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Submodule Voltage Estimation Scheme in Modular Multilevel Converters with Reduced Voltage Sensors Based on Kalman Filter Approach

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Abstract— This paper presents a new voltage estimation method for the submodule (SM) capacitor in a modular multilevel converter (MMC). The proposed method employs a Kalman filter (KF) algorithm to estimate the SM voltages of the converter. Compared with sensor-based methods, this scheme requires only one voltage sensor to achieve the voltage-balancing of the converter. This sensor is connected to the total arm voltage; the proposed algorithm requires also the switching patterns of each upper SM switch which are provided by the controller used without the need for extra sensors. The substantial reduction in the number of voltage sensors improves the system reliability and decreases its cost and complexity. Extensive simulation and experimental analyses carried out to validate the proposed estimation scheme under different conditions include steady-state analyses, the effect of variations in capacitance and inductance, of the impact of low carrier and effective switching frequency on the accuracy of the estimation, step changes to the load, and a range changes in DC voltage. The results obtained are experimentally verified using a single-phase MMC.

Index Terms— Modular multilevel converter (MMC); capacitor voltage estimation; Kalman filter (KF); reduced number of sensors; voltage-balancing control; pulse width modulation (PWM).

I. INTRODUCTION

Since the modular multilevel converter (MMC) was introduced in 2003 [1] it has become a competitive candidate for many medium and high power applications. In comparison with conventional multilevel converters, MMCs are characterized by low switching losses due to the low switching operating frequency required, flexibility [2], and low harmonic distortion which allows the use of smaller filters. MMCs have been proven to be suitable for different applications such as electrical vehicles, variable speed drives, high-voltage direct current systems (HVDC), battery storage systems (BSSs), DC-DC power conversion and flexible AC transmission systems (FACTSs) [3, 4].

On the other hand, as with most conventional converters, the MMC has specific control requirements. For instance, the voltage-balancing of the submodule (SM) capacitors in the converter is critical. However, due to the series of cascaded SMs which are used to construct the converter, the reliability of the MMC is an important challenge [5]. In one example of a real application based on the MMC is presented in [6], where hundreds of SMs per leg were used. This also requires a great many voltage sensors in order to achieve the voltage-balancing of the system. This problem has been extensively investigated in recent research [3, 7]; but many voltage sensors are always used in such studies. However, it would be preferable if this issue could be resolved with lower cost and complexity.

Several proposals have been attempted to minimise the number of voltage and current sensors required. For instance, successful simulation and practical results have been achieved with fewer current sensors [8-10]. However, no reductions in voltage sensor number were discussed in those studies. Another attempt based on an open-loop scheme has been suggested, where fixed PWM signals were applied to the converter [11]. Although, this proposed scheme does not use any sensors since it does not require any form of feedback control, the well-known disadvantages of open-loop control schemes may threaten the performance of the system. In some recent studies, online observers have been introduced to estimate individual SM voltages [12, 13]. For example, fewer voltage sensors could be achieved based on a sliding mode where the proposed method merely monitors the total input voltage and arm current of the converter [12]. This technique has been proposed for fault detection scheme. However, variations in SM capacitance were not considered in this study. In an attempt to ameliorate this problem, the estimation of capacitance values for each individual SM was considered in [13]. This improvement provides an important solution against concerning capacitance; however, in all observer-based methods the effect of variations associated with arm inductor values was not included in the design. In very recent research [14, 15], the voltage-balancing of a seven-level MMC has been achieved with important reductions in the number of voltage sensors required, where the lowest number of voltage sensors needed is two when seven-level MMC is used. Two sensors are contributed to measure total arm voltage of the converter. On the other hand, the main
concern with this method is that an advanced voltage-balancing method must be incorporated to guarantee stability.

This paper proposes a new voltage estimation scheme which aims to reduce the number of voltage sensors required in the MMC. The arrangement of sensors used is similar to those presented in previous studies [14, 15]. However, the proposed scheme uses only one voltage sensor per arm to achieve the voltage-balancing of the converter. Each sensor is connected to the total arm output voltage of the SMs. For the first time in MMC applications, and for the purpose of estimating the voltage across each SM capacitor, the proposed method here applies a Kalman filter (KF) algorithm. In comparison to some recursive algorithms, KF is more capable of reducing the side effects caused by sensor noise. A most valuable contribution of the proposed technique is that only the measured total arm voltage and the switching states of the SMs are required. The values of the switching states are accessed directly from the digital signal processor (DSP) controller, which means that no extra sensors are required. Unlike in some previously proposed schemes, the proposed scheme does not require an advanced voltage-balancing method. Extensive evaluations have been conducted into the effect of variations in SM capacitance on the MMC in recent studies. For example, the three-inductor (Ls) bridge configuration is presented in previous studies [14, 15], (from (n + 1) to 2n) as described in Fig. 1(a).

### TABLE I

<table>
<thead>
<tr>
<th>State of the SM</th>
<th>S_x</th>
<th>S_y</th>
<th>V_SM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bypassed</td>
<td>ON</td>
<td>OFF</td>
<td>V_Cx</td>
</tr>
<tr>
<td></td>
<td>OFF</td>
<td>ON</td>
<td>0</td>
</tr>
</tbody>
</table>

#### III. PROPOSED ESTIMATION SCHEME FOR MMCs

#### A. MMC Voltage Modelling and Sensor Arrangement

The proposed method is applied to a single-phase MMC based on the half-bridge configuration as described earlier in Fig. 1. Only two voltage sensors are required to achieve the voltage-balancing of one leg of the converter. The proposed sensors arrangement is illustrated in Fig. 1(a), where the upper sensor is connected between the top cell of the arm to the bottom cell terminals within the same arm, whilst the second sensor is positioned between SM_{(n+1)} and SM_{2n}. In this research, only the MMC with the half-bridge configuration is examined. However, the proposed estimation
method can also be applied to other multilevel converters, such as the cascaded H-bridge converter (CHC) and flying capacitor converter (FCC). The only difference required is to consider the specific relationship between the state of the capacitor and its related switches.

The relationship between the output upper and lower arm voltages, individual SM voltages and semiconductor switching states for an N-level converter can be derived as follows:

\[
\begin{align*}
u_u(t_0) &= S_1(t_0) V_{c1}(t_0) + \ldots + S_n(t_0) V_{cn}(t_0) \\
\vdots &= \vdots + \ldots + \vdots \\
u_u(t_j) &= S_1(t_j) V_{c1}(t_j) + \ldots + S_n(t_j) V_{cn}(t_j) \\
u_l(t_0) &= S_{n+1}(t_0) V_{e(n+1)}(t_0) + \ldots + S_{2n}(t_0) V_{e2n}(t_0) \\
\vdots &= \vdots + \ldots + \vdots \\
u_l(t_j) &= S_{n+1}(t_j) V_{e(n+1)}(t_j) + \ldots + S_{2n}(t_j) V_{e2n}(t_j)
\end{align*}
\]

(4)

(5)

where the sampling time of the data being processed is assumed to be constant for the whole measurement, in which: \(t_1 - t_0 = t_2 - t_1 = \ldots = t_j - t_{j-1} = \Delta t\) (sampling time). Conduction losses and semiconductor voltage drop are neglected in (4) and (5). Therefore, it is assumed that \(S_x(t_i) = PWM_x(t_i)\). This assumption has already been proven to be sufficient for the MMC for different voltage estimation techniques [12-14]. As a result, the switching state signals \((PWM_x(t_i))\) can be taken directly from the DSP without the need for the extra implementation. Therefore, (4) and (5) can be rewritten in a matrix form (6) as follows:

\[
\begin{align*}
u_u(t_i) &= S_x(t_i) V_{c}^T(t_i) \\
u_l(t_i) &= S_x(t_i) V_{e}^T(t_i)
\end{align*}
\]

(6)

(7)

Note that, in equation (6) \(x = 1, 2, \ldots, n\) and in equation (7) \(x = (n + 1), (n + 2), \ldots, 2n\).

B. Proposed Kalman Filter Voltage Estimation Scheme

The KF is a sequential mathematical-based estimator [20] which is widely used in power electronics applications to estimate state and system parameters in differential equations or state-space model representations. The KF has the ability to remove the effect of measurement noise which may be caused by sensors [5, 21, 22]. It is also guaranteed to cope with white Gaussian processing noise [22]. This makes this algorithm superior to some other recursive algorithms. Table II shows the generalised sequence for KF implementation when a linear system is implemented. For simplicity, it is assumed that the linear system can be described as follows:

\[
y(t_i) = \theta_1(t_i) \theta_1(t_i) + \theta_2(t_i) \theta_2(t_i) + \ldots + \theta_n(t_i) \theta_n (8)
\]

where the aim is to identify the values of \(\theta_1(t_i), \theta_2(t_i), \ldots, \theta_n(t_i)\), for which \(i = 0, 1, 2, \ldots, j\) \(y(t_i)\) is the available measured data, and \(\theta_1(t_i), \theta_2(t_i), \ldots, \theta_n(t_i)\) are other known variables.

Therefore, (8) can be rewritten as follows:

\[
y(t_i) = \Phi_x^T(t_i) \theta_x(t_i) (9)
\]

where \(\Phi_x^T(t_i) = [\theta_1(t_i) \theta_2(t_i) \ldots \theta_n(t_i)]^T\)

For real system implementation of (9), some other noise is always incorporated with this mathematical model [22]. Therefore, the unknown parameter \(\theta(t_i)\) is incorporated with processing noise \(w(t_i)\) with covariance matrix \(Q(t_i)\), where \(Q(t_i)\) is an N\(\times\)N diagonal matrix. In addition, when the measurement \(y(t_i)\) is taken to identify \(\theta(t_i)\), measurement noise \(v(t_i)\) should also be considered and added to the model. This measurement noise has a variance of \(\sigma(t_i)\) where \(\sigma(t_i)\) is a real positive number \(\sigma(t_i) > 0\) [21]. Therefore, considering such noise with the parameter \(\theta(t_i)\) and equation (9) gives the following updated model [21]:

\[
\begin{align*}
\theta(t_i) &= \theta(t_{i-1}) + w(t_i) \\
y(t_i) &= \Phi_x^T(t_i) \theta_x(t_i) + v(t_i)
\end{align*}
\]

(10)

(11)

The estimation of \(\theta(t_i)\) is performed as demonstrated in the implementation sequence in Table II [5, 21, 22].

Due to the similarity between the linear dynamic model described in (9) and the voltage MMC model described earlier in (6) and (7), a new updated model can be formulated for the MMC. The only difference is to substitute \(y(t_i), \Phi_x^T(t_i)\) and \(\theta_x(t_i)\) in (9) by total SM arm voltages \(u_u(t_i)\) or \(u_l(t_i)\), switching states \(S_x(t_i)\) and SM voltage \(V_{e}^x(t_i)\). Therefore, incorporating measurement and processing noise into the model described earlier in (6) and (7) gives the following developed model:

\[
\begin{align*}
u_u(t_i) &= S_x(t_i) V_{c}^T(t_i) + v(t_i) \\
u_l(t_i) &= S_x(t_i) V_{e}^T(t_i) + v(t_i) \\
V_{c}^x(t_i) &= V_{e}^x(t_i - 1) + w(t_i)
\end{align*}
\]

(12)

(13)

(14)

Because the upper arm implementation is independent of the lower arm, only the upper arm is described here. Therefore, following the general sequence illustrated in Table II, this results in the following implementation.

To start up the proposed KF algorithm, the covariance matrix \(P(t_0)\), and estimated voltage \(\hat{V}_{e}^x(t_0)\) should be initialized with \(P(t_0)\) and \(\hat{V}_{e}^x(t_0)\). As in conventional recursive algorithms, \(P(t_0)\) in the KF algorithm is \(P(t_0) = G_1,\)
where G is a large and positive constant number whilst I is an \( xxx \) identity matrix, where \( x \) is the number of SMs. An adaptive Kalman gain is then calculated as follows:

\[
K(t_i) = \frac{P(t_{i-1})S(t_i)}{S(t_i)P(t_{i-1})S(t_i)+r(t_i)}
\]

(15)

Based on the sequence of implementation in Table II, the error of the upper arm is calculated as follows:

\[
e_u(t_i) = u_u(t_i) - \hat{u}_u(t_i)
\]

(16)

As the first sampling time is processed, \( P(t_{i-1}) = P(t_0) \), and the variance coefficient \( r(t_j) \) in this implementation of the KF is defined as a constant number for the whole sampling time, therefore it is assumed that: \( r(t_i)=r(t_2)= ... =r(t_j) \). The SM voltage estimation values for the upper arm are then updated with the error calculated using (16) and the Kalman gain derived from (15) and the previously estimated values \( \hat{V}_{cx}(t_{i-1}) \). Therefore, to estimate these voltages in one prediction step ahead, the upper SM voltage estimated values can be identified as follows:

\[
\hat{V}_{cx}(t_i) = \hat{V}_{cx}(t_{i-1}) + K(t_i)e_u(t_i)
\]

(17)

To further enhance the algorithm, the new covariance matrix is then updated recursively with the values \( K(t_i) \) and \( Q(t_i) \) as shown in Table II. Therefore, a new prediction step ahead of \( P(t_{i-1}) \) can be calculated as follows:

\[
P(t_i) = P(t_{i-1}) - \frac{P(t_{i-1})S(t_i)S(t_i)P(t_{i-1})}{r(t_i)+S(t_i)P(t_{i-1})S(t_i)} + Q(t_i)
\]

(18)

The proposed upper arm voltage estimation scheme, with its associated voltage-balancing control used is shown in Fig.2. The voltage-balancing algorithm used here is similar to the algorithm presented in [23]. It should be noted that the voltage-balancing used in this paper is not linked to the proposed estimation method, which means it is completely independent of the voltage-balancing method used. Therefore, any other voltage control methods can be used with this proposed estimation scheme. In comparison with the algorithm presented in [23], the voltage-balancing of the SM capacitors used here depends on the estimated voltages (\( \hat{V}_{cx} = \hat{V}_{cn} \)) rather than the actual voltages. These voltages \( \hat{V}_{cx} = \hat{V}_{cn} \), are sorted in descending order to charge and discharge the capacitors depend on upper arm current direction. Once the upper current is positive, the capacitors with the lowest voltage will be charged. On the other hand, when the upper current is negative, the capacitors with the highest voltage will be discharged. The algorithm also defines how many capacitors should be involved in this process. In other words, for each output voltage level, there is a required number (\( \beta \)) of capacitors that need to be charged or discharged. A Phase disposition PWM (PD-PWM) is used in the simulation and experimental analyses. A unit delay (\( Z^{-1} \)) is applied to the switching patterns (\( PW_{M1}, PW_{M2}, ... PW_{Mn} \)) obtained in order to switch \( S_1, S_2, ... S_n \) at the appropriate time (see Fig. 2).

For ease of demonstration, assume that the PD-PWM is used for a 4-level MMC only as shown in Fig. 3 and therefore, the number of SMs required for each level can be determined as follows:

- For level one in Fig. 3, the number of the involved SMs for the upper arm, which is determined by switching \( S_1, S_2 \& S_3 \), is 3. In the same instant, the number required for the lower arm is 0. The total should be always 3 for the whole period of this level (i.e. \( \beta_{upper} + \beta_{lower} = 3 \)).

- For level two, the number of the involved SMs for the upper arm, which is determined by switching \( S_1, S_2 \& S_3 \), is 2 (\( \beta_{upper} = 2 \)). In the same instantaneous time, the lower number required for the arm is 1 (\( \beta_{lower} = 1 \)).

- Similarly, for level three, the number of the SMs involved for the upper arm is 1 and 2 for the lower arm.

- For level four, the number of the involved SMs for the upper arm which is determined by switching \( S_1, S_2 \& S_3 \), is 0. In the same time, the number required for the lower arm for \( \beta_{lower} \) is 3.

---

**Fig. 2. Upper arm proposed estimation scheme and associated voltage-balancing control for N-level.**

**Fig. 3. Voltage-balancing / sorting algorithm for upper arm with 4-level MMC.**
IV. SIMULATION ANALYSES

A single-phase 9-level MMC is simulated using the MATLAB package with the aim of validating the proposed estimation scheme. Sixteen SMs are used for the leg, while one voltage sensor instead of eight per arm is used. The converter, the DC voltage source and the load parameters are tabulated in Table IV. The validation of the proposed method is confirmed below according to the results of different simulations.

A. Steady-State Operation Performance

In this part of the simulation study, a comparison of the proposed estimation scheme and a sensor-based scheme is conducted with a constant R-L load. Fig. 4 shows the performance of the converter waveforms where voltage sensors are used for each SM (sensor-based method). In contrast, Fig. 5 illustrates the performance of the proposed estimation scheme under the same load conditions. In comparing the two methods, only small deviations in the upper arm SM voltages can be observed (see Fig. 5 (a)). However, this error does not have any noticeable effect on neither the output voltage waveform nor the output current waveform. It should be noted that, with the proposed method, only two voltage sensors are used rather than sixteen when the sensor-based method is used.

B. Effect of Parameter Variation

In comparison with the observer-based methods which were proposed in [12, 13], the proposed method is completely independent of variations in arm inductance. This is because the arm inductance is not included in the estimation algorithm design. However, further investigation in terms of capacitance uncertainty is required.

Extensive simulation tests have been carried out to validate the robustness of the proposed estimation method against
capacitance variation. Here, C1 is chosen as an example with different capacitance of deviations: ±15% and ±30%. For each case, random capacitances are chosen for the other SM arm capacitances (C2~C8). For example, as shown in Fig. 6 when C1 has deviations of ±15% from its nominal capacitance (case I), C2~C8 are also given random deviations of -20%, +10%, +5%, -15%, +40%, -30%, and +60%.

For case I, Fig. 6(a) shows the reference and estimated voltage for C1 where ±15% variation is considered, and Fig. 6(b) illustrates the error for ±15% variation. It can be observed that the maximum error for both (±15%) is only around 1.3%. Figs 6(c) and 6(d) show the effect of these variations on the other arm capacitators. For case II, C1 is given as ±30% variations of its nominal capacitance while the other capacitators are given different random capacitances as illustrated in Table III. The error when the variation in C1 is given as -30% is almost 0.8%; however, with +30% variation the maximum error can be observed to be around 1.1%.

| TABLE III Capacitance Variations in (C1~C8) |
|----------------|----------------|
| Capacitor | Case I | Case II |
| C2 | -20% = 1600μF | +5% = 2100μF |
| C3 | +10% = 2200μF | -15% = 1700μF |
| C4 | +5% = 2100μF | +40% = 2800μF |
| C5 | -15% = 1700μF | -30% = 1400μF |
| C6 | +40% = 2800μF | +60% = 3200μF |
| C7 | -30% = 1400μF | -20% = 1600μF |
| C8 | +60% = 3200μF | +10% = 2200μF |

C. Effect of Load Change on Estimator Performance

To further validate the proposed estimation scheme, a dynamic test is also carried out with ±100% step change in the load conditions applied to the converter as shown in Fig. 8. At 0.3s the R-L load is increased first by +100% and then at 0.4s it is forced back to the original value. The effect of these changes on estimated Vc1 is shown in Fig. 8(b). The estimation error does not exceed 0.6% in both cases as can be seen in Fig. 8(c).

D. Effect of Low Carrier and Effective Switching Frequency on Estimator Performance

Owing to the ability of the MMC to work at different carrier frequency when different voltage-balancing control methods are used, the proposed estimation method is further investigated, as shown in Fig. 9. The effect of different low carrier frequencies is shown respectively (fc = 1500, 250 and 45 Hz) for all eight SMs. Column (a) in the figure for example, represents the voltage error for SM1 to SM8 respectively when fc = 1500 Hz. For all carrier frequencies used, the error of the estimation voltage across C1 does not exceed 1%. These results confirm the ability of the proposed method to work at low carrier frequency. Another test has been carried out in Fig. 10 to investigate the effect of using voltage-balancing method with low effective switching reduction on the proposed estimation scheme. Similar to the method introduced in [24] has been implemented for this test.

E. DC Fault and Start-up Performance

To further validate the proposed estimation scheme, a fault in the DC source is applied to the MMC. In this case study, a sudden drop of 50% in the DC voltage is considered. The corresponding changes in the output waveforms of the converter as well as the performance of the voltage estimation across C1 are shown in Fig. 11 (a), (b) and (c) respectively.
The start-up estimation performance of $V_{C1}$ is shown in Fig. 12. For the reference voltage, the capacitor is assumed to be pre-charged at its reference voltage (i.e. $V_{C1}(t_0) = 1250$ V). As can be seen from Fig. 12 the proposed KF estimation scheme successfully traced the reference voltage within a very short time.

V. EXPERIMENTAL ANALYSES

A single-phase 4-level MMC scaled down laboratory prototype is developed to validate the proposed estimation scheme. Fig. 13(a) shows the block diagram of the complete experimental platform, whilst the real setup of the experimental test bench is shown in Fig. 13(b). The converter consists of six SMs. The switching devices used are IRF530N power MOSFET, whilst the SM capacitors are the VISHAY 561000μF with a rated voltage of 63V. According to the manufacturer the capacitor variations are ± 20%. Table IV shows more details about the system including the R-L load values. A TMS320F28335 controller (Texas Instruments) is used to control the converter. The proposed KF estimation algorithm and the voltage-balancing algorithm are uploaded to the controller with the help of Code Composer Studio (CCS5.5) development tools.

The converter is operated at 2.5 kHz switching frequency with a dead-time of 3μs.

Fig. 10. The effect of effective switching frequency on the proposed estimation method. (a) Estimated voltages for $V_{C1}\sim V_{C8}$ based on [23]. (b) Effective switching frequency for S1. (c) Estimated voltages for $V_{C1}\sim V_{C8}$ based on [24]. (d) Effective switching frequency for S1.

This is accomplished using the Embedded Coder Support Package in MATLAB/Simulink to generate the required C code for all associated blocks in the MATLAB/Simulink models.

Fig. 11. Performance of the proposed method during DC fault. (a) Output current response. (b) Output voltage response. (c) The effect of the DC fault on the estimated $V_{C1}$.

Fig. 12. Performance of the proposed estimation scheme during start-up transient condition.

Fig. 9. Performance of the proposed estimation scheme with low carrier frequencies for all eight SMs. (a) Voltage error across $C_1\sim C_8$ when $f_c=1.5$ kHz was used. (b) Voltage error across $C_1\sim C_8$ when $f_c = 750$ Hz was used. (c) Voltage error across $C_1\sim C_8$ when $f_c = 45$ Hz was used.
To evaluate the performance of the proposed estimation scheme, extensive tests at different operating conditions are carried out, including investigation of steady-state and dynamic analyses.

**A. Steady-State Operation Performance**

A comparison has been made between the proposed estimation scheme and the sensor-based method to verify the simulation results. A constant R-L load is applied to the converter, and its output waveforms are illustrated in Fig. 13 based on the sensor-based method. The three upper capacitor voltages are shown in Fig. 14 (a), whilst the output load current and voltage waveforms are shown in Fig. 14(b) and (c). Comparison with the proposed estimation scheme, Fig. 15 (b) and (c) shows no differences in terms of the output converter waveforms for current and voltage. However, similar to the results achieved earlier in the simulation analysis, the three capacitor voltages shown in Fig. 15 (a) exhibit slight deviations in comparison with those in Fig. 14 (a). However, as described above, there is no noticeable impact on the output waveforms of the converter, which validates the simulation results. Zoomed-in output wave forms of Fig. 14(b), (c) and Fig. 15 (b), (c) are illustrated in Fig. 16 (a) and (b) respectively. In addition, Fig. 17 compares between measured and estimated voltage across $C_1$, $C_2$, and $C_3$. Samples of the measured voltages for the upper and lower arms are illustrated in Fig. 18.

**B. Effect of Load Change on Performance**

Further validation for dynamic change operation is illustrated in Fig. 19. In this study, step changes in the load resistance ($R$) are considered, where the value of $R$ is altered between 33 $\Omega$ and 68 $\Omega$ first, and then between 68 $\Omega$ and 33 $\Omega$. For both cases, as can be seen in Fig. 19, the capacitor voltages still track the reference voltage $\frac{V_{dc}}{n}$, which confirms the simulation results.

![Experimental set-up. (a). Block diagram. (b). The experimental test bench.](image)

![Experimental results of the sensor-based method at constant R-L load. (a) Upper SM voltage capacitors. (b) Output current and voltage waveforms.](image)

![Experimental results of the proposed estimation scheme at constant R-L load. (a) Upper SM voltage capacitors. (b) Output current and voltage waveforms.](image)
investigation, a sudden increase of approximately 90% in the DC voltage is applied to the system. It can be observed from Fig. 21 that the voltage across \( C_1 \) rapidly and successfully reacts to this change.

Fig. 16. Zoomed-in of output voltage and current of the sensor-based method and proposed estimation scheme. (a) Output voltage and current of sensor-based scheme. (b) Output voltage and current of the proposed estimation scheme.

Fig. 17. Experimental results of the voltages across \( C_1 \), \( C_2 \) and \( C_3 \) when the sensor-based method and proposed estimation scheme are used. (a) Zoomed-in \( V_{c1}, V_{c2}, \) and \( V_{c3} \). (b) Zoomed-in \( \hat{V}_{c1}, \hat{V}_{c2}, \) and \( \hat{V}_{c3} \)

Fig. 18. Upper and lower arm voltages.

Fig. 19. Step load change analysis of the load resistance (R) in the proposed method.

Fig. 20. Fault in the DC voltage and corresponding changes in converter waveforms.
VI. CONCLUSION

In this paper, a new voltage estimation scheme for the MMC is proposed in which a new employment of the KF algorithm is developed for the converter. Comprehensive studies of a one-leg MMC have been conducted to demonstrate the effectiveness of the proposed scheme in simulation and experimental environment analyses. Extensive steady-state and dynamic analyses have been performed. The results show that the proposed estimation scheme succeeded in providing accurate voltage estimation results, and therefore the voltage-balancing of the MMC is achieved with only one voltage sensor per arm. Using this proposed scheme, any conventional voltage-balancing technique can be easily incorporated. This development facilitates an important reduction in the number of voltage sensors required. Consequently, this improvement will reduce the total cost of the converter and reduce its complexity. The most promising application of the proposed scheme is to contribute a strategy to identify faults. Finally, the proposed method can also be applied to CHCs and FCCs.

References

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