then back to 1.0 pu at 3.0 sec at a rate of 4 pu/s. Fig. 6 shows the RTDS simulation results for this case and it can be observed that the power was reversed with minor overshoots in power. It can be noted that the low damped DC resonance mode gets excited and produce oscillations in DC voltages when the power order is changed from -1.0 pu to 1.0 pu. This oscillatory behavior also creates few oscillations in AC voltages.

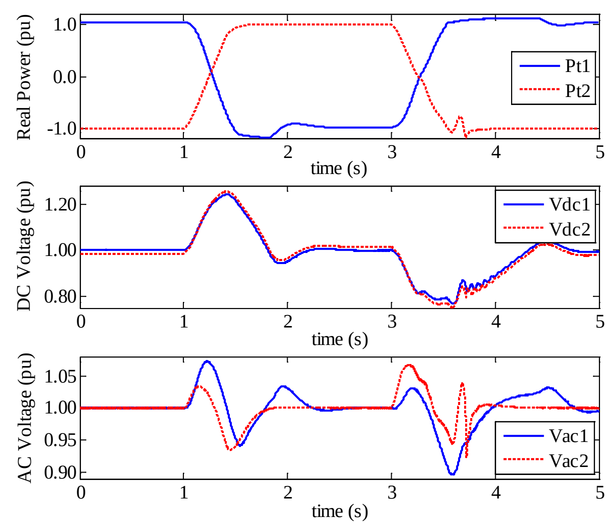

Fig. 6. Simulation results of the power reversal study (a) terminal real powers, (b) DC voltages, and (c) terminal AC voltages

C. AC System Strength Change

AC system strength information is very important when designing HVDC links as it impacts the system stability. To investigate the effect of system strength on MMC-VSC system performance, the Short Circuit Ratio (SCR) of the AC system connected to terminal-2 was changed from 2.0 to 5.0, 3.0, 1.5, and 2.0 respectively at 2, 4, 6, and 8 sec while maintaining the SCR of AC system-1 at 2.0. Fig. 7 illustrates the simulation results for this case and it can be observed that the AC system strength impacts the MMC-VSC system performance. Further it can be noted that transients are large when the AC system strength goes to low values (SCR_2=1.5 at 6 sec).

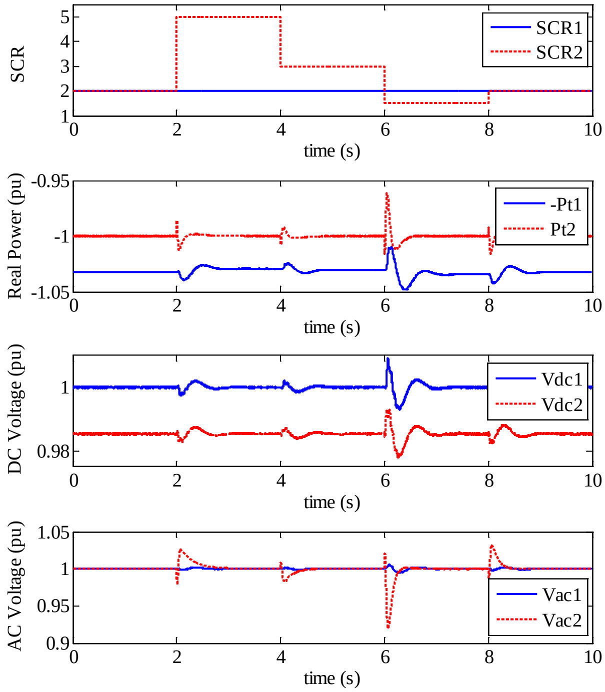

Fig. 7. Simulation results for change in SCR-2 (a) SCR values, (b) terminal real powers, (c) DC voltages, and (d) terminal AC voltages

D. Circulation Current Suppression

Circulation current is a unique and an undesirable phenomenon in MMC converters and it significantly contributes to the converter power loss. Therefore to reduce the converter power loss, each converter control system is equipped with a Circulation Current Suppression Control (CCSC). To evaluate the performance, the CCSC of MMC-1 was enabled at 0.1 s and the simulation results are presented in Fig. 8. The simulation results confirm that the CCSC successfully eliminates the circulation current and makes the arm currents sinusoidal. It also satisfies the fact that the presents of circulation current does not affect either the terminal AC voltage or the AC line current.

E. AC Fault Study

Faults are unpredictable events in power systems and a three phase to ground fault (LLLG) is considered to be the most severe fault among all AC faults. In this study LLLG faults with 0.1 Ω impedance and duration of 10 fundamental cycles were considered. Faults were applied at network terminals one at a time and the system behaviors are explained through EMT simulation results.

Fig. 9 shows the system behavior when the fault was applied at the terminal-1 AC bus-bar. It was interestingly noted that post fault system oscillations are highly dependent on the DC voltage controller proportional gain. A larger proportional gain (KP_{Vdc}=3.0) for the DC voltage controller, brings the system back to normal faster.

The same AC fault was then applied to the MMC-2 terminal and the simulation results are shown in fig. 10. It can be observed that the recovery is slow in the inverter side compared to that of the rectifier side. Even though the DC voltage controller is placed at the rectifier end, the inverter post fault oscillations are also sensitive to the DC voltage controller proportional gain. Again a larger proportional gain for the DC voltage controller provides better damping.

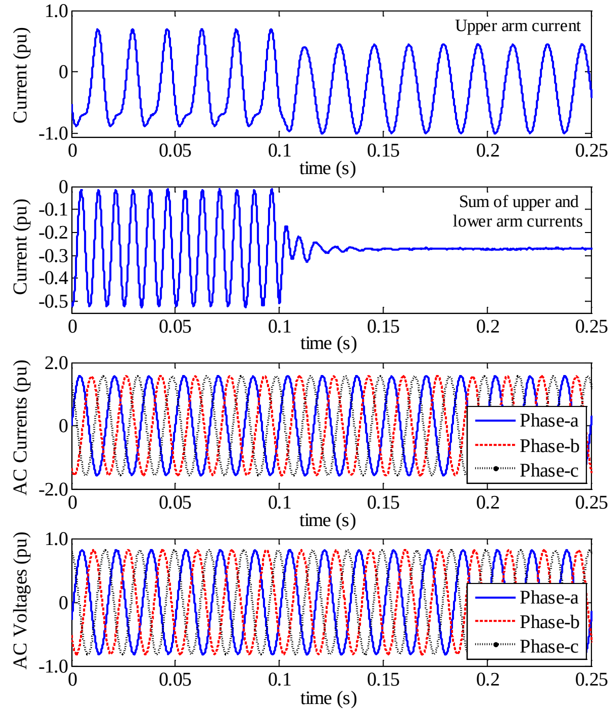

Fig. 8. Simulation results of the circulation current suppression (a) phase-a upper arm current, (b) sum of phase-a arm currents, (c) terminal AC voltages, and (d) AC line currents

The post fault oscillations observed were with a frequency less than 1.5 Hz and that agrees with the small-signal stability analysis results given in table I (controller mode with 1.27 Hz frequency). Further it can be seen in table I that the DC voltage controller state participates in this mode.

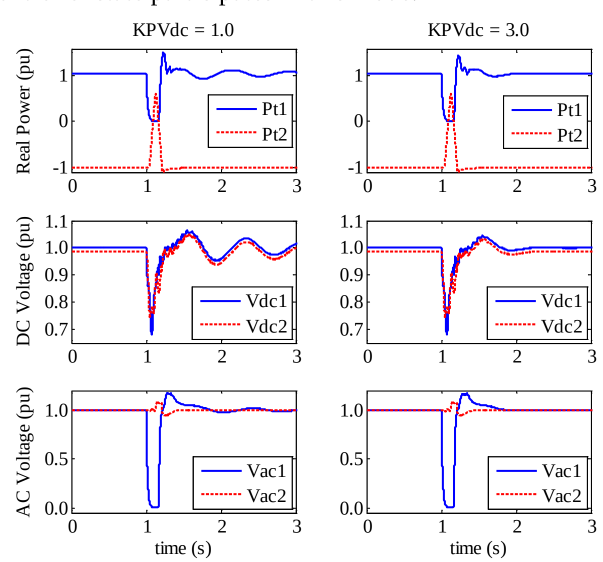

Fig. 9. Simulation results for a three phase fault at MMC-1 network terminal (a) terminal real powers, (b) DC voltages and, (c) terminal AC voltages

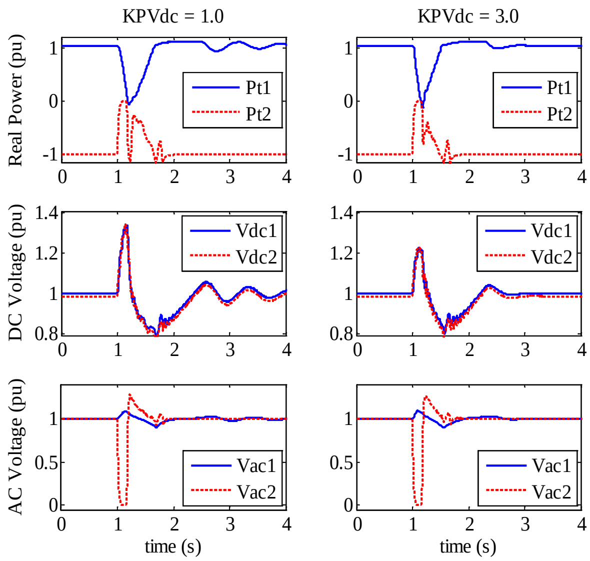

Fig. 10. Simulation results for three phase fault at MMC-2 network terminal (a) terminal real powers, (b) DC voltages and, (c) terminal AC voltages

VI. Conclusions

EMT modelling of a point-to-point MMC-VSC system for real-time and off-line simulation studies is presented in this paper. The test system is modelled using standard library models available in RTDS simulator and also using few user defined control components. To mathematically investigate the system dynamics, a linearized state-space model is also developed and validated against the non-linear EMT simulation. The transient oscillatory behaviors observed in time domain simulations are related to the small-signal stability analysis results. It is observed that the electrical resonance between the DC transmission line inductor and MMC capacitors is the low damped mode presence in the system and it gets excited when transients occur in the system. It is also revealed through EMT simulations that post AC fault oscillations are sensitive to the DC voltage controller proportional gain and this observation agrees with the small-signal stability analysis. Based on simulations results it can be said that transient stability or small-signal stability analysis has to be performed for the whole MMC-VSC system to see the impact of DC system dynamics and controller interactions.

VII. Appendix

The point-to-point MMC-VSC system developed in this paper is a 500 kV DC, 500 MW symmetrical mono-pole system. The electrical network parameters are given in table II and the control system parameters are given in table III.

TABLE II
Physical System Parameters

Parameter	Value
AC system voltage	230 kV (L-L RMS)
SCR	2.0∠84°
Converter transformer	230:250 Y/Δ
Transformer impedance	0.18 pu on 575 MVA
DC line	400 km transmission line
DC line parameters	7.17 Ω, 0.74 H, 5 µF
Sub-module	250 per arm (Half-bridge)
Sub-module parameters	10000 µF
Arm inductor	50 mH

TABLE III
Control System Parameters

Parameter	Gain Value
PLL	K_P=50, K_I=250
DC voltage controller	K_P=3, K_I=20
Active power controller	K_P=1, K_I=20
AC voltage controller	K_P=1, K_I=20
Reactive power controller	K_P=1, K_I=20
d-axis current controller	K_P=0.5, K_I=100
q-axis current controller	K_P=0.5, K_I=100
Current magnitude limit	1.2 pu
Voltage magnitude limit	1.1 pu

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IX. Biographies

Sakthivel Arunprasanth received the B.Sc. (Eng.) and the M.Sc. (Eng.) degrees from the University of Peradeniya, Peradeniya, Sri Lanka, in 2010 and 2013, respectively. He is currently a Ph.D. candidate with the power systems research group at the Department of Electrical and Computer Engineering, University of Manitoba, Winnipeg, MB, Canada. He is also a Mitacs scholarship intern at the RTDS Technologies Inc., Winnipeg, MB, Canada. His research interests include transient and small-signal stability studies of HVDC and HVAC systems, and power system simulation.

Udaya Annakkage received the B.Sc. (Eng.) degree from the University of Moratuwa, Moratuwa, Sri Lanka, in 1982, and the M.Sc. and Ph.D. degrees from the University of Manchester Institute of Science and Technology (UMIST), Manchester, U.K., in 1984 and 1987, respectively. He is presently a Professor with the University of Manitoba, Winnipeg, MB, Canada. He was the Head of Electrical and Computer Engineering Department, University of Manitoba, from 2008 to 2012. His research interests include power system stability and control, security assessment and control, operation of restructured power systems, and power system simulation.

Prof. Annakkage was an editor for the IEEE TRANSACTIONS ON POWER SYSTEMS from 2009 to 2012. He is currently the convenor of CIGRE Working Group on Application of Phasor Measurement Units for monitoring power system dynamic performance.

Chandana Karawita received the B.Sc. (Eng) degree from the University of Moratuwa, Sri Lanka in 2002 and the M.Sc. and Ph.D. degrees from the University of Manitoba, Canada in 2006 and 2009, respectively. He joined TransGrid Solutions, Canada in 2007 and now serving as a senior electrical engineer. Chandana has specialized in power systems planning studies for HVDC and HVAC integrations and wind power generation. He is also a specialist in small signal stability assessment and power system stabilizer tuning, HVDC interaction studies and sub synchronous oscillation studies of power systems. He was instrumental in developing a software package to analyze sub synchronous interactions in power systems. Chandana is still involving in academic research as an adjunct professor in the University of Manitoba.

Rick Kuffel graduated from the University of Manitoba, Canada with B.Sc.EE and M.Sc.EE degrees in 1984 and 1986 respectively. After graduating he first joined Brown Boveri (BBC) Switzerland working in their HVDC Project Simulation Center. He later returned to Winnipeg and joined Teshmont Consultants where he worked primarily in their simulation and studies group. In 1990 Mr. Kuffel moved to the Manitoba HVDC Research Centre where he was involved in development of the RTDS real time digital simulator and in 1994 became a founding principal of RTDS Technologies Inc. His interests include electromagnetic transient simulation, real time testing of control and protection systems, HVDC control strategies, Modular Multilevel Converters, DC Grids and the integration of renewable energy sources in traditional power systems.