Variable Slope Trapezoidal Circulating Current Injection to Attenuate Capacitor Voltage Ripple in Modular Multilevel Converter Based Variable Speed Motor Drives Application

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Abstract—The main challenge in using the Modular Multilevel Converter-based constant-torque variable-speed motor drives is increased sub-module capacitor voltage ripples (SM-CVR) at low-fundamental frequency operation due to the inverse relationship between SM-CVR and operating frequency. A variable slope trapezoidal circulating current (CC) is injected with square wave common-mode voltage (CMV) to address the increase in the SM-CVR issue. Compared to sinusoidal CC and sinusoidal CMV injection, the proposed injection technique can reduce the peak of the CC in the range of 0% to 50%, resulting in lesser device stress and improved efficiency. Simulation results of the proposed technique are presented, and they are further compared with the existing injection techniques to show the superiority.

Index Terms—Modular Multilevel Converter, Variable Speed Motor Drives, Capacitor Voltage Balancing, Capacitor Voltage Ripple Reduction.

I. INTRODUCTION

In recent years, modular multilevel converters (MMCs) have been trending in medium and high power applications due to their commendable features: modularity, scalability, fault-tolerant operation, better harmonic profile [1]. These traits fascinated researchers to employ MMC for various applications. The first MMC was proposed by Marquardt et al. [2] for high voltage direct current (HVDC) transmission, and later it was investigated for other applications such as medium voltage motor drives, power quality improvement, and renewable integration [1]. Also, current research is inclined towards extending these applications to electric vehicles [3], electric ships [4], and railway traction systems [5].

One of the leading technical challenges in the MMC-based adjustable speed motor drives at constant-torque low-speed operation is the increased magnitude of sub-module (SM) capacitor voltage ripple (CVR). This is due to the inverse dependence of SM-CVR on the fundamental frequency of the MMC, and this leads to increased rating values of the converter elements and affects stability [6]. Due to this, the use of MMC in variable-speed motor drives is still limited.

Over the years, various researchers have proposed different techniques in the literature to address the issue of increased SM-CVR during low fundamental frequency operation [7]. One of the first control techniques proposed is the injection of high-frequency common-mode voltage (CMV) and circulating current (CC) of various shapes to attenuate the CVR. An injection scheme based on sinusoidal CMV and CC was first presented in [9]. In [8], it was shown that the peak of CC increases in MMC with respect to speed. Since injections are required mainly at low-frequency operation, tapering-off was presented for injections in [9]. In [8], sinusoidal CMV and CC injection reflect increased device voltage and current ratings.

Two new injection methods were proposed in [6] to address this problem, where method 1 used square wave CMV and sinusoidal CC. On the other hand, method 2 used square wave...
CMV, and third harmonic injected sinusoidal CC to reduce the peak of CC to a certain level. A scheme based on square wave CMV and CC injection was presented in [10] to further reduce the peak of CC. But this technique is not scalable because a square wave CC reflects the enormous magnitude of the voltage across the arm inductor at its discontinuous points, which might pose control issues [6]. Furthermore, in [11], to reduce the peak of injected CC, a relaxation on CVR is allowed instead of stringent conditions to make it to zero.

The second approach presented in the literature to tackle increased SM-CVR during low fundamental frequency operation uses power channels between upper arm SMs and lower arm SMs [13] and between three phases in Y-connected fashion [14]. Alternatively, the third approach includes a modified operation of the MMC with variable DC-link voltage to reduce the SM-CVR. In [15], the DC-link voltage is regulated using a chopper switch. Another approach was presented in [16] to control the DC-link of MMC using the back-to-back (BTB) configuration. However, the BTB configuration of MMC increases cost, size, and control complexity.

This paper proposes a variable slope trapezoidal CC to reduce the peak value of CC injected. The main advantage of the proposed scheme is, using variable slope parameter $d$, the CC peak value is adjusted. Further, this paper is organized as follows; section II gives the basic understanding of MMC. Section III discusses CVR inverse dependency on the fundamental-frequency and injection techniques to address the increased SM-CVR during low-frequency operation. In section IV, results were presented to verify the proposed technique. Finally, section V concludes the presented paper.

II. MODULAR MULTILEVEL CONVERTER

The three-phase configuration of MMC shown in Fig. 1 consists of three legs and each leg consists of two arms termed as upper arm $(u)$ and lower arm $(l)$ respectively. Each arm of MMC contains $N$ number of half-bridge (HB) SMs connected in series (to get $N+1$ levels in the output voltage) along with an arm inductance $(L)$ which has a coil resistance $(r)$. In the HB-SMs [See Fig.1b.], when $S_1$ is ON ($\overline{S}_1$ is OFF), current flows through SM capacitor, it means SM is inserted and SM voltage is $V_{C,sm}$. Similarly, when $\overline{S}_1$ is ON ($S_1$ is OFF), the current will not flow through the SM capacitor, which means that the SM is bypassed. In Fig. 2, the per-phase equivalent circuit for MMC is given and $V_{dc}, I_{dc}, v_{xs}$, and $i_{xs}$ are the DC link voltage, DC link current, output phase voltage, and line current respectively, where $x \in \{a, b, c\}$ represents the phase. Similarly, the arm quantities are expressed by $i_{xy}$ and $v_{xy}$, where $y \in \{u, l\}$ represents an arm.

Applying Kirchhoff’s voltage law to the equivalent circuit of per phase MMC in Fig. 2, and assuming that the voltage drops across $r, L$ are negligible, the following equations are obtained.

$$V_{dc} = v_{xu} + v_{xl}$$

$$v_{xs} = \frac{-v_{xu} + v_{xl}}{2}$$

Similarly, applying Kirchhoff’s current law expressions for circulating current ($i_{xd}$) and output current ($i_{xs}$) of phase $x$ are obtained and given by,

$$i_{xd} = \frac{i_{xu} + i_{xl}}{2}$$

$$i_{xs} = i_{xu} + i_{xl}$$

In equations 1 and 2, for a sinusoidal pulse with modulation (PWM), the modulating signal, output current, and circulating currents are defined as [12]

$$v_{xs} = m_a \cdot \frac{V_{dc}}{2} \cdot \sin(\omega t)$$

$$i_{xs} = I \cdot \sin(\omega t - \phi)$$

$$i_{xd} = \frac{v_{xs} \cdot i_{xs}}{V_{dc}}$$

Where $m_a$ is modulation index ranges from 0 to 1, $\phi$ is the initial power factor angle, $\omega$ is the system output frequency in rad/sec, and $I$ is the peak value of the output line current.

III. CAPACITOR VOLTAGE RIPPLE

The arm voltage and current cause power fluctuations, leading to the SM capacitor voltage ripple. The energy stored in a single SM is given by

$$E_{xy}(t) = \int p_{xy} dt + E_{xy}(0)$$

$$E_{xyh}(t) = \frac{E_{xy}(t)}{N}$$

Where $E_{xy}(t)$ is energy stored in the arm, $E_{xyh}(t)$ is the energy stored in a single SM, and $h$ is the sub-module index number. Upon substituting equation 1 to 3 in equation 4 the final expression for change in energy fluctuations given by [12],

$$\Delta E_{xyh} = \frac{1}{4Nf_s} V_{dc} I (e_{max} - e_{min})$$
Where $e_{max}$ and $e_{min}$ are the maximum and minimum values of the function $e$, given by

$$
e = \frac{f_s^2 - f_{sr}^2}{4\pi f_{sr}^2} \cos (2\pi f_s t - \phi) + \frac{f_s^2}{8\pi f_{sr}^2} \cos (2\pi f_s t + \phi) + \frac{f_s^2}{24\pi f_{sr}^2} \cos (6\pi f_s t - \phi)$$

(6)

where $f_s$ and $f_{sr}$ are the operating and rated frequencies. Further, change in SM energy is also given by,

$$\Delta E_{xyh} = \frac{1}{2} C_{sm}(V_c + \Delta v_{Cyh})^2 - \frac{1}{2} C_{sm}(V_c - \Delta v_{Cyh})^2$$

(7)

By equating equations 5 and 7, the final expression for CVR expression is derived as,

$$\Delta v_{Cyh} = \frac{I}{8C_{sm} f_s} (e_{max} - e_{min})$$

(8)

The interpretation of (8) is that CVR of SM a has direct dependency on load current and inverse dependency on the operating frequency. As a result, under constant-torque low-fundamental frequency operation CVR is magnified.

### A. Injection of high-frequency common mode voltage and circulating current

Injection of high-frequency CMV and CC is a possible solution to attenuate the CVR. It is possible to use various shapes of CMV and CC waveform injections like sine, square, and third harmonic [7]. The modified arm voltages and currents after injections are given as,

$$v_{xu} = \frac{V_{dc}}{2} - v_{xs} - v_{xh}$$

(9)

$$v_{xl} = \frac{V_{dc}}{2} + v_{xs} + v_{xh}$$

$$i_{xu} = \frac{i_{xs}}{2} + i_{xd} + i_{xh}$$

(10)

$$i_{xl} = -\frac{i_{xs}}{2} + i_{xd} + i_{xh}$$

The power fluctuations in individual SM after high frequency injections can be obtained as,

$$p_{xyh} = \frac{1}{N} (0.5V_{dc}i_{xz} - 0.5v_{xs}i_{xz}) + \frac{1}{N} (0.25V_{dc}i_{xz} - v_{xs}i_{xz}$$

(11)

$$- v_{xh}i_{xh}) + \frac{1}{N} (0.5V_{dc}i_{xh} - v_{xs}i_{xh} - v_{xh}i_{xh}$$

$$- 0.5v_{xh}i_{xh})$$

In equation 11, term 1 is zero at the steady state condition since the output power is equals to the input power. Also term 2 should become zero to attenuate ripple power by means of high-frequency injections. So, equating term 2 to zero yields,

$$v_{xh}i_{xh} = 0.25V_{dc}i_{xz} - v_{xs}i_{xz}$$

(12)

Further simplifying the equation 12 yields expressions for $V_h$ and $I_h$ as,

$$V_h = V_{dc}(1 - m_a)$$

(13)

$$I_h = k \cdot k_c \cdot \frac{0.25V_{dc}i_{xz} - v_{xs}i_{xz}}{V_h}$$

where, $V_h$ and $I_h$ are the peak values of the high-frequency CMV and CC respectively, $k_c$ is the control variable used to limit the CC injection at higher $m_a$ and $k$ is the scaling factor. In equation 13, the peak of injected CMV is chosen to depend on the operating modulation index. This is to ensure better utilization of the total voltage blocking capacity of the arm. Likewise, the peak of CC injected depends on $V_h$ and $k$. Based on the shape of the injection waveform selected for CMV and CC, different values of $k$ are presented in Table I, and it is clear that the peak of $I_h$ is minimum for technique 3. However, technique 3 is not feasible in practice due to increased voltage drop across the arm inductor for square wave CC [6]. A variable slope trapezoidal CC technique is presented in the following subsection to address the mentioned problem. Meanwhile, A detailed analysis of the low-frequency operation of MMC and injection techniques is presented in [12] and [6].

### B. Variable slope trapezoidal CC and square wave CMV injection

A variable slope trapezoidal CC is shown in Fig. 3, where $d$ is the variable slope parameter. The relation between the scaling parameter $k$ and $d$ is derived in this subsection. From equation 12, the amount of average power delivered by high-frequency components over a cycle is given by,
TABLE II
MMC AND MOTOR PARAMETERS

| MMC rating | SI Unit |
|------------|---------|
| Output power ($P_o$) | 1 MW |
| DC link voltage ($V_{dc}$) | 7 kV |
| Number of SMs (N) | 20 |
| Initial Capacitor voltage ($V_c$) | 350 V |
| Operating frequency ($f_o$) | 0-60 Hz |
| Carrier frequency ($f_{sw}$) | 500 Hz |
| Arm inductance ($L_{arm}$) | 1 mH |
| Arm resistance ($R_{arm}$) | 0.1 |
| SM capacitance ($C_{sm}$) | 8 mF |

| Motor Ratings | SI unit |
|---------------|---------|
| Output power ($P_s$) | 1250 hp |
| Line voltage ($V_s$) | 4160 V |
| Stator current ($I_s$) | 150 A (rms) |
| Rated speed ($N_r$) | 1189 rpm |
| Rated torque ($T_e$) | 7490 N-m |
| Number of pole pairs(p) | 3 |

\[
P_{hf} = \frac{4}{T_s} \int_0^{T_s} v_{xh} i_{xh} \cdot dt
= \frac{4}{T_s} \left[ \int_0^{t_1} v_{xh} i_{xh} \cdot dt + \int_{t_1}^{T_s} v_{xh} i_{xh} \cdot dt \right]
= \frac{4}{T_s} \left[ \int_0^{t_1} V_h I_h \frac{t}{4} \cdot dt + \int_{t_1}^{T_s} V_h I_h \cdot dt \right]
= V_h \cdot I_h \cdot (1 - 0.5d)
\]

Looking at equations 13 and 14, expression for $k$ is obtained as,

\[
k = \frac{1}{(1 - 0.5d)}; \quad 0 \leq d \leq 1
\]

If the $d$ is zero, the trapezoid becomes the square, and $k$ has value 1. If the $d$ is 1, then the trapezoid becomes the triangle, and $k$ has a value of 2. Visualization of equation 15, which is $k$ control using the variable slope parameter $d$, is shown in Fig. 9. From Fig. 9, it is always preferred to have a lower $k$ value to have a lower peak value of CC. This proposed injection technique’s advantage is that it can take the peak CC value between technique 1 and technique 3 by varying slope parameter $d$. On the other hand, to avoid the CC discontinuity, thereby limiting the voltage across the arm inductor, the minimum value of $d_{min}$ is limited to 0.04.

IV. RESULTS AND DISCUSSION

The effectiveness of the proposed injection technique is verified through simulation, using MATLAB/Simulink, with the parameters given in Table II [12].

The MMC is connected to a 7 kV dc source and a 1250 hp induction motor(IM) on the load side. Visualization of Eq. 8 and validation of it using simulations for the system in Table II is shown in Fig. 4. In Fig. 4, the variation of CVR
in percentage with respect to operating frequency is shown. The curve indicates that CVR increases as the operating frequency decreases, proving the inverse dependence of CVR on operating frequency [See Eq. 8].

The simulated output waveforms of MMC-based IM drive without injections at 100% motor speed, and 40% rated load torque are shown in Fig. 5. Fig. 5.a shows corresponding line currents flowing into the induction motor, and the peak value of line currents is 100A at 40% of rated load torque. Fig. 5.b shows the upper arm and lower arm voltages of phase-α. Both the upper and lower arm SM capacitor voltages are balanced but fluctuate around 350 V with the ripple value of 17.5 V, which ensures good performance. Fig. 5.c shows CVR for both upper and lower arms for change in motor speed from 100% to 16.6% of the rated speed and at 40% rated load torque. It is observed that CVR increases as the motor speed decreases and settles at 129.75 V, which is 7.4 times higher than that at the rated speed. The increased CVR affects the system reliability, and therefore high-frequency CMV and CC were injected to attenuate the increase in capacitor voltage ripple. The results are shown in Fig. 6 and Fig. 7.

In Fig. 6.a, Injections were disabled intentionally during the transition of motor speed from rated speed to 16.6% of the rated speed. On the other hand, during motor speed transition, CVR increases from 17.5 V to 129.75 V. At \( t = 3.6 \) seconds, square wave CMV and sinusoidal CC (Technique 2) are injected to attenuate the CVR, and this injection effectively attenuates the CVR to tolerable limits, which shows the effectiveness of the injected scheme. The CC and arm current waveforms for technique 2 are shown in Fig. 6.b, and the peak values of arm current and injected CC are 138.5 A and 72.5 A, respectively. Now, with the proposed injection technique, \( d \) is adjusted to 0.2, and the results for the same are presented in Fig. 7. In Fig. 7.a, capacitor voltage ripple increases from 17.5 V to 129.75 V during the transition of motor speed from rated speed.
speed to 16.6% of rated speed. At $t = 3.6$ seconds injected the square wave CMV and proposed CC, which attenuates the CVR to tolerable limits like technique 2. However, the advantage of the proposed technique is shown in Fig. 7.b. In Fig. 7.b, arm current and injected CC have a peak value of 123.8 A and 56.5 A. In a fair comparison between proposed technique and technique 2, technique 2 injects peak CC of 72.5 A, and the proposed approach injects peak CC of 56.5 A, while both were successfully attenuating the CVR to the same limits. The difference in the peak of injected CC conveys that the proposed scheme requires devices with lesser ratings to fulfill the given design constraint.

For the proposed scheme, the dynamic variation of $d$ at 16% rated speed and 40% rated load is shown in Fig. 8. Here, currents settle after $d$ change in less than 0.25 seconds. It is visible that as the $d$ increases in steps, the peak of CC increases (i.e., $I_h$) while having CVR in limits, which is consistent with Eq. 13 and Eq. 15. Furthermore, The relation between $d$, $k$ and $I_h$ are shown in Fig. 9. In Fig. 9, the simulated variation of $I_h$ validates with the theoretical variation of $I_h$. The difference around 2 A in simulated and theoretical values of $I_h$ is due to simplifying assumptions made in theoretical calculations.

V. CONCLUSION

In this paper, a new injection technique is proposed to attenuate the SM CVR of MMC-based constant-torque variable-speed motor drive. The proposed strategy is based on square wave CMV and variable slope trapezoidal CC injection to reduce the SM CVR effectively. An expression relating the variable slope parameter $d$ and scaling factor $k$ is derived for the proposed technique. The significant advantage of the proposed technique is that it significantly increases the efficiency by reducing the conduction losses and device current ratings of the overall drive system. The ability to achieve techniques 2 and 3 [See Table I] in terms of the peak of CC injected by varying $d$ is another advantage of the proposed scheme. The superiority in the performance of the proposed scheme is verified through extensive simulation studies.

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