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# A Simplified Model Design of MMC-HVDC Transmission System for Steady State and Transient Stability Analyses

**Marwan Rosyadi[1], Atsushi Umemura[2], Rion Takahashi[2], Junji Tamura[2], Takamori Uchiumi[3], Masanori Mori[3], Hiroki Miyata[3]**

[1]Department of Electrical Engineering, Faculty of Engineering, Universitas Muhammadiyah Surabaya, Surabaya, Indonesia
[2]Department of Electrical and Electronic Engineering, Kitami Institute of technology, Kitami, Japan
[3]HVDC Interconnection System Planning and Engineering Section., Eng. Dept., Hokkaido Electric Power Network Inc, Japan

## Article Info

## ABSTRACT

A simplified model of a Modular Multilevel Converter (MMC) implemented on a High Voltage Direct Current (HVDC) transmission system is presented in this study for the analysis of steady-state and transient stabilities. The simplified model design's goal is to reduce the complication of MMC circuit as well as the simulation time of the analysis. The validity of the model design has been examined using the PSCAD/EMTDC simulation program, where the simulation outcomes of the detailed model and the simplified model are contrasted. It has been established that the simplified model is accurate enough and that simulation time can be substantially decreased. It is concluded that the suggested model design is very significant as a simplified model for analyzing the steady state and transient stabilities of MMC-HVDC Transmission System.

## Corresponding Author:

Marwan Rosyadi
Department of Electrical Engineering, Universitas Muhammadiyah Surabaya
Jl. Raya Sutorejo No.59, Sutorejo, Mulyorejo, Surabaya, Jawa Timur, Indonesia, 60113
Email: rosyadi@um-surabaya.ac.id

## 1. INTRODUCTION

The increasing need for solving the global warming and a deregulated electricity market has brought about the penetration of high capacity of power plant sourced from renewable energy into grid systems such as wind farm based offshore system, in which a high-voltage transmission system is needed which are more efficient, more inexpensive, more robust, and controllable. In addition, the transmission system is required to be able to cope with large power fluctuations without losing its stability. For overcoming those problems, the HVDC transmission system becomes an answer to meet the needs of transferring large amounts of electrical energy safely and reliably. HVDC transmission system is at lower cost than High Voltage Alternating Current (HVAC) system above break-even distance [1].

The Modular Multilevel Converter (MMC) is a novel converter concept designed for medium and high voltage applications in HVDC technology [2], [3]. The MMC has numerous advantages over conventional converters such as two or three levels converter, that is, high efficiency, good quality of voltage and current outputs, modularity and scalability, and small capacity of DC capacitors [4]. Therefore, the HVDC transmission with MMC system has been received considerable attention from engineers in the academic and industrial recently.

Power system stability analysis is particularly important in power system design. Simulation study of the MMC system with detailed model representations performed by using e.g., PSCAD/EMTDC or

MATLAB/Simulink becomes incredibly challenging because the need to include numerous sub-modules (SMs) based Insulated Gate Bipolar Transistors (IGBTs) in the simulation study. In the case of Trans Bay HVDC cable project with +/-200 kV DC transmission voltage rating, which is the first HVDC system using MMC system, its converter system is configured by 201 levels of MMC. The MMC requires around 2400 IGBTs with anti-parallel diodes and 1200 sub-modules capacitor which connected electrically [5]. Simulation studies by using such detailed model may become inefficient. Therefore, the dynamic behavior analysis of MMC-HVDC transmission system should be represented by standard simplified model which is suitable for simulating the time domain instantaneous responses.

The efforts to simplify MMC-HVDC transmission system have been reported in some papers [6]–[9]. The simplified models are based on phasor model approach and are represented as two level or three levels converter with small modification. The fast and simultaneous simulation method for the MMC-HVDC transmission system was implemented to decrease the computational time for transient analysis [10]. In the method, the large sized admittance matrix including many nodes of the MMC part in the detailed model is modeled into a simple electrical equivalent circuit by using Thevenin or Norton theorems. However, this method still needs to simplify the overly complex admittance matrix. The other simplification approaches such as equivalent circuit model, MMC switching function model, detailed nonlinear IGBT model, and the Average Value Model (AVM) for dynamic performance analysis are presented in some papers [11]–[13]. The AVM approach can reduce the computation time significantly. However, at least 40 μs of simulation time step is needed to get sufficient accuracy.

In the previous work, simplification of MMC circuit has been developed in the average model for permanent magnet wind turbine generator [14]. The MMC system is implemented on the converters (rectifier and inverter) of the wind generator. The designed average model of the wind generator, however, cannot be directly applied to the MMC-HVDC transmission system model. Therefore, a novel approach is required for developing a simplified model of the MMC-HVDC transmission system.

In this study, a simplified model design for MMC-HVDC transmission system is proposed. The SMs-based IGBT is not explicitly modeled in the MMC circuit in the model design; instead, the MMC circuit is only represented by sources of voltage and current. Therefore, large time step (100 μs) of simulation can be used. In addition, the model does not require complex mathematical simplification. Moreover, one of the advantages of this simplified model is that it can be easily applied to electromagnetic transient simulation analyses on standard software such as PSCAD/EMTDC or MATLAB/Simulink. One thing to keep in mind is that the simplified model is meant to be an alternative model to the simpler models that have been created.

## 2. HVDC TRANSMISSION SYSTEM MODEL

Figure 1 illustrates the power system model used in this study for the simulation, which is a two-connected areas power system with an HVDC transmission system. Two independent AC power systems are connected through a 200 MVA (±100 kV) symmetrical monopolar HVDC transmission line. The HVDC transmission line is used to transfer electric power from Area 1 to Area 2. Both the rectifier station and the inverter station utilize the MMC system, which connects them via A 75-kilometer power cables. The π equivalent circuit model represents the power cable.
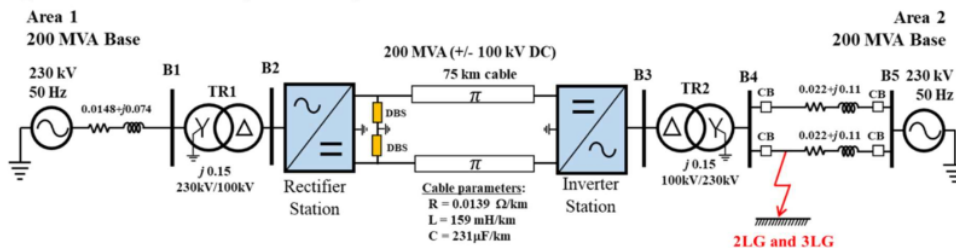


Figure 1. Two power systems connected by MMC-HVDC transmission line model

Two Dynamic Braking Systems (DBSs) are installed in DC output terminal of MMC circuit of the inverter. The rectifier station is connected to Area 1 through a 230kV/100kV rectifier transformer (TR1) and single circuit of transmission line. On the other hand, the inverter station is linked to Area 2 via a 100kV/230kV inverter transformer (TR2) and 230 kV transmission lines. The transmission lines are designed with two circuits. The parameters of transmission line are written in $R+jX$ form, where $R$ represents for the resistance and $X$ for the reactance. The parameters of the MMC presented in Table 1. The operating mechanism of the rectifier station is to transform the voltage from AC to DC forms. Furthermore, the rectifier station also regulates the

active power flow from Area 1 into the HVDC transmission circuit. On the other hand, the inverter station transforms the voltage from DC to AC forms. The inverter station works to maintain the HVDC transmission's DC voltage at its rated voltage, which enables active power from Area 1 to be delivered to Area 2. The reactive power output, which is constrained by the converters' capacity, can be independently adjusted by the rectifier and inverter. (i.e.., PQ diagram of converter).

Table 1. Parameters of Modular Multilevel Converter

| Parameter | Value | Unit |
|---|---|---|
| Power | 200 | MVA |
| AC Voltage | 100 | kV |
| AC Frequency | 50 | Hz |
| DC Voltage | $\pm 100$ | kV |
| SM per arm | 8 | module |
| SM Capacitor | 3400 | μF |
| Arm Inductor | 15.9 | mH |
| Arm Resistor | 0.05 | Ω |
| Reactor Inductance | 15.9 | mH |
| Reactor Resistance | 0.05 | Ω |
| DC capacitor | 1750 | μF |

## 3.    Detailed Model of MMC System

As previously stated, performing a simulation study for the MMC based on its detailed model in real configuration is extremely difficult, as hundreds of sub-modules must be considered. Therefore, the detailed model of the MMC in the power system illustrated in Figure 1 is represented by nine levels of MMC system. In the converter stations, the MMC system is made up of 48 sub-modules (96 IGBTs with antiparallel diodes and 48 sub-module capacitors).
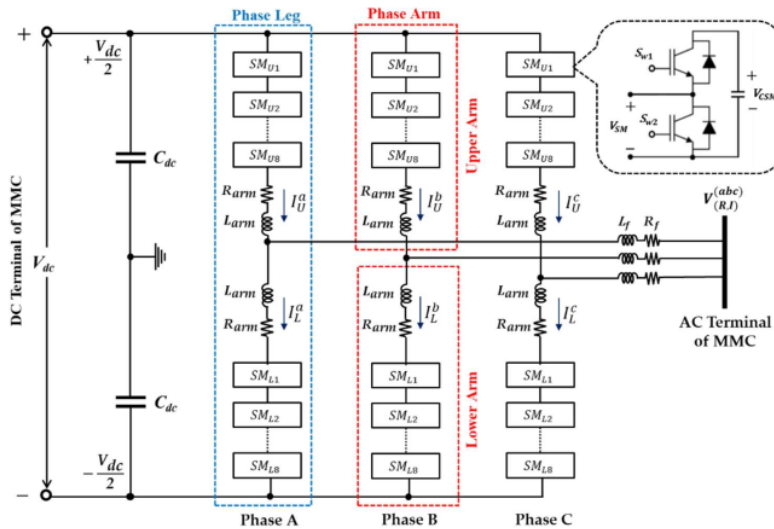


Figure 2. Configuration of the 9-levels circuit MMC circuit in three phase topologies

### 3.1. Configuration of MMC Circuit

The MMC configuration in three phase topologies is shown in Figure 2. Each phase has a phase leg, which is made up of two-phase arms. The phase arm has 8 sub-modules ($SM_{U1...,8}$ for upper arm and $SM_{L1...,8}$ lower arm), arm resistance ($R_{arm}$), and arm inductor ($L_{arm}$). The arm inductors serve as an interface impedance between the AC grid system and the MMC circuit, and serve for limiting the circulating arm current between the valve and phase legs [15]. The sub-module is half bridge type configuration which consists of two IGBTs and a sub-module capacitor ($C_{SM}$). The two antiparallel diodes are installed in parallel with the IGBTs. Point of connection between the upper and the lower arms is linked to the MMC AC terminal by inductance filter ($L_f$) and resistance filter ($R_f$). The filter can reduce the current and voltage ripples of the AC side output. Each terminal end for upper arms and lower arms is connected to each other, and respectively become positive

(+) and negative (−) output terminal of DC circuit. The DC capacitors ($C_{dc}$) are installed on the DC circuit for reducing the DC voltage ripple.

In operating of MMC circuit, the DC voltage ($V_{dc}$) is distributed to entire sub-module capacitor ($C_{SM}$). Then, the sub-module capacitor status consistently becomes charging and discharging according to the operating mode of the IGBTs switching state and current arm polarities. Sub-module capacitor status in detail can be seen in Table 2.

Table 2. Operating condition of sub-module based on switching state

| Switching State | | Arm Current Polarity | Terminal Voltage of Sub-Module | Sub-Module Capacitor Status |
|---|---|---|---|---|
| Sw1 | Sw2 | | | |
| ON | OFF | + | $V_{CSM}$ | Charge |
| OFF | ON | + | 0 | Bypass |
| ON | OFF | − | $V_{CSM}$ | Discharge |
| OFF | ON | − | 0 | Bypass |

**3.2. Control Mechanism of The MMC**

Numerous publications contain modeling designs and control techniques for the MMC-HVDC Transmission system have been reported [15]–[19]. Figure 3 presents the control scheme commonly used in MMC-based HVDC systems. Voltage Source Converters (VSCs) connect two independent AC power systems, allowing both converter stations to control the active power. One of the converters, however, should be used to control the HVDC transmission line voltage. In this work, the inverter station regulates the voltage on the HVDC transmission line while the rectifier station controls the active power. Each converter has the ability to independently regulate the reactive power output.

Three-phase current and voltage at AC output terminal of the rectifier and the inverter $\left(I_{(R,I)}^{(abc)}, V_{(R,I)}^{(abc)}\right)$ are fed to each main controller. Then, the main controllers will control the three-phase reference voltage for each phase arm $\left(V_{U(R,I)}^{*(abc)} \text{ and } V_{L(R,I)}^{*(abc)}\right)$ of the MMC circuit. In three-phase MMC circuit, a circulating current can occur on the phase legs. Moreover, the voltage level difference between sub-modules on upper and lower phase arms also can occur which can cause unbalance voltage on the sub-module capacitor [17]. The inner controller of MMC is introduced in the controller schemes for solving this problem. The new three phase voltages as references for modulating $\left(V_{U(R,I)}^{**(abc)} \text{ and } V_{L(R,I)}^{**(abc)}\right)$ are obtained from the MMC inner controller. For the modulation technique, the multicarrier-based Phase Shifted Pulse Width Modulation (PS-PWM) is implemented. The PS-PWM technique generates the PWM signals $Sw_{U(R,I)}^{(i)}$ and $Sw_{L(R,I)}^{(i)}$ to trigger the IGBT's gates of the sub-modules in the MMC circuit.
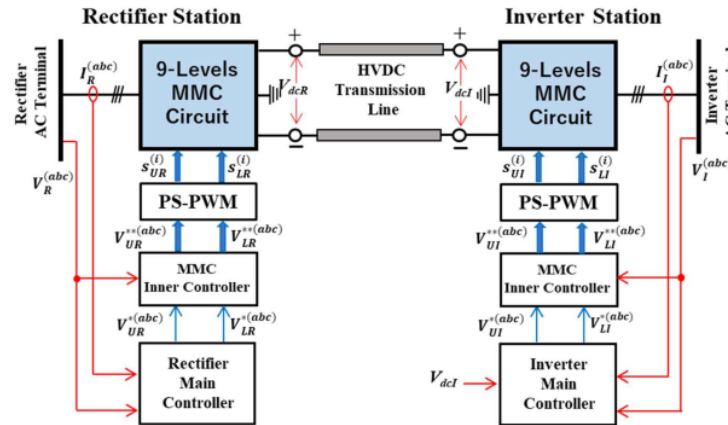


Figure 3. Control scheme of MMC based HVDC

Figures 4 and 5 show the main controllers for the rectifier and inverter, respectively. The vector control method-based conventional VSC is used for the control loop strategy for rectifier and inverter [18]. For this purpose, by using Park Transformation three-phase voltage and current from the MMC AC terminal output are converted into the $dq$-axis form. The phase angles of grid voltage ($\theta_R$ or $\theta_I$) are detected by using Phase

Locked Loop (PLL) controller. It should be noted that the original block set models of the Park Transformation equation and the PLL technique available on the master library of PSCAD/EMTDC is used in this study [20]. The power meter calculates the instantaneous powers and the three phase rms voltmeter measures the rms voltage from the MMC AC terminal output. The parameters fed to the converter controllers are in per unit (pu).
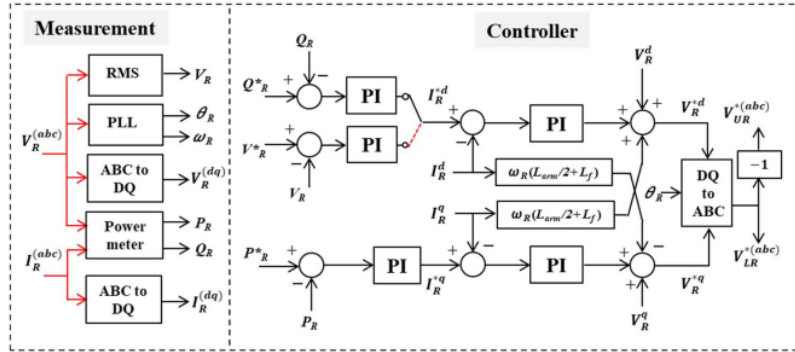


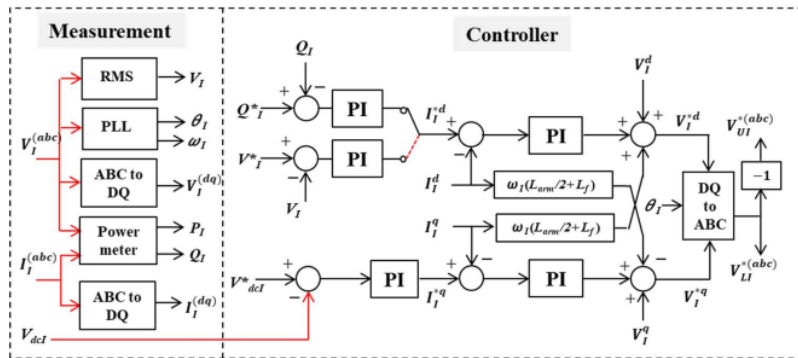Figure 4. Rectifier main controller



Figure 5. Inverter main controller

The inner current loop and outer power loop controllers of the MMC are made up of four PI controllers. In the rectifier main controller, the q-axis current ($I_R^q$) controls the flow of active power ($P_R$), while the d-axis current ($I_R^d$) controls the reactive power ($Q_R$) of the rectifier station. Under certain circumstances, the d-axis current can be chosen to regulate the voltage of the AC terminal rather than the reactive power. The references can be set to zero for reactive power ($Q^*_R$) and 1.0 pu for AC voltage ($V^*_R$). In the inverter main controller, the DC transmission line voltage ($V_{dc}$) is maintained at rated voltage by controlling the inverter q-axis current ($I_I^q$). The reactive power ($Q_I$) or the AC terminal voltage ($V_I$) of the inverter can be regulated through the inverter d-axis current ($I_I^d$). The reactive power reference, like the rectifier controller mechanism, can be set to zero, or the reference voltage can be set to 1.0 pu. If the inverter AC voltage falls below 85% due to a short circuit, the inverter main controller switches from normal to fault mode. The inverter's main controller would switch from reactive power control to voltage control.

Figure 6 depicts the MMC inner controller. The MMC inner controller is implemented to the rectifier and the inverter stations. The MMC inner controller is made up of two SM capacitor voltage balancing controllers and a circulating current controller. The function of the circulating current controller is to prevent circulating current flows through the phase legs [21]. The circulating current ($I_{cir}^{(abc)}$) can be calculated by summing the arm currents ($I_U^{(abc)}$ and $I_L^{(abc)}$) divided by two. The circulating current is converted into the d-axis and q-axis currents ($I_{cir}^{(dq)}$), which are independently set to zero using PI controllers. The PI controllers adjust the circulation voltages ($V_{cir}^{(dq)}$), which are then inverted into a three-phase voltage form ($V_{cir}^{(abc)}$). The MMC inner controller produces new reference voltages $V_U^{**(abc)}$ and $V_L^{**(abc)}$ for upper and lower arms, respectively. To control voltage balancing of all capacitors, extra controllers must be installed throughout the SMs [22].
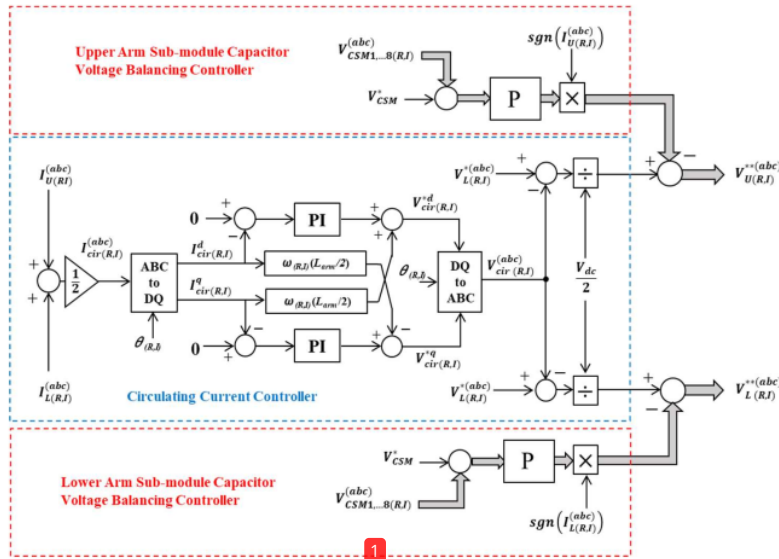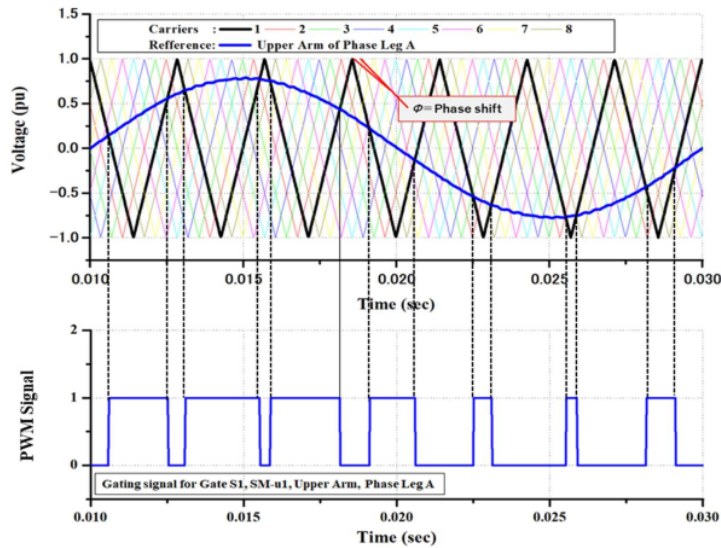
Figure 6. The MMC inner controller



Figure 7. PS-PWM technique process

### 3.3. PS-PWM Technique

The PS-PWM technique uses multiple triangle carrier signals along the horizontal axis with same frequency and voltage amplitude. The number of triangle carrier signal required is given by number of levels of MMC ($N$) minus one. Nine levels of MMC circuit requires eight triangle carrier signals. The generating pulse process of multi-carrier PS-PWM technique is shown in Figure 7. The phase shift ($\phi$) of each carrier signal can be calculated as follows [23]:

$$\emptyset = 380°/(N-1) \tag{1}$$

### 3.4. Dynamic Braking System (DBS)

A DBS is installed across an HVDC transmission terminal to dissipate energy and limit transmission line overvoltage caused by transient disturbance on the AC grid system such as a short circuit. The DBS can

help to increase capability of Fault Ride Through (FRT) of HVDC system. According to IEC Standard 62747:2014, the DBS is recommended to be implemented in HVDC transmission system [24]. The DBS installation structure is determined by the type of HVDC system. Figure 8 depicts the basic structure of DBS that installed on symmetrical monopolar type of HVDC transmission system. The rectifier MMC circuit has two DBSs installed on the DC side. The DBS is composed of a group of semiconductors breaking valve and a breaking resistance ($R_{dbs}$). The active power output of the inverter will abruptly decrease if there is a transient grid disturbance on the grid. Meanwhile, the rectifier station continues to supply active power to the HVDC circuit, and hence the power unbalance occurs between both stations. As consequence, the DC voltage on the transmission line increases significantly. The DBS will dissipate the active power in the braking resistance $R_{dbs}$ by operating the semiconductor breaking valve (DBS valve). The DBS device is operated according to the HVDC voltage condition during a disturbance event. The DBS is executed when the HVDC transmission line voltage reaches the threshold limit (1.05 pu). The maximum value of $R_{dbs}$ is selected according to nominal power rating of the HVDC link.
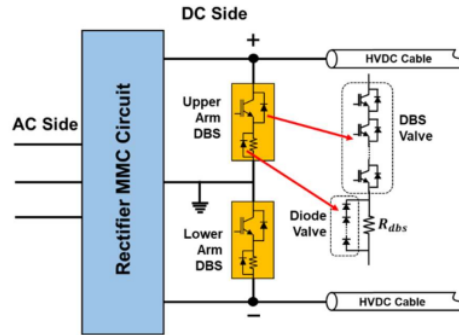


Figure 8. Basic structure of DBS on symmetrical monopolar HVDC transmission line

## 4. Simplified Model of MM-HVDC Transmission System

The equivalent approach model of a traditional Voltage Source Converter (VSC) could be considered to represent the MMC-HVDC transmission system in a simplified model [25]. Figure 9 depicts the VSC equivalent model, in which three-phase voltage source and a current source connected to the AC and DC sides, respectively, represent the converter. The converter is connected to grid voltage sources ($v_s^{(abc)}$) through phase reactor, $L_f$ (filter inductor) and $R_f$ (filter resistance). The voltage across the filter inductor for each phase can be expressed using Kirchhoff Voltage Low (KVL):

$$L_f \frac{d}{dt} i_f^{(abc)} = v_s^{(abc)} - v_{con}^{(abc)} - R_f i_f^{(abc)} \qquad (2)$$

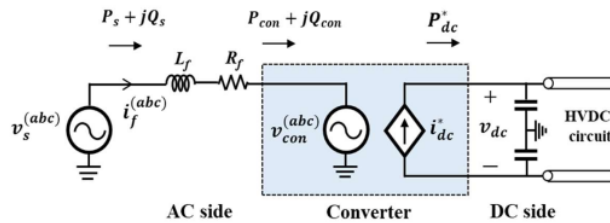where, $v_{con}^{(abc)}$ is three phase terminal voltage of the converter.



Figure 9. Equivalent model of VSC

The $v_{con}^{(abc)}$ is equivalent to the three-phase voltage at the AC output terminal of the MMC circuit. Consider the electrical MMC circuit in the equivalent model in Figure 10 for more details. The $v_{con}^{(abc)}$ can be regulated by the three phase arm voltages ($v_U^{*(abc)}$) and ($v_L^{*(abc)}$). The differential equations are obtained by applying KVL to both arm:

$$\frac{V_{dc}}{2} = v_{con}^{(abc)} + R_{arm}i_U^{(abc)} + L_{arm}\frac{di_U^{(abc)}}{dt} + v_U^{*(abc)} \tag{3}$$

$$\frac{V_{dc}}{2} = -v_{con}^{(abc)} + R_{arm}i_L^{(abc)} + L_{arm}\frac{di_L^{(abc)}}{dt} + v_L^{*(abc)} \tag{4}$$
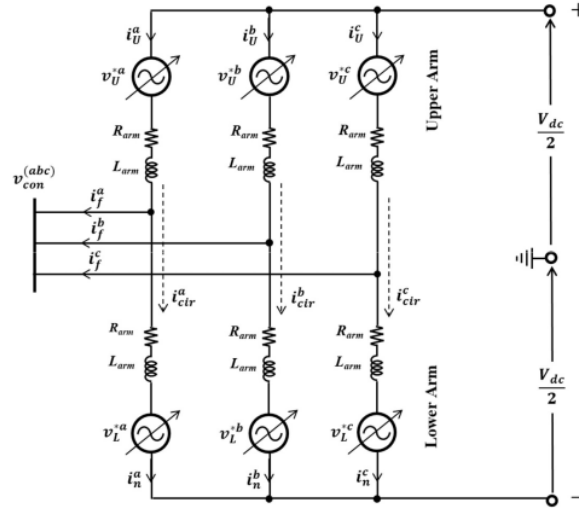


Figure 10. Equivalent of electrical MMC circuit.

From the figure, it is evident that:

$$i_f^{(abc)} = i_U^{(abc)} - i_L^{(abc)} \tag{5}$$

Circulating current is defined as follows:

$$i_{cir}^{(abc)} = \frac{i_U^{(abc)} + i_L^{(abc)}}{2} \tag{6}$$

The voltage at the MMC terminal output is calculated using the following equation:

$$v_{con}^{(abc)} = e^{(abc)} - \frac{L_{arm}di_f^{(abc)}}{2\,dt} - R_{arm}i_f^{(abc)} \tag{7}$$

where, $e^{(abc)}$ is the inner emf of three phases, expressed as:

$$e^{(abc)} = \frac{v_L^{*(abc)} - v_u^{*(abc)}}{2} \tag{8}$$

In Equation (7), the $v_{con}^{(abc)}$ can be controlled through emf $e^{(abc)}$ adjustment components $v_U^{*(abc)}$ and $v_L^{*(abc)}$. Returning to Figure 9, Equation (2) could be expressed in the $dq0$ frame as:

$$L_f\frac{di_f^d}{dt} = v_s^d - R_f i_f^d - v_{con}^d + \omega_s L_f i_f^q \tag{9}$$

$$L_f\frac{di_f^q}{dt} = v_s^q - R_f i_f^q - v_{con}^q - \omega_s L_f i_f^d \tag{10}$$

where, $\omega_s$ is angular frequency of the grid. The grid powers for both active and reactive in the complex form are expressed as:

$$P_s + jQ_s = \left(v_s^d i_f^d + v_s^q i_f^q\right) + j\left(v_s^q i_f^d - v_s^d i_f^q\right) \tag{11}$$

The power flow to the converter are also known as:

$$P_{con} + jQ_{con} = \left(v_{con}^d i_f^d + v_{con}^q i_f^q\right) + j\left(v_{con}^q i_f^d - v_{con}^d i_f^q\right) \tag{12}$$

In the steady state condition, the $q$-axis assumes alignment with the vector $\bar{v}_{con}^{(dq)}$, the $d$-axis becomes zero, and the powers of the converter is expressed as:

$$P_{con} = v_{con}^q \, i_f^q \tag{13}$$

$$Q_{con} = v_{con}^q \, i_f^d \tag{14}$$

Therefore, the $q$-axis current ($i_f^q$) and the $d$-axis current ($i_f^d$) could control independently the active and reactive powers.

The DC power ($P_{dc}^*$) flows into the HVDC transmission line and is adjustable by injecting the DC current ($i_{dc}^*$). Because reactive power has no effect on injected power to the DC side, the following relationship holds:

$$P_{dc}^* = P_{con} \Rightarrow v_{dc} \, i_{dc}^* = v_{con}^d i_f^d + v_{con}^q i_f^q \tag{15}$$

Finally, the dc current injected to the HVDC circuit can be calculated as:

$$i_{dc}^* = \frac{v_{con}^d i_f^d + v_{con}^q i_f^q}{v_{dc}} \tag{16}$$

To simplify the complicated MMC-HVDC transmission system model, IGBTs switching phenomena and modulation process in MMC rectifier and MMC inverter should be neglected in simulation analysis. Referring to Figures 9 and 10, a detailed scheme of the proposed simplified MMC-HVDC transmission system model is presented in Figure 11. The MMC circuit for a rectifier station or inverter station is made up of two electrical main circuits that are linked to the AC and DC side systems. The three-phase MMC arm circuit is made up of three-phase voltage sources, arm resistances, and arm inductors that are connected to the converters' AC terminals via the point of common connection. The DC voltage ($V_{dc}/2$) powers the entire arm circuit. The three-phase voltage external input ($V_{U(R,I)}^{*(abc)}$ and $V_{L(R,I)}^{*(abc)}$) are obtained from the MMC main controller, and the DC voltage external input ($\frac{V_{dc}}{2}$) is measured from the HVDC transmission line. A DC current source represents the MMC circuit for the interface to the DC side, and the external current input ($I_{dc(R,I)}^*$) can be calculated using Equation (15).
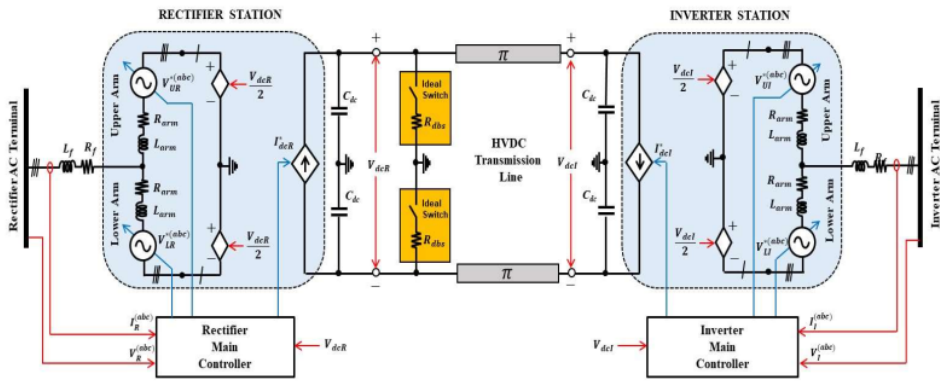


Figure 11. MMC-HVDC Transmission system in simplified model

The main controller schemes and control methods for both the rectifier and inverter controllers in the detailed model can be applied also in the simplified model. Therefore, the rectifier and the inverter controllers presented in Figures 4 and 5 can also be used in the simplified model. In this study, the profile voltage of SM capacitor and profile circulation current on the phase leg in the proposed simplified model are assumed ideal. Therefore, the MMC inner controller is not considered. Furthermore, the steady-state and transient analyses focus on the profile voltage, current, and power output excursion on AC and DC sides of the MMC.

The transmission circuit of HVDC is configured by symmetrical monopolar type as well as the electrical topology in the detailed model. However, the DBSs which installed across the HVDC transmission line is represented by an ideal switch and a braking resistance for each arm. The switch is executed when the HVDC circuit voltage exceeds the voltage threshold, 1.05 pu.
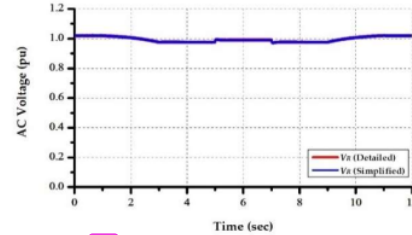
## 5.    Simulation Study

The model of two areas of the power system linked by the HVDC transmission line illustrated in Figure 1 is analyzed in the simulation study. The PSCAD/EMTDC software is used for the simulation study. The simulations were run on the PC (Intel I7-9700 CPU @3.0 GHz RAM 64 GB). A comparative responses analysis between the detailed and the simplified models was validated under steady-state and transient disturbances.

### 5.1. Simulation and Anaysis in Steady State Study

In this simulation study, the responses of terminal voltages and powers output of the HVDC transmission system during steady-state disturbance are analyzed. The simulation results are presented in Figures 12(a) to 12(f). For steady state disturbance, the up-down ramps and step changes in active power reference are applied to the rectifier main controller as depicted in Figure 12 (a). First, the up-ramp reference is gradually increased from 0.0 pu to 1.0 pu. Second, the step change reference is applied two times, at 5.0 sec from 1.0 pu to 0.8 pu, and at 7.0 sec from 0.8 pu to 1.0 pu. The down-ramp reference is activated at 9.0 sec, where the reference is gradually decreased from 1.0 pu to 0.0 pu.
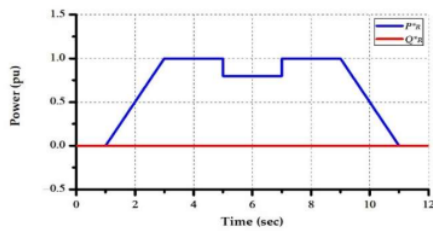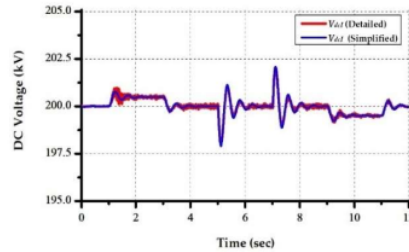
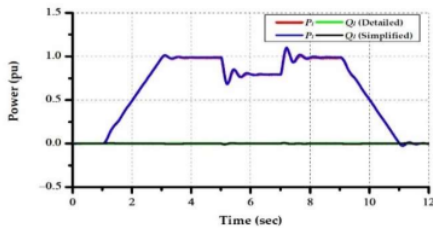(a) Active and reactive powers references        (b) AC voltage response at Bus B1
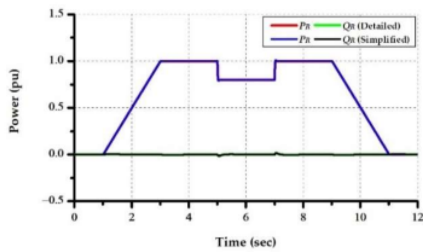
(c) Active and reactive power responses at Bus B1        (d) DC voltage response at the transmission line

(e) Active and reactive power responses at Bus B4        (f) AC voltage response at Bus B4

Figure 12. Simulation results in steady state condition

During the simulation, the reactive power of the converter stations is maintained to zero. According to simulation results shown in Figures 12 (b) to 12 (f), the AC terminal voltage, the powers of both the converter station, and the DC voltage of the transmission line of the simplified model have the same response as the detailed model. In the steady-state condition, the simplified model has adequate precision, which can be confirmed. In addition, as presented in Table 3 the simplified model can reduce simulation time more significant compared to the simulation time obtained by the detailed model.

Table 3. Computation time for 12 sec simulation time

| | Computation Time | |
| --- | --- | --- |
| | Simplified Model | Detailed Model |
| Simulation time step | 100 µs | 10 µs |
| Real time duration | 7 seconds | 70 minutes |

### 5.1. Simulation and Analysis in Transient Study

Asymmetrical two lines to ground fault (2LG) and symmetric three lines to ground fault (3LG) at the transmission line of Area 2 are regarded as network disturbances in the transient case study. Figure 1 depicts where the faults are located. Circuit breaker (CBs) on the faulted circuit are opened at 0.2 seconds following the occurrence of the fault at 0.1 seconds. The CBs are reclosed at 1.0 second under the presumption that the fault has been fixed.

The simulation results of the transient study for 2LG and 3LG are shown in Figures 13 and 14, respectively. According to the profile AC voltage, active and reactive power response at BUS B1, the faults (2LG or 3LG) in Area 2 had no effect on the Area 1. This is because, the DBS device can absorb the supplied active power from Area 1 when unbalanced power occurred between the inverter and the rectifier caused by the faults, hence the overvoltage on the HVDC transmission line can be well anticipated. The DC voltage responses are shown in Figures 13(c) and 14(c). Due to the voltage drop during the faults, the active power to Area 2 on Bus 4 abruptly decreased. After the faults are cleared, the active power can be restored to its original state. Meanwhile, the inverter supplies reactive power during the fault and returns to its original position once the fault is resolved. Based on the simulation results, the proposed simplified model of the MMC-HVDC transmission system has adequate precision in transient responses in the cases of 2LG and 3LG disturbances.



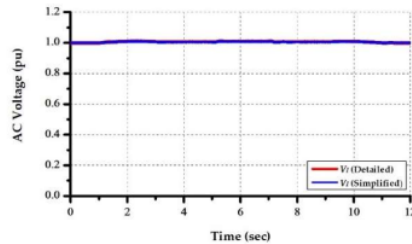(a) AC voltage response at Bus B1          (b) Active and reactive power responses at Bus B1

(c) DC voltage response at the transmission line          (d) Active and reactive power responses at Bus B4

(e) AC voltage response at Bus B4
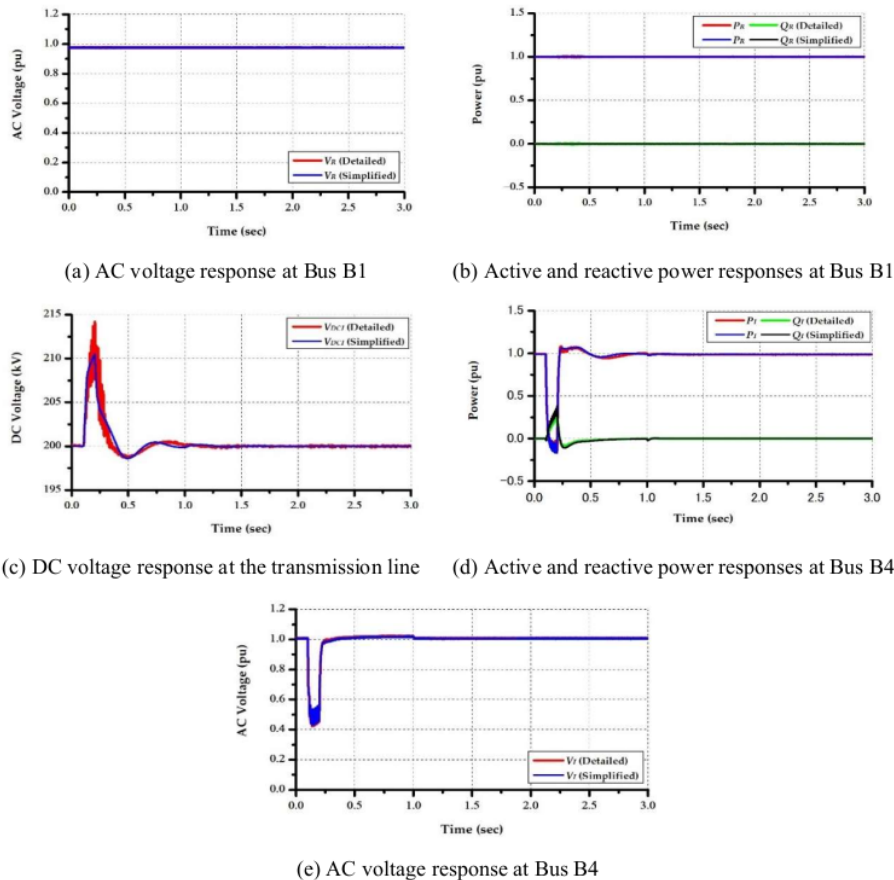
Figure 13. Simulation results of transient study for 2LG

(a) AC voltage response at Bus B1

(b) Active and reactive power responses at Bus B1

(c) DC voltage response at the transmission line

(d) Active and reactive power responses at Bus B4

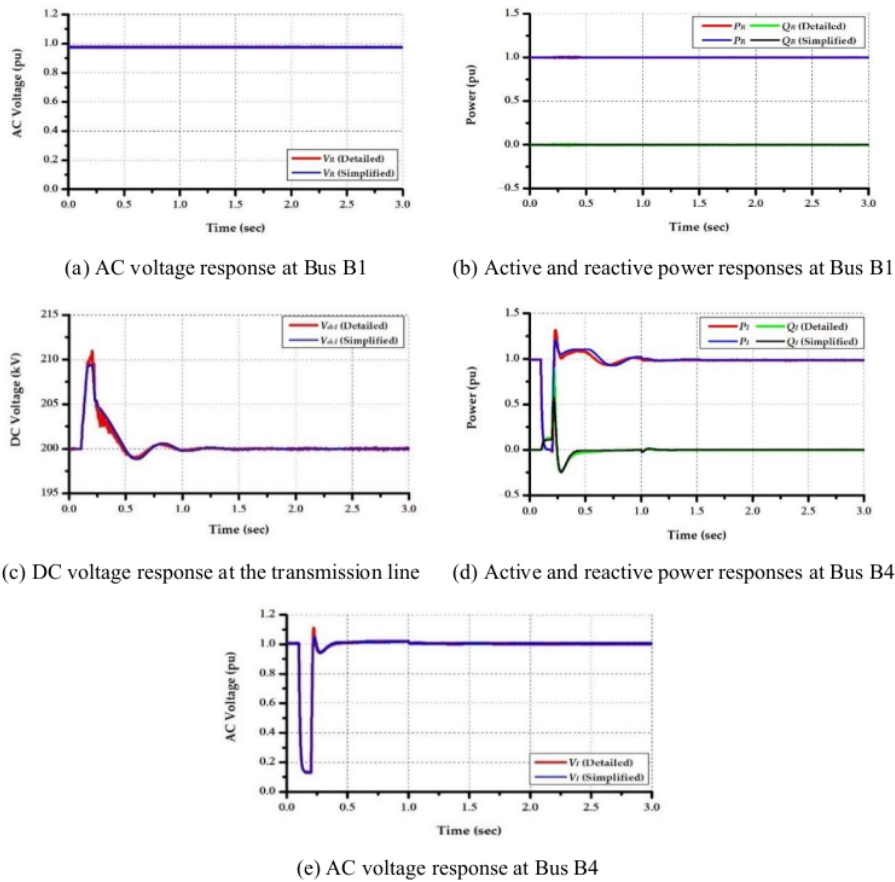(e) AC voltage response at Bus B4

Figure 14. Simulation results of transient study for 3LG

## 6.    CONCLUSION

In this paper, a simplified model design for an MMC-HVDC transmission system is presented. The PSCAD/EMTDC program was used to perform a comparison response analysis of the proposed simplified model and the detailed model in steady state and transient conditions to confirm the validity of the proposed simplified model. Ramp and step input signals are used in steady state analysis. In the transient analysis of an AC system, asymmetrical two lines to ground fault and symmetrical three lines to ground fault are considered disturbances. It is possible to verify that the simplified model is accurate enough. In addition, simulation time can be significantly reduced. In Europe, for example, HVDC transmission systems based on MMC technology have been widely used in offshore wind farms connected to onshore grids via long transmission cables [26]–[29]. The New Hokkaido-Honshu HVDC Link, an MMC-based HVDC interconnection line, has recently begun operation in Japan as well [30], [31]. The simplified model proposed here can be used to effectively analyze the dynamic properties of power systems such as MMC-HVDC transmission lines. In a future study, the authors intend to extend the proposed simplified model to analyze multi-area power systems with multiple HVDC transmission terminals.

# REFERENCES

[1]   N. R. Watson, J.D. Watson, "An Overview of HVDC Technology," *Energies*, vol. 13, pp. 4342, 2020, doi.org/10.3390/en13174342.
[2]   J. Qin, M. Saeedifard, A. Rockhill and R. Zhou, "Hybrid Design of Modular Multilevel Converters for HVDC Systems Based on Various Submodule Circuits," *IEEE Transactions on Power Delivery*, vol. 30, no. 1, pp. 385-394, Feb. 2015, doi: 10.1109/TPWRD.2014.2351794.
[3]   X. Shi, Z. Wang, B. Liu, Y. Liu, L. M. Tolbert and F. Wang, "Characteristic Investigation and Control of a Modular Multilevel Converter-Based HVDC System Under Single-Line-to-Ground Fault Conditions," *IEEE Transactions on Power Electronics*, vol. 30, no. 1, pp. 408-421, Jan. 2015, doi: 10.1109/TPEL.2014.2323360.
[4]   S. Debnath, J. Qin, B. Bahrani, M. Saeedifard and P. Barbosa, "Operation, Control, and Applications of the Modular Multilevel Converter: A Review," *IEEE Transactions on Power Electronics*, vol. 30, no. 1, pp. 37-53, Jan. 2015, doi: 10.1109/TPEL.2014.2309937.
[5]   A. Beddard, M. Barnes and R. Preece, "Comparison of Detailed Modeling Techniques for MMC Employed on VSC-HVDC Schemes, " *IEEE Transactions on Power Delivery*, vol. 30, no. 2, pp. 579-589, April 2015, doi: 10.1109/TPWRD.2014.2325065.
[6]   S. P. Teeuwsen, "Simplified dynamic model of a voltage-sourced converter with modular multilevel converter design, " *in Proc. 2009 IEEE/PES Power Systems Conference and Exposition*, 2009, pp. 1-6, doi: 10.1109/PSCE.2009.4839922.
[7]   D. Jovcic and A. A. Jamshidifar, "Phasor Model of Modular Multilevel Converter With Circulating Current Suppression Control," *IEEE Transactions on Power Delivery*, vol. 30, no. 4, pp. 1889-1897, Aug. 2015, doi: 10.1109/TPWRD.2014.2372780.
[8]   N. -T. Trinh, M. Zeller, K. Wuerflinger and I. Erlich, "Generic Model of MMC-VSC-HVDC for Interaction Study With AC Power System," *IEEE Transactions on Power Systems*, vol. 31, no. 1, pp. 27-34, Jan. 2016, doi: 10.1109/TPWRS.2015.2390416.
[9]   S. Liu, Z. Xu, W. Hua, G. Tang and Y. Xue, "Electromechanical transient modeling of modular multilevel converter based multi-terminal HVDC systems," *in Proc. 2014 IEEE PES General Meeting | Conference & Exposition*, 2014, pp. 1-1, doi: 10.1109/PESGM.2014.6938791.
[10]  U. N. Gnanarathna, A. M. Gole and R. P. Jayasinghe, "Efficient Modeling of Modular Multilevel HVDC Converters (MMC) on Electromagnetic Transient Simulation Programs," *IEEE Transactions on Power Delivery*, vol. 26, no. 1, pp. 316-324, Jan. 2011, doi: 10.1109/TPWRD.2010.2060737.
[11]  J. Peralta, H. Saad, S. Dennetiere, J. Mahseredjian and S. Nguefeu, "Detailed and averaged models for a 401-level MMC-HVDC system," *in Proc. 2013 IEEE Power & Energy Society General Meeting*, 2013, pp. 1-1, doi: 10.1109/PESMG.2013.6672356.
[12]  H. Saad et al., "Dynamic Averaged and Simplified Models for MMC-Based HVDC Transmission Systems," *IEEE Transactions on Power Delivery*, vol. 28, no. 3, pp. 1723-1730, July 2013, doi: 10.1109/TPWRD.2013.2251912.
[13]  H. Saad et al., "Modular Multilevel Converter Models for Electromagnetic Transients," *IEEE Transactions on Power Delivery*, vol. 29, no. 3, pp. 1481-1489, June 2014, doi: 10.1109/TPWRD.2013.2285633.
[14]  M. Rosyadi, A. Umemura, R. Takahashi, J. Tamura, "Detailed and Average Models of a Grid-Connected MMC-Controlled Permanent Magnet Wind Turbine Generator," *Applied Sciences*, vol 12, 2022, pp.1619, doi.org/10.3390/app12031619.
[15]  CIGRE Working Group B4.70, "Guide for Electromagnetic transient studies involving VSC converter," Technical Brochure Reference 832, April 2021.
[16]  M. Davies, M. Dommaschk, J. Dorn, J. Lang, D. Retzmann, D. Soerangr, "HVDC PLUS-Basics and Principle of Operation," Siemens Energy Sector Report E T PS SL/DSoe/Re, 10 Aug 2008.
[17]  A. Timofejevs, D. Gamboa, "Control of MMC in HVDC applications," M. S. thesis, Dept. of Energy Technology, Aalborg University, Denmark, 30 May 2013.
[18]  W. Li, L.A. Gregoire, J. Bélanger, "Control and performance of a modular multilevel converter system," *in Proc. of CYCRE Canada Conference on Power Systems*, Halifax, Canada, 6-8 September 2011.
[19]  Y. Wang, S. Liao, Q. Xu, L. Wang, J. M. Guerrero, " Coordinated design of control parameters for improving interactive and internal stability of MMC-HVDC," *International Journal of Electrical Power & Energy Systems*, vol. 140, 108065, 2022, doi.org/10.1016/j.ijepes.2022.108065.
[20]  PSCAD V5 Application Help Available online: https://www.pscad.com/webhelp-v5-ol/ol-help.htm. (accessed on 17 January 2021).
[21]  Q. Tu, Z. Xu and J. Zhang, "Circulating current suppressing controller in modular multilevel converter," *in Proc. IECON 2010 - 36th Annual Conference on IEEE Industrial Electronics Society*, 2010, pp. 3198-3202, doi: 10.1109/IECON.2010.5675048.
[22]  R. Darus, G. Konstantinou, J. Pou, S. Ceballos and V. G. Agelidis, "Comparison of phase-shifted and level-shifted PWM in the modular multilevel converter," *in Proc. 2014 International Power Electronics Conference (IPEC-Hiroshima 2014 - ECCE ASIA)*, 2014, pp. 3764-3770, doi: 10.1109/IPEC.2014.6870039.
[23]  L. G. Franquelo, J. Rodriguez, J. I. Leon, S. Kouro, R. Portillo and M. A. M. Prats, "The age of multilevel converters arrives," *IEEE Industrial Electronics Magazine*, vol. 2, no. 2, pp. 28-39, June 2008, doi: 10.1109/MIE.2008.923519.
[24]  The International Electrotechnical Commission, "Terminology for voltage-sourced converters (VSC) for high-voltage direct current (HVDC) systems," IEC STANDARD 62747:2014, 2014
[25]  G. Stamatiou, "Analysis of VSC-based HVDC systems," Ph.D. dissertation, Department of Energy and Environment, Chalmers University of Technology, Gothenburg, Sweden, 2016.
[26]  CIGRE Working Group B4.72. DC grid benchmark models for system studies. Technical Brochure Reference 804, June 2020.
[27]  HVDC PLUS – the decisive step ahead. Available online: https:// assets.siemens-energy.com/siemens/assets/api/uuid:83dc80ed-cbd6-4027-9e 48-83a87eab8e0b/ 263_ 160390_ws_hvdcplususlowres.pdf
[28]  T. Hennig, "State-of-the-art offshore power system in the German bight and technical mid-term expansion options," *in Proc. Offshore Wind R&D Conference 2015*, Bremerhaven, Germany, 13-15 October 2015.
[29]  Energy from sea to land. Available online: https://www.tennet.eu/fileadmin/user_upload/Our_Grid/Offshore_Germany/2020_From_Sea_to_Land_Webversion.pdf
[30]  S. Sato, T. Uchiumi, A. Miura, T. Murao, K. Suzuki, "The construction of New Hokkaido-Honshu HVDC Link Project," in Proc. CICRE Paris 2018, B4-132, pp 1-8, 2018.
[31]  M. Mori, J. Chiba, A. Miura, K. Shimada, Y. Chiba, D. Suzuki, "Functions and Commissioning Test of New Hokkaido-Honshu HVDC Link," *in Proc. CIGRE Paris 2020*, B4-127, pp 1-8, 2020.

# BIOGRAPHIES OF AUTHORS

**Marwan Rosyadi** is a researcher/educator in Electrical Engineering Department at the Universitas Muhammadiyah Surabaya, Surabaya, Indonesia. He received B.Eng degree in electrical engineering from Institut Teknologi Adhi Tama Surabaya (ITAS) in 2004, M.Eng degree in electrical engineering from Institut Teknologi Sepuluh Nopember (ITS) in 2006, and Dr. Eng. degree from Kitami Institute of Technology in 2013. His research interests are dynamic stability and control of power system including large scale wind farms, solar farm, Battery Energy Storage, FACT devices, hydrogen generator, and HVDC transmission system.

**Atsushi Umemura** received Dr. Eng. degree from Tokyo Denki University and joined Ohashi Engineering Co. Ltd. He became an Assistant Professor in the department of Electrical and Electronic Engineering, Kitami Institute of Technology in 2012, and has been an Associate Professor in the same department since 2020. His research interests include robotics, mechatronics, and power electronics.

**Rion Takahasi** received the B.Sc. Eng. and Dr. Eng. Degrees from Kitami Institute of Technology, Japan, in 1998 and 2006 respectively, all in Electrical and Electronic Engineering. Now he is working as Associate Professor in Department of Electrical and Electronic Engineering, Kitami Institute of Technology. His major research interests include analysis of power system transient, FACTS and wind energy conversion system. He is a member of IEEE.

**Junji Tamura** received his B. Sc. Eng. Degree from Muroran Institute of Technology, Japan, in 1979 and M.Sc. Eng. and Dr. Eng. degrees from Hokkaido University, Japan, in 1981 and 1984 respectively, all in electrical engineering. He became a lecturer in 1984, an Associate Professor in 1986, and a Professor in 1996 at the Kitami Institute of Technology, Japan. Dr. Tamura is a Senior Member of the IEEE Power Engineering Society.

**Takanori Uchiumi** received the B. Eng., M. Eng. and D. Eng. degrees from Muroran Institute of Technology, Japan, in 1995, 1997 and 2004 respectively, all in Electrical and Electronic Engineering. Now he works for Hokkaido Electric Power Network, Inc. as Manager of Power System Planning Section., Eng. Dept..

**Masanori Mori** received the B. Eng. and M. Eng. degrees from Muroran Institute of Technology, Japan, in 2001 and 2003 respectively, all in Electrical and Electronic Engineering. Now he works for Hokkaido Electric Power Network, Inc. as member of HVDC Interconnection Planning and Engeneering Section., Eng. Dept.

**Hiroki Miyata** received the B. Eng. and M. Eng. degrees from Hokkaido University, Japan, in 2010 and 2012 respectively, all in Applied Physics and Engineering. Now he works for Hokkaido Electric Power Network, Inc. as member of HVDC Interconnection Planning and Engeneering Section., Eng. Dept.

# Marwan1310

6  Marwan Rosyadi, Atsushi Umemura, Rion Takahashi, Junji Tamura, Noriyuki Uchiyama, Kazumasa Ide. "Simplified Model of Variable Speed Wind Turbine Generator for Dynamic Simulation Analysis", IEEJ Transactions on Power and Energy, 2015
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10  Daichi Suzuki, Noriko Kawakami, Masanori Mori, Takanori Uchiumi. "Commissioning test and Operation results of New Hokkaido-Honshu HVDC Link", 2022 International Power Electronics Conference (IPEC-Himeji 2022-ECCE Asia), 2022
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14    Hazem, Khaled M., and Mohamed M. Zakaria Moustafa. "Performance and control of a back to back MMC-HVDC for asynchronous ac networks interconnection", 2015 IEEE 28th Canadian Conference on Electrical and Computer Engineering (CCECE), 2015.
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21  "Transient Analysis of Power Systems", Wiley, 2015
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22  Heya Yang, Yufei Dong, Wuhua Li, Xiangning He. "Average-Value Model of Modular Multilevel Converters Considering Capacitor Voltage Ripple", IEEE Transactions on Power Delivery, 2017
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23  Junqiao Liu, Marwan Rosyadi, Atsushi Umemura, Rion Takahashi, Junji Tamura. "A Control Method of Permanent Magnet Wind Generators in Grid Connected Wind Farm to Damp Load Frequency Oscillation", IEEJ Transactions on Power and Energy, 2014
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25  Linda Sartika, Atsushi Umemura, Rion Takahashi, Junji Tamura. "Wind Turbines Cluster System Composed of Fixed Speed Wind Generators Controlled by Cluster Converter based VSC-HVDC System", IEEJ Transactions on Power and Energy, 2018
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26  estudogeral.sib.uc.pt
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27  M. Fawzi, Fernando Briz, A. E. Kalas. "DC short circuit ride-through strategy for a full-bridge MMC HVDC transmission system", 2017 19th European Conference on Power Electronics and Applications (EPE'17 ECCE Europe), 2017
Publication
<1%

28  Marwan Rosyadi, S. M. Muyeen, Rion Takahashi, Junji Tamura. "Voltage stability control of wind farm using PMSG based variable speed wind turbine", 2012 XXth International Conference on Electrical Machines, 2012
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32  Ilves, Kalle, Staffan Norrga, Lennart Harnefors, and Hans-Peter Nee. "Analysis of arm current harmonics in modular multilevel converters with main-circuit filters", International Multi-
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Conference on Systems Sygnals & Devices, 2012.
Publication

33    Jian Yang, Shurui Mao, Xiaodong Li, Zheng Xu. "Influence Mechanism and Suppression Control of the MMC on Short-Circuit Current Under AC Faults", IEEE Access, 2020
Publication    <1%

34    Trinh, Ngoc-Tuan, Marcus Zeller, Klaus Wuerflinger, and Istvan Erlich. "Generic Model of MMC-VSC-HVDC for Interaction Study With AC Power System", IEEE Transactions on Power Systems, 2015.
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35    odr.chalmers.se
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36    M.H. Ali. "Transient Stability Improvement by Fuzzy Logic-Controlled Braking Resistor", International Journal of Power and Energy Systems, 2005
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37    Sheng Liu, Zheng Xu, Wen Hua, Geng Tang, Yinglin Xue. "Electromechanical Transient Modeling of Modular Multilevel Converter Based Multi-Terminal HVDC Systems", IEEE Transactions on Power Systems, 2014
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49  Alsadah, Muhammad, and Fernando Mancilla-
    David. "Modeling and control of grid-
    connected photovoltaic power plants utilizing    <1 %
    a simplified model of the modular multilevel
    converter", 2014 North American Power
    Symposium (NAPS), 2014.
    Publication

50  Ankit Yadav, S. N. Singh, S. P. Das.
    "Development of EMT Model for Circulating
    Current Control", 2018 5th IEEE Uttar Pradesh   <1 %
    Section International Conference on Electrical,
    Electronics and Computer Engineering
    (UPCON), 2018
    Publication

51  Firouz Badrkhani Ajaei, Reza Iravani.
    "Dynamic Interactions of the MMC-HVDC Grid
    and its Host AC System Due to AC-Side           <1 %
    Disturbances", IEEE Transactions on Power
    Delivery, 2016
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52  Haitian Wang, Guangfu Tang, Zhiyuan He,
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    Temperature Analysis in the Modular             <1 %
    Multilevel Converters for HVDC Transmission
    Systems", Journal of Power Electronics, 2015
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53  Kazunobu Oi, Shota Urushibata, Yugo Tadano, Yukihiko Sato. "Experimental verification of bidirectional modular multilevel cascaded converter suitable for applying 120‑degree discontinuous pulse width modulation maximum", Electrical Engineering in Japan, 2021
Publication

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54  Luis M. Castro, Enrique Acha, Claudio R. Fuerte-Esquivel. "A novel VSC-HVDC link model for dynamic power system simulations", Electric Power Systems Research, 2015
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<1 %

55  Shenghui Cui, Hak-Jun Lee, Jae-Jung Jung, Younggi Lee, Seung-Ki Sul. "A Comprehensive AC-Side Single-Line-to-Ground Fault Ride Through Strategy of an MMC-based HVDC System", IEEE Journal of Emerging and Selected Topics in Power Electronics, 2018
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**62** Haitian Wang, Guangfu Tang, Zhiyuan He, Jie Yang. "Efficient Grounding for Modular Multilevel HVDC Converters (MMC) on the AC Side", IEEE Transactions on Power Delivery, 2014
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**63** Marwan Rosyadi, S. M. Muyeen, Rion Takahashi, Junji Tamura. "Stability Augmentation of Wind Farm using Variable Speed Permanent Magnet Synchronous Generator", IEEJ Transactions on Industry Applications, 2011
Publication
<1 %

**64** Apparao Dekka, Venkata Yaramasu, Ricardo Lizana Fuentes, Deepak Ronanki. "Modular multilevel converters", Elsevier BV, 2021
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**65** J. Renedo, A. Garcia-Cerrada, L. Rouco, L. Sigrist, I. Egido, S. Sanz Verdugo. "Development of a PSS/E tool for power-flow calculation and dynamic simulation of VSC-
<1 %

HVDC multi-terminal systems", 13th IET International Conference on AC and DC Power Transmission (ACDC 2017), 2017

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