Design of internal dynamics based MMC controller for HVDC transmission

Ankit Yadav | Sri Niwas Singh | Shyama Prasad Das

Department of Electrical Engineering, Indian Institute of Technology Kanpur, Kanpur, Uttar Pradesh, India

Correspondence
Ankit Yadav, Department of Electrical Engineering, Indian Institute of Technology Kanpur 208016, Uttar Pradesh, India.
Email: ankity@iitk.ac.in

Abstract
Currently, the modular multilevel converter (MMC) is the most advanced voltage source converter topology. Because the MMC is a converter topology, the most common approach for controller design is considering the conventional converter model to design the controller accordingly. Though this approach ignores the internal dynamics of the MMC, the modular structure enables distribution of the capacitors in six arms of the MMC. However, this distribution leads to a complex internal dynamic that affects the controller operation and cannot be disregarded. In this study, a detailed fundamental and circulating current model of the MMC is developed while considering its internal dynamics. The detailed modelling reveals cross- and inter-couplings. On the basis of the detailed model and analysis of the couplings, three controllers have been proposed. Moreover, the performances of the proposed and conventional controllers have been analysed and compared under steady-state and active and reactive power changes. The proposed controllers are observed to achieve improved decoupling compared to that achieved by the conventional controller.

1 | INTRODUCTION
Modular multilevel converters (MMCs) are currently the most advanced voltage source converter topologies. As proven in [1], the MMC is the most optimal linear time-invariant converter in terms of arm current distribution. Any topology that outperforms it would be either a non-linear or time-varying system. Further, with the recent advancements in high voltage direct current (HVDC) breakers [2, 3], the MMC has become much more competent. MMCs can be applied in several areas, including HVDC, medium voltage drives, flexible AC transmission systems, D-STATCOM, and solar and wind energy. Their modular structure resolves the long-existing scalability issue of VSCs [4]. Moreover, MMCs are infused with advantages such as modularity, transformer-less and filter-less operations, higher power quality, and reduced operating cost. However, this approach leads to a series-parallel combination of 3N capacitors; moreover, complex control objectives are also presented in this case. Multiple concurrent control objectives include phase currents and power flow control, sub-module (SM) voltage balancing, minimising of circulating current, minimising of SM voltage ripple, maintenance of DC voltage, ripple-free DC link current and handling of DC faults.

During the last decade, MMC technology has evolved notably. Figure 1 depicts the architecture of an MMC, which is primarily a collection of SMs. The half-bridge SM (HBSM) is the most economical and simple SM among all alternatives [5]. The first commercial MMC-HVDC system (i.e. the Trans Bay Cable Project), which was commissioned in 2010, has 100 HBSMs in each arm. Authors in [6] have presented the modelling of 400MW monopolar scheme of the Trans Bay cable project designed for ±200kV and 1.026kA, DC voltage and current, respectively. Later, the authors in [7] have investigated the interaction between voltage and current inside the SM. The authors have also developed the equivalent circuit by replacing the MMC arm with a set of equivalent fundamental, DC, cumulative, and differential voltage sources. To provide a clear insight [8] and [9], have developed and compared electromagnetic transient models of the MMC. In [10], the authors have defined the operating limits by analysing the $P_r-Q_v$ operating range of the MMC.

The major features of the MMC are its internal dynamics and control. However, the most common design approaches...
ignore the internal dynamics of MMCs. More importantly, the presence of 3N capacitors leads to complexities that cannot be disregarded when designing the controller. In [11], the internal dynamics of the SM capacitor (SMC) and its impact on stability have been analysed. In [12], the dynamics of the MMC under an unbalanced grid have been investigated. However, conventional PI-based controllers have been used for controller design, whereby the internal MMC dynamics have been ignored. In [13] and [14], the model predictive control (MPC) is presented using the mathematical model of the MMC, while considering its internal dynamics. The MPC proposed by [13] reduces the calculation burden via decoupling of the SMC voltage control from the cost function and preselection of control options for upcoming sampling time. Indirect MPC, presented in [14], employs a mathematical model-based pre-derived stability margin for defining the cost function. The drawback of MPC here, however, is the high computational burden, high complexity, high sensitivity to weighting factors and variable switching frequency [15]. In [16] and [17], arm current control is proposed. In [16], the phase currents and circulating currents are derived from arm-current measurements, which are then transformed to the d-q axis variable for the purpose of control. In the d-q coordinate, the PI controllers are applied for achieving the control objectives. Meanwhile, in [17], all of the six arm currents are controlled directly using a dedicated PR controller for each arm. This increases the number of controllers, though all the arm currents can be controlled independently. However, in [16] and [17], the coupling between active and reactive power is not analysed. In [18], six intermediate controllable voltages (ICVs) have been derived, corresponding to the phase current, DC, and circulating current from the arm current measurement. Controlling the ICVs leads to decoupled control of each of the six arms. However, the complete control structure employs six controllers—one for each ICV and an additional PI controller—resulting in a highly complex control architecture.

In [19], the authors have analysed the cause of 3rd-order voltage ripple of the SMC on the 3rd-order harmonic current under transformer-less operation and have proposed a PR controller for the same. The authors have acknowledged the coupling between active and reactive power. The authors in [20] have analysed the coupling of electrical quantities in SM and have noted the internal dynamics in the MMC modelling and primary controller design. However, they have not considered 3rd-order harmonic voltage ripple in SMC. Further, they have ignored the internal dynamic for the auxiliary controller and used the conventional model. In the current study, the internal dynamics [11] based model has been developed and turned out to be similar to the control plant presented in [20] with the addition of 3rd harmonic SMC voltage ripples.

The contributions of this study can be summarised as follows:

i Considering the internal dynamics of the MMC, this study presents a detailed model of the MMC fundamental AC and 2nd-order circulating current.

ii Three sets of the controllers have been derived by considering the inter-couplings and cross-couplings of models. These controllers enable improved power decoupling compared to that of the conventional control method.

iii The significance of inter-couplings, cross-couplings, and SMC voltage ripples in the overall operations has been analysed.

iv A comparative performance analysis of the proposed controllers (with respect to the conventional controller) indicates that the simplified version of the controller outperforms the other control methods.

The remainder of this study is organised as follows. Section 2 presents the MMC architecture, its conventional model, and the control structure. In Section 3, the development of a detailed mathematical model of the MMC has been described. On the basis of the detailed models, three new control structures are derived and are described in Section 4. The comparative performance analysis of these models is presented in Section 5. A brief discussion of the proposed controllers is also included. The conclusion is presented in Section 6.

2 CONVENTIONAL MODEL AND CONTROL

In the MMC, the SMs are stacked in series with a resistor and an inductor to form an arm. A combination of two such arms makes a leg. An arm is considered upper or lower in accordance with its location in the configuration. A parallel combination of three such legs, each corresponding to a phase yields the MMC architecture presented in Figure 1 [8]. SMs are the building block...
of MMCs and are available in a wide range of configurations as presented by [5]. This study utilises HBSSM, which is the most economical among all SMs.

The well-accepted approach for controlling the MMC is to control fundamental and circulating current by implementing two parallel controllers: primary and auxiliary. The primary controller aims to maintain reference fundamental current based on AC side power requirements. To achieve this, it needs to control the voltage \( v_{ij} \), whereas the auxiliary controller aims to eliminate the circulating current. The voltage \( v_{ij} \) is a function of the upper and lower arm voltages, and these voltages are a function of \( N \), \( u_i \), and \( S_{ij} \). Thus, we can synthesise any desired value of voltage \( v_{ij} \) via a proper arm switching function [21].

Under the balanced operation, all three phases of the MMC behave identically with a phase shift of 120°. Therefore, hereafter, the equations and analysis of phase ‘A’ are also valid for the remaining two-phases. Consequently, the subscript ‘j’ has been omitted for simplicity.

The upper and lower arm currents of the MMC are the sum of three components, that is, (i) DC current, (ii) fundamental frequency AC current, and (iii) 2nd-order circulating current. The circulating current of 4th and higher orders are neglected owing to their negligible magnitudes. The arm currents can be defined as in (1) as follows:

\[
\begin{align*}
    i_u &= \frac{1}{2} I_{dc} - \frac{1}{2} I_s \sin(\omega t + \alpha_i) + I_{cir} \sin(2\omega t + \alpha_i) \\
    i_l &= \frac{1}{3} I_{dc} + \frac{1}{2} I_s \sin(\omega t + \alpha_i) + I_{cir} \sin(2\omega t + \alpha_i)
\end{align*}
\] (1)

Here, the circulating current and DC current component are equal for both arms, whereas the fundamental component is of opposite polarity. The MMC equivalent circuits for the fundamental and 2\textsuperscript{nd}-order circulating current are derived as illustrated in Figure 2.

The mathematical model of the same can be defined as in (2), where \( L_{eq} = L_i + L_{arm}/2 \), \( R_{eq} = R_{arm}/2 \), \( V_{u1} \) is the fundamental and \( V_{u2} \) is the 2\textsuperscript{nd}-order harmonic voltage component of the upper arm.

\[
\begin{align*}
    V_{u1} &= -V_i + (S \ast L_{eq} + R_{eq}) I_s \\
    V_{u2} &= -(S \ast L_{arm} + R_{arm}) I_{cir}
\end{align*}
\] (2)

For this conventional circuit, the d-q model (also known as the control plant) of the fundamental AC current and the 2\textsuperscript{nd}-order circulating current are presented in Figures 3(b) and 3(d), respectively. Figures 3(a) and 3(c) depict the d-q based conventional primary and auxiliary controllers. Meanwhile, the primary controller is derived from the d-q model of fundamental AC current, whereas the auxiliary control is derived from the 2\textsuperscript{nd}-order circulating current model.

Both controllers operate in parallel to provide the switching function defined by (5) [22, 23]. These models, as well as the derived controllers, are based on the traditional understanding of a converter; thus, they ignore the internal dynamics of the MMC. Traditionally, the capacitor is connected on the DC terminal, isolated from the AC network, whereas in the MMC, the SMCs are interlinked with both AC and DC networks. The transformation from a three-phase model to a d-q model replaces the alternating variable with equivalent d-q axis variables that are constant [24, 25]. This simplifies the control of the system as tracking a constant reference is much simpler than an alternating reference, which experiences phase lag issues. However, as illustrated in Figure 3(b), in conventional VSCs, the d-q axis variables are coupled together by an inducer. The q-axis coupling component \((\omega L_{eq} I_{eq})\) is subtracted from the input voltage of the d-axis, and similarly, the d-axis coupling component \((\omega L_{eq} I_{eq})\) is added in the input voltage of q-axis. Thus, the change in the d-axis variable affects the q-axis variable and vice-versa. For a power converter operating under \( P_{ac} \) (active power) - \( Q_{ac} \) (reactive power) control, the coupling reflects as a coupling between \( P_{ac} \) and \( Q_{ac} \). Decoupling the two axes means eliminating the coupling effect of the inducer. Similarly, in the d-q based PI controller shown in Figure 3(a), the q-axis coupling component \((\omega L_{eq} I_{eq})\) is added in the controller output of d-axis, whereas the d-axis coupling component \((\omega L_{eq} I_{eq})\) is added in the controller output of q-axis.
subtracted from the controller output of the q-axis. The decoupling will result in an independent control d- and q-axes current and thus of \( P_d \) and \( Q_q \). Usually, the d-q based PI controller facilitates the power decoupling. However, the same is not evident in the MMC owing to the increased coupling between electrical quantities. A detailed analysis of the same is presented in the next section. Further, the performance of the controller is not as appropriate as is desired.

3  |  DETAILED MODELLING

For a more efficient controller to be developed, the internal dynamics of the MMC should be considered. An insight into this aspect has been provided in [11] and [23]. The relationship between the arm current and the SMC voltages is defined as

\[
S_{d,i} = C \frac{du_{di}}{dt} \quad \text{and} \quad S_{q,i} = C \frac{du_{qi}}{dt}
\]

The SMC voltage is a sum of the DC component and the AC ripples of the fundamental and harmonic components (4), ignoring the fourth- and higher-order harmonic ripples [7].

[4]

\[
u_c = \overline{v} + \sum_{k=1}^{\infty} \nu_{dk} \sin(k \omega t + \theta_k)
\]

\[
S_d = \frac{1}{2} V_{dc} - \frac{1}{2} V_{dc} M \sin(\omega t + \beta_f), \quad S_q = \frac{1}{2} V_{dc} - \frac{1}{2} V_{dc} M \sin(2\omega t + \beta_f) + v_{cir} \sin(2\omega t + \beta_c)
\]

Equation (5) defines the average switching function for the MMC, which includes (i) DC component, (ii) fundamental AC component, and (iii) 2nd-order harmonic component. The harmonic function is as a result of the auxiliary controller, which is intended to minimise the circulating current in the MMC arms by generating a reverse voltage ripple that nullifies the exiting one.

As mentioned in Section 2, the synthesis of voltage \( v_a \), which governs the current flow between the AC network and MMC, is a function of the upper and lower arm voltages. These arm voltages are a function of the number of SMs per arm, SMC voltage and arm switching function, as defined in (6).

\[
v_a = N \cdot S_a, \quad v_l = N \cdot S_l
\]

If the average switching function (5) and SMC voltage (4) are substituted in (6), the detailed expression for upper arm voltage is obtained as in (7), where \( v_{ndc} \) is a DC component, and \( v_{nk} \) is the \( k \)th component of the upper arm voltage, defined in (8). The expression for the lower arm voltage is similar to that for the upper arm voltage, with identical DC and even-order components. However, the odd-order components are of opposite polarity.

\[
v_a = v_{ndc} + v_{n2} + v_{n3} + v_{n4} + v_{n5}
\]

\[
v_{ndc} = \frac{N}{2} \overline{v} + \frac{N}{4} M \nu_{A1} \cos(\beta_f - \theta_1) + \frac{N \nu_{cir}}{2V_{dc}} \nu_{r2} \cos(\beta_c - \theta_2)
\]

\[
v_{n2} = -\frac{N}{2} M \nu_{A1} \sin(\omega t + \beta_f) - \frac{N}{4} M \nu_{A1} \cos(\omega t + \beta_2 - \beta_f)
\]

\[
v_{n3} = \frac{N \nu_{cir}}{2V_{dc}} \nu_{r3} \cos(\omega t + \beta_3 - \beta_f)
\]

\[
v_{n4} = \frac{N \nu_{cir}}{2V_{dc}} \nu_{r4} \cos(4\omega t + \beta_3 + \beta_1)
\]

\[
v_{n5} = \frac{N \nu_{cir}}{2V_{dc}} \nu_{r5} \cos(5\omega t + \beta_3 + \beta_1)
\]

Applying KVL in the MMC for the fundamental frequency current yields (9). Similarly, applying KVL for the 2nd-order circulating current yields (10) as follows:

\[
\frac{di}{dt} = \frac{1}{L_{eq}} (v_l + v_{n4} - R_{eq} i)
\]

\[
\frac{di_{cir}}{dt} = \frac{R_{arm} i_{cir}}{L_{arm}} - \frac{u_{n2}}{L_{arm}}
\]

Using (8), (9), and (10), the fundamental and circulating currents in the d-q coordinate can be obtained as follows:

\[
\frac{di_{al}}{dt} = -\omega L_{eq} + \frac{V_{al}}{L_{eq}} - \frac{R_{eq} i_{al}}{L_{eq}} - \frac{N V_{cir} \nu_{A1}}{2L_{eq}} V_{dc} + \frac{N \nu_{cir} \nu_{A2}}{2L_{eq}} V_{dc}
\]

\[
- \frac{NV_{cir} \nu_{A3} - NV_{cir} \nu_{A4}}{2L_{eq}} V_{dc} + \frac{N \nu_{cir} \nu_{A5}}{2L_{eq}} V_{dc}
\]
\[
\frac{dl_{id}}{dt} = \omega I_d + \frac{V_{id}}{L_{eq}} - I_{qd} - \frac{R_{arm}}{L_{arm}} I_{qd} - \frac{N_{uc1} V_{dc}}{2 I_{eq} V_{dc}} + \frac{N_{uc2} V_{dc}}{2 I_{eq} V_{dc}}
\]
\[
+ \frac{N_{uc3} V_{dc}}{2 I_{eq} V_{dc}} - \frac{N_{uc4} V_{dc}}{2 I_{eq} V_{dc}} - \frac{N_{uc5} V_{dc}}{2 I_{eq} V_{dc}} - \frac{N_{uc6} V_{dc}}{2 I_{eq} V_{dc}}
\]
\[
\frac{dl_{iq}}{dt} = -2 \omega I_q + \frac{R_{arm}}{L_{arm}} I_{iq} - \frac{N_{uc1} V_{dc}}{2 I_{eq} V_{dc}} + \frac{N_{uc2} V_{dc}}{2 I_{eq} V_{dc}} + \frac{N_{uc3} V_{dc}}{2 I_{eq} V_{dc}} + \frac{N_{uc4} V_{dc}}{2 I_{eq} V_{dc}}
\]
\[
+ \frac{N_{uc5} V_{dc}}{2 I_{eq} V_{dc}} - \frac{N_{uc6} V_{dc}}{2 I_{eq} V_{dc}} - \frac{N_{uc7} V_{dc}}{2 I_{eq} V_{dc}} - \frac{N_{uc8} V_{dc}}{2 I_{eq} V_{dc}}
\]
\[
\frac{dl_{iq}}{dt} = -2 \omega I_q + \frac{R_{arm}}{L_{arm}} I_{iq} - \frac{N_{uc1} V_{dc}}{2 I_{eq} V_{dc}} + \frac{N_{uc2} V_{dc}}{2 I_{eq} V_{dc}} + \frac{N_{uc3} V_{dc}}{2 I_{eq} V_{dc}} + \frac{N_{uc4} V_{dc}}{2 I_{eq} V_{dc}}
\]
\[
+ \frac{N_{uc5} V_{dc}}{2 I_{eq} V_{dc}} - \frac{N_{uc6} V_{dc}}{2 I_{eq} V_{dc}} - \frac{N_{uc7} V_{dc}}{2 I_{eq} V_{dc}} - \frac{N_{uc8} V_{dc}}{2 I_{eq} V_{dc}}
\]

where \( d-q \) variables can be defined as follows: \( I_d = I_1 \sin \alpha \), \( I_q = I_1 \cos \alpha \), \( I_{id} = I_2 \sin \alpha \), \( I_{iq} = I_2 \cos \alpha \), \( u_{1d} = u_1 \sin \theta_1 \), \( u_{1q} = u_1 \cos \theta_1 \), \( u_{2d} = u_2 \sin \theta_2 \), \( u_{2q} = u_2 \cos \theta_2 \), \( u_{3d} = u_3 \cos \theta_3 \), \( u_{3q} = u_3 \sin \theta_3 \), \( V_{dc} = \frac{1}{2} MV_{dc} \sin \beta_1 \), \( V_{q} = \frac{1}{2} MV_{dc} \cos \beta_1 \).

On the basis of (11) and (12), a detailed d-q model for the fundamental and circulating current of the MMC has been developed, as depicted in Figures 4(a) and 4(b), respectively. These models consider the voltage harmonic components up to the 3rd order. As mentioned previously, 3N capacitors of the MMC are distributed among its six arms. These capacitors facilitate the energy exchange between the AC and DC sides. Thus, the fundamental current \( I_{id}, I_{iq} \) and the DC side current \( I_d \) are mutually coupled through the SMCs. This results in a coupling between active power \( P_{ac} \), reactive power \( Q_{ac} \), and DC power \( P_{dc} \). Further, as expressed in Equations (6)–(8), the control signals for maintaining the desired fundamental and DC currents also generate 2nd- and higher-order frequency voltages, which in turn induce undesired circulating currents. These unwanted circulating current variables are mutually coupled with the fundamental and DC variables. These coupled three-phase variables are transformed into d-q coordinates using dynamic phasors. As is evident from Figure 4(a) and Equation (11), the d-q axis variables of the fundamental frequency current model are coupled through the inductor \( L_{eq} \) as well as the capacitor voltage component \( u_{2d} \). Similarly, as shown in Figure 4(b) and Equation (12), the d-q variable of the 2nd harmonic circulating current is coupled through the inductor \( L_{arm} \). Further, the input to the fundamental frequency current model \( (V_{id} \text{ and } V_{iq}) \), along with the circulating current model \( (V_{idq} \text{ and } V_{iqq}) \), interact with SMC voltage, and the result is added in the d-q axis of the circulating and fundamental current models, respectively. In summary, unlike in the conventional model shown in Figure 3, the detailed fundamental frequency current model exhibits two cross-couplings, whereas the initial model exhibits only one. The d- and q-axes are cross-coupled through the inductor \( L_{eq} \) as in the conventional model. An additional coupling is caused by the 2nd-order harmonic voltage ripple of SMC. Further, there exists an inter-coupling between fundamental and circulating current model, and both are linked through SMC voltage ripple. The fundamental and 2nd-order circulating voltages \( (\text{i.e. } V_{idq}, V_{idq} \text{ and } V_{idq}) \) interact with capacitor voltage ripples, and their outcome forms the inter-coupling component.

4 PROPOSED CONTROLLER

On the basis of the developed models, a new set of controllers has been derived, as follows: (i) Detailed, (ii) Mix and (iii) Simplified controllers.

In the design of a conventional controller (Figure 3a), the coupling effect of the inductor on the d-q axis variables of the current model is nullified by adding/subtracting the respective component in the controller. A similar philosophy has been applied to develop the proposed controllers. Further, the impact analysis of coupling components helps in simplifying the control structure.
The detailed model of the MMC includes cross- and inter-couplings, which were not considered in the conventional models. Further, the SMC voltage ripple up to the 3rd order has been included. Considering these factors, detailed primary and auxiliary controllers have been designed, as shown in Figures 5(a) and 5(b), respectively. When these two controllers operate in parallel, the combined structure is termed as the detailed controller.

The coupling effect of inductor $L_{pq}$ is reflected by subtraction of $\omega L_{pq}I_{pq}$ and addition of $\omega L_{pq}I_{d}$, respectively, in d- and q-axes of the fundamental frequency current model (Figure 4(a)). Similarly, the effect of inductor $L_{arm}$ in 2nd-order circulating current model (Figure 4(b)) is represented by the subtraction of $2\omega L_{arm}I_{arm}$ and addition of $2\omega L_{arm}I_{arm}$ in d- and q-axes, respectively. To nullify the coupling effect of the inductor, a similar term is included in the detailed controller. In Figure 5(a), $\omega L_{arm}I_{arm}$ is added, whereas $\omega L_{arm}I_{d}$ is subtracted from the PI controller output of d- and q-axes, respectively. Similarly, in Figure 5(b), $2\omega L_{arm}I_{arm}$ is added, whereas $2\omega L_{arm}I_{arm}$ is subtracted from d- and q-axes, respectively. The additional cross-coupling in the fundamental frequency current model is from the 2nd harmonic SMC voltage component $u_{2qg}$. As illustrated in Figure 4(a), $u_{2qg}V_{qg}$ is subtracted from the d-axis variable $-(2\pi f + u_{2dq})V_{ad}$, and similarly, $u_{2qg}V_{qd}$ is subtracted from the q-axis variable $-(2\pi f + u_{2dq})V_{qd}$. To nullify this cross-coupling effect in Figure 5(a), $u_{2qg}V_{qg}$ and $u_{2qg}V_{qd}$ are added in $V_{ad}$ and $V_{aq}$, respectively. As mentioned in the previous section, there also exists inter-coupling between the fundamental and circulating current model. The functions of the circulating current reference voltages $V_{cird}$ and $V_{cirq}$ and arm voltages ripples are added to the d- and q-axes of Figure 4(a). To nullify the effect of these inter-coupling components, the variables $V_{id}$ and $V_{iq}$ are included in the primary controller of Figure 5(a). $V_{id}$ and $V_{iq}$ are functions of the circulating current controller output $V_{cmd}$, $V_{cirq}$, and voltage ripples. Similarly, in the case of the circulating current model of Figure 4(b), the inter-coupling is a function of $V_{ad}$, $V_{aq}$, and the arm voltage ripples, and to nullify them, variables $V_{ad}$ and $V_{aq}$ are included in the circulating current controller, shown in Figure 5(b). These variables are a function of the primary controller outputs $V_{ad}$ and $V_{aq}$, and arm voltage ripples. The proposed set of detailed controllers aims to eliminate the cross-couplings due to inductors $L_{arm}$, $L_{arm}$ and SMC voltage component $u_{2qg}$, along with the inter-coupling between fundamental and circulating current models.

The detailed controller experiences increased circulating current and ripples in the DC. Therein, the magnitude of the inter-coupling signal from the primary to auxiliary controllers is significantly larger (approximately 10X) than the signal of the auxiliary controller. Even a small change for the primary controller is significantly large with respect to the auxiliary controller. Therefore, inter-coupling from the primary to auxiliary controllers affects the performance of the auxiliary controller adversely.

### 4.2 Mix controller

To eliminate the drawbacks of the detailed controller as well as minimise its complexity, a combination of the detailed primary (Figure 5a) and conventional auxiliary controllers (Figure 3d) has been applied. The new combination is termed as the mix controller, and it considers the cross-coupling of the d-q axis and inter-coupling from the circulating to the fundamental current models. However, the inter-coupling from the fundamental to the circulating current models has been ignored.

### 4.3 Simplified controller

As depicted in Figure 5(a), subtraction of the inter-coupling component $V_{id}$ from $V_{jp}$ yields $V_{qj}$. Similarly, on the q-axis, $V_{ip}$ and $V_{ip}$ yield $V_{aq}$. These two signals, $V_{ad}$ and $V_{aq}$, are further utilised to generate the final control command. To reduce the complexity, the inter-coupling for the mix controller has been analysed. The system under analysis was initially operating at 400 MW and 0 MVAR. At 0.04 s, the active power is increased by 50 MW. Initially, under steady-state, the inter-coupling component $V_{id}$ is 2% of $V_{dp}$ and on the q-axis, $V_{aq}$ is less than 1% of $V_{dp}$. Further, under the transient condition, when the active power has been raised by 50 MW, the ratios attain maximum values of 2.5% and 1%, respectively. Figure 6 presents the ratio of the d- and q-axes components, respectively. $d_{ratio}$ and $q_{ratio}$ can be...
Because the inter-coupling components are very small and have no significant impact on the overall performance of the controller, they have been removed, which yields the simplified structure shown in Figure 7. For the circulating current control, the conventional auxiliary controller has been implemented. The combined set is termed as a simplified controller that considers the additional cross-coupling between the d-q axis while entirely ignoring the inter-couplings.

5 RESULTS AND DISCUSSION

The performance of the controllers was analysed on the real-time digital simulator (RTDS). The MMCs under observation are designed for 500 MVA, 166 KV line-to-line AC voltage, and 320 kV line-to-line DC voltages. The three MMCs, identical to each other in all aspects except the controller, have been designed and operated simultaneously. All the three controllers; conventional, detailed, and simplified, have identical values of the PI parameters. Figure 8 presents the performance comparison of the controllers. Plots for the conventional controller are represented using dashed lines. Dash-dot lines represent the detailed controller, whereas the simplified controller is represented using solid lines. Plots of the mix controller are excluded, as they overlap with those of the simplified controller. For analysis, the following three case scenarios have been considered: (i) base case, (ii) change in active power, and (iii) change in reactive power.

5.1 Base case

The base case primarily involves the steady-state performance analysis of the controllers. The operating conditions are set to \( P_{ac} = 400 \text{ MW} \) and \( Q_{ac} = 0 \text{ MVar} \) with rated AC and DC terminal voltages. Figure 8(a) represents the base case operation. The \( P_{dc} \) and \( Q_{dc} \) plots indicate that three controllers can maintain the reference active and reactive power as well as rated DC voltage. The \( I_{dc} \) represents the current flow over the DC line. With constant DC voltage, this also results in a snapshot of DC power flow. In the case of the detailed controller, \( I_{dc} \) contains oscillating components which lead to DC power oscillation. The conventional as well as simplified controllers therefore do not experience this drawback. \( I_{d} \) and \( I_{q} \) are the d-q components of the circulating current. Their plot verifies that all three controller sets successfully eliminate the 2nd-order circulating current. The plot for \( I_{d} \) is the DC component of the SMC voltage. However, as depicted in the plots, it also involves oscillations. The oscillations are relatively very high in the case of the detailed controller, whereas they are of a significantly low magnitude in the case of the simplified and conventional controllers. Further, the average DC voltage of the simplified controller is slightly lesser than that of the conventional controller, which can reduce the stress on the SMC. In terms of fundamental frequency ripple of the SMC voltage (i.e. \( n_{d1} \) and \( n_{q1} \)), the detailed controller achieves poor performance, whereas the simplified controller achieves a slightly higher value of the d-component than that achieved by the conventional controllers. For \( n_{d1} \), the conventional and simplified controllers lead to an almost constant value, with the simplified controller having a slightly higher value. However, the detailed controller leads to sustained oscillations. For \( n_{q1} \), the detailed controller also shows sustained oscillations, whereas the results from the simplified and conventional controllers are almost constant and overlapping.

In summary, for steady-state operation, the performance of the simplified controller is as good as that of the conventional controller, even slightly better in terms of the SMC voltage. However, the detailed controller achieves a poor performance as it introduces ripples in the DC current, DC power, and SMC voltage. In terms of internal dynamics, the performance of the simplified controller is equivalent to that of the conventional controller.

5.2 Change in active power

Figure 8(b) presents the transient case scenario for the performance comparison of the controllers. Initially, the MMCs were operating under base case values (i.e. \( P_{ac} = 400 \text{ MW} \), \( Q_{ac} = 0 \text{ MVar} \), \( V_{dc} = 400 \text{ kV} \), \( V_{ac} = 166 \text{ kV} \)).
FIGURE 8  Result for (a) base case $P_a = 400$ MW and $Q_a = 0$ MVAR. (b) Change in active power from 400 to 450 MW. (c) Change in reactive power from 0 to 50 MVAR.

0 MVAR and rated voltages). At the time instant 0.04 s, the active power reference is changed by 50 MW. All the controllers responded relatively similarly in terms of active power flow. The active power flow achieves the new reference almost instantly and settles quickly to the final value. The overshoot (in the zoomed section) is maximum for the detailed controller (i.e. 14 MW) and minimum for conventional controller (i.e. 7 MW). For the simplified controller, it is 11.5 MW, which is in between the values for the other two controllers. However, the simplified controller attains an almost stable reference value, slightly before the conventional controller. In contrast, the detailed controller takes the longest duration and leads to sustained oscillation, although of minimal magnitude. The impact on reactive power is significantly different. At the instant of change, all the three controllers lead to overshoot, as in case of active power flow. However, the reactive power exchange reduces to a near-zero value in 15–20 ms, and attains zero value over time, for the proposed controllers. Meanwhile, in the case of conventional controller, the reactive power exchange is sustained at significantly higher values for a longer period. In other words, the proposed controllers achieve better decoupling than the conventional controller. The DC current plots present a
similar observation for the transient case as in the base case. The detailed controller achieves a higher overshoot as well as oscillations, whereas the conventional controller achieves lower overshoot values and attains a steady value at a significantly faster rate. At the transient instant, the simplified controller traces the path of the conventional controller but takes a few extra milliseconds to settle. For the 1st oscillation, the magnitude and time-period for the simplified controller are identical to those of the conventional controller. However, in successive cycles, the time-period of the oscillations increases gradually for the simplified controller with respect to the conventional controller. Additionally, the decay of oscillation amplitude is slower for the simplified controller than for the conventional controller. The detailed controller exhibits the highest magnitude of oscillation as well as takes the longest duration in attaining the steady-state value.

The terminal DC voltage experiences a sudden change in values and oscillations, as a result of power redistribution among the SMCs. The very low magnitude oscillation is sustained for a while and dies out over time. Here, the detailed controller also exhibits the highest magnitude of oscillation with respect to the other two controllers. The power redistribution increases the circulating current between the arms, and the same is reflected by \( I_{dcl} \) and \( I_{dgy} \). These variables attain relatively high values with the detailed controller and take a significantly longer duration to be eliminated than in the cases of the other two controllers. As presented in \( I_{dcl} \) plot, the conventional and simplified controllers track the same path up to the second cycle. Thereafter, the conventional controller attains a relatively constant value, whereas the simplified controller exhibits small magnitude oscillations for a few more cycles before attaining a steady-state band. For \( I_{dgy} \), both the conventional and simplified controllers trace the same path and settle in an equal duration.

In terms of ripples in the DC component of the SMC voltage, the performance of the simplified controller is intermediate. However, the magnitude of the oscillation for the simplified controller is slightly greater than that for the conventional controller, whereas it is significantly lower than that for the detailed controller. In terms of average values, it outperforms both counterparts and yields slightly lower values than those of the other two controllers; thus, the voltage strain of the SMC is reduced more efficiently than in its alternative. Similarly, for the fundamental component (\( u_{k1d} \) and \( u_{k1q} \)), the values of the simplified controller are also better than those of the detailed controller, whereas they are slightly poorer than those of the conventional controller. The conventional controller attains a relatively constant value after four oscillations, and the signals from all the three controllers overlap for the first oscillation. However, the time-period for the simplified and detailed controllers increases gradually. The magnitude of oscillation for the simplified controller is lower than that for the detailed controller, and it also decays at a significantly higher rate.

In summary, under transient conditions, the simplified controller achieves better decoupling than the conventional controller while avoiding high ripples in variables as in the case of the detailed controller.

### 5.3 Change in reactive power

Another test for the transient scenario is performed by varying the reactive power support from the MMC to the AC grid. Figure 8(c) presents the plots for the controller performance. The MMCs are reset to the base case operating conditions with 400 MW active power flow and 0 MVar reactive power support. At 0.04 s, the reactive power support from the MMCs was increased to 50 MVar. As presented in the reactive power plots, all three controllers efficiently achieve their primary objective of charging \( Q_{ac} \) support. As shown in the zoomed box, the overshoot is 7.5 MVar for the conventional controller and is 8.8 MVar for the other two controllers. As the difference is just 1.3 MVar for change in 50 MVar, none of the controllers exhibit any significant advantage over the others in terms of the overshoot. In terms of attaining the constant reference value, the simplified controller outperforms the other two, as it settles earlier than the other two controllers. Further, similar to the previous test case, the simplified controller achieves better decoupling, as can be observed from the active power plots. At the change in \( Q_{ac} \) reference, all the three controllers experience a sudden overshoot in active power. Nevertheless, the simplified controllers re-attain a value in ±2 MW band across the reference of 400 MW within 20 ms, whereas the other two controllers take a significantly longer time period and oscillations.

In terms of the DC current and terminal voltage, the performances of all the three controllers are more are less similar. All three lead to ripples in the DC current, which settles the earliest in the case of the conventional controller, whereas the simplified and detailed controllers have a higher magnitude of the slower decay rate of oscillation. Ripples in the DC voltage are negligible for all the three MMCs. Re-distribution of power among SMCs causes the circulating current as is presented in the circulating current plots. The magnitudes of ripples are higher for the detailed controller. At the transient instant, the d-axis circulating current experiences a high magnitude spike for the detailed controller, which is followed by gradually decaying oscillations. \( I_{ord} \) plot for the simplified and conventional controllers traces the same path and are free from any spikes. For q-axis circulating current, all the three controllers lead to oscillations of very small magnitudes, which die out gradually. The time taken to eliminate them is relatively equal for all the three controllers. The simplified controller, which achieves relatively better performance in reducing the SMC voltage stress in the previous two test cases, does not provide any significant advantage under reactive power change transients. All the three controllers lead to oscillations in the DC as well as fundamental components of the SMC voltage. The average values of voltage parameters are similar for all the three MMCs. The signals from the conventional controller attain a relatively constant value, faster than the others. The magnitude of oscillation for the simplified and detailed controller are nearly equal.

In summary, under the transient conditions, owing to change in the reactive power, the simplified controller facilitates better decoupling than that in the case of the other two alternatives.
In terms of circulating current, its performance is better than that of the detailed controller but is equivalent to that of the conventional controller.

5.4 Discussion

The conventional model of the MMC ignores the inter- and cross-couplings, as has been presented in the detailed modelling. Thus, the controllers based on the conventional model inherently cannot handle the increased coupling. The proposed detailed controller includes additional cross- (between d-q axis) and inter-couplings (between primary and auxiliary controllers) components. Consideration of the additional d-q axis cross-coupling improves the decoupling. On the contrary, the consideration of inter-coupling leads to increased circulating current and DC current ripples. Further, inter-coupling signals from the primary controller affect the auxiliary controller adversely, as even a small change in the primary controller is significantly large with respect to the auxiliary controller. This drawback has, however, been eliminated in the mix controller.

In the mix controller, the detailed auxiliary controller is replaced by the conventional auxiliary controller. Thus, it basically ignores the inter-coupling from the fundamental current model to the circulating current model while maintaining inter-coupling from the auxiliary to primary controllers. Further, as presented in Figure 6, with mix architecture, the contributions of inter-couplings from the auxiliary to primary controller is negligible and thus, has been removed to yield a simplified version. The plots for the mix controller are identical to those of the simplified controller and are therefore omitted for simplicity. Excluding primary to auxiliary inter-coupling reduces the oscillation and excluding auxiliary to primary controllers minimises the complexity. Thus, the final version considers cross-coupling only, which is significantly simpler than the detailed controller. In terms of decoupling (active and reactive power), detailed and simplified controllers achieve better performance than the conventional controller. However, as mentioned above, the detailed controller experiences increased circulating current and DC current ripples. Meanwhile, the simplified controller is free from those drawbacks. Thus, the simplified controller outperforms all the other controllers. However, a relatively higher magnitude and a slow rate of decay of oscillations in the arm variable can be observed as limitations of the simplified controller in comparison to the conventional controller. Further, the presented work can be extended to consider the unbalanced grid conditions.

6 Conclusion

The modular structure of the MMC presents several advantages over the other converter topologies. However, the modular approach leads to complexities in modelling and operations. Because the MMC is a converter topology, the most common approach involves consideration of the conventional converter model for designing the controller. Thus, the conventional control structure is obtained.

In this study, we develop a detailed d-q model of the fundamental and circulating current of the MMC. The developed model includes cross-coupling of the d-q axis in the fundamental current model and inter-coupling between the fundamental and circulating current models. On the basis of the detailed model, we propose three controllers. First, a set of detailed primary and auxiliary controller models considers all inter- and cross-couplings. Next, a mix controller is derived using the detailed primary and conventional auxiliary controllers. This control structure considers all couplings except primary to auxiliary inter-coupling. If the remaining inter-coupling is excluded, a simplified version is yielded that considers only cross-couplings. In the detailed controller, inter-coupling from the primary to the auxiliary controller leads to oscillations. In the mix controller, inter-coupling from the auxiliary to the primary controllers presents no significant advantage owing to its relatively small magnitude. MMC models and controllers are simulated on RTDS for the steady state as well as the transient state. Changes in active and reactive powers are the two transient scenarios considered. Here, the comparative performance analysis reveals that all proposed controllers outperform the conventional controller in terms of decoupling the active and reactive powers. However, the detailed controller leads to oscillations owing to inter-coupling between the primary and auxiliary controllers. The simplified controller is, however, free from this drawback. Apart from exhibiting improved decoupling, the proposed simplified controller also reduces the voltage stress of SM capacitors.

NOMENCLATURE

- $N$: Number of submodules
- $V_{dc}$: DC voltage
- $v_{uj}$: Phase voltages ($j \in \{a, b, c\}$)
- $i_{uj}$: Fundamental frequency component of AC phase currents ($j \in \{a, b, c\}$)
- $v_{cj}$: Fundamental frequency phase voltages at arm inductor ends ($j \in \{a, b, c\}$)
- $I_{ct}$: converter transformer inductance
- $L_{arm}$: arm inductance
- $R_{arm}$: arm resistance
- $v_{aj}$: upper arm voltages of phase ‘$a$’
- $v_{bj}$: lower arm voltages ‘$b$’
- $S_{aj}$: upper and lower arm average switching function
- $u_{aj}$: upper and lower arm SM’s capacitor voltage
- $i_{aj}$: upper and lower arm current
- $I_{dc}$: DC current
- $i_{cir}$: circulating current
- $\alpha_s$: phase angle of fundamental current
- $\alpha_c$: phase angle of circulating current
- $\bar{V}_c$: DC component of SM’s capacitor voltage
- $\mu_{ck}$: magnitude of $k^{th}$ order AC ripple of SM’s capacitor voltage
- $\theta_k$: angle of $k^{th}$ order AC ripple of SM’s capacitor voltage
- $\hat{M}$: modulation index
- $\phi_f$: phase angle of fundamental current controller output
- $v_{cir}$: magnitude of circulating current controller output
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