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Reference Submodule-Based Capacitor Monitoring Strategy for Modular Multilevel Converters

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Abstract--**The modular multilevel converter (MMC) is attractive for medium or high-power applications because of the advantages of its high modularity, availability, and high power quality. Reliability is one of the most important challenges for the MMC consisting of a large number of submodules (SMs). The capacitor monitoring is one of the important issues in the MMC. This paper proposed a reference submodule (RSM)-based capacitor monitoring strategy for the capacitance estimation in the MMC, where the capacitances in the monitoring SMs can be estimated based on the capacitor voltage relationship between the RSM and the monitoring SMs. The proposed monitoring strategy does not rely on the information of all capacitor voltage and current, which effectively simplifies the algorithm for capacitance estimation. The simulation studies with the time-domain professional tool PSCAD/EMTDC are conducted and a down-scale MMC prototype is also tested in the laboratory with the proposed capacitor monitoring strategy. The study results confirm the effectiveness of the proposed capacitor monitoring strategy.**

Index Terms— **Capacitor, modular multilevel converters (MMCs), monitoring, submodule.**

I. INTRODUCTION

Modular multilevel converters (MMCs) have been regarded as one of the most competitive converters for medium to high-voltage high-power applications with the advantages such as the excellent output voltage waveforms, very high efficiency [1, 2], etc. A multilevel voltage can be produced with the flexible operation of the MMC while reducing average switching frequency without compromising the power quality [3, 4]. Recently, due to the easy construction, assembling, and flexibility in converter design, the MMC becomes promising for various applications such as machine drives [5], electric railway supplies [6] and microgrid [7].

Reliability is one of the most important challenges for the MMC. The MMC consists of a large number of devices (e.g. switch, diode and capacitor) and each device can be considered as a potential failure point [8, 9]. Recently, a number of studies about the switch and diode faults in the MMC have been reported. The sliding mode observer [10], Kalman filter [11], state observer [12], etc. are employed in the MMC. Through the comparison between the estimated values and the measured values, the switch open-circuit fault is detected. A resilient framework is presented for fast fault diagnosis and restoration about the switch open-circuit faults in the MMC [13]. The clustering algorithm based method and a calculated capacitance based method are introduced for detecting the switch open-circuit faults [14]. The supervisory sensor is presented in the MMC, where the switch fault can be diagnosed by comparing the output voltages of a set of submodules (SMs) [15]. A varistor-based SM configuration is presented for the fault diagnosis and protection under the diode open-circuit faults in the MMC [16].

The electrolytic capacitor is widely considered for the MMC in some applications such as motor drive and microgrid [5], [7], [17-21] based on its feature such as high capacitance per unit volume. Due to the chemical process, aging effect, etc., the capacitor in the MMC would gradually deteriorate, which is normally expressed by the capacitance drop [22-24]. Normally, the deteriorated capacitor needs be replaced when its capacitance drops below the threshold value, such as 80% of the rated value [22]. As a consequence, the MMC has to work with the different capacitances in the different SMs, which would affect the performance of the MMC [25]. Therefore, an effective capacitor monitoring method to estimate the capacitance is essential for the MMC, from which a predictive maintenance is possible, leading to the better reliability of the MMC.

Several studies have been presented for the capacitor condition monitoring. Reference [22] presented a condition monitoring scheme for capacitors in the MMC, where the capacitance in the SM is estimated by a recursive least square algorithm based on the capacitance estimation using the information of the capacitor voltage, arm current and SM switching state. However, an ac current is required to be injected into the circulating current, which increases capacitor

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voltage ripple and affects MMC performance. Reference [23] employed a Kalman filter algorithm to estimate the SM capacitance in the MMC, which estimates the capacitance based on the capacitor voltage and current. However, the Kalman filter algorithm complicates the capacitance estimation. Reference [24] presented a simple capacitor monitoring algorithm, which can estimate the capacitances in the SMs based on the relationship between the arm average capacitance and the capacitance in each SM of the arm. However, the above methods need to monitor all SMs' switching states for calculating the capacitor current and estimate all SMs' capacitances based on the integral computation, which complicate the capacitor monitoring algorithm.

In this paper, a reference submodule (RSM)-based capacitor monitoring strategy is proposed. Based on the capacitor voltage relationship between the RSM and the monitoring SMs, the capacitance in the monitoring SMs can be estimated with simple algorithm. The proposed strategy does not rely on the information of all capacitor voltage and current for capacitance estimation, which effectively simplifies the computation in comparison with the aforementioned methods [22-24].

This paper is organized as follows. Section II presented the operation of the MMC. Section III proposed the RSM-based capacitor monitoring for the MMC. The system simulation and experimental tests are presented in Sections IV and V, respectively, to show the effectiveness of the proposed capacitor monitoring strategy. Finally, the conclusions are presented in Section VI.

II. OPERATION PRINCIPLE OF MMCS

A. *Structure of MMCs*

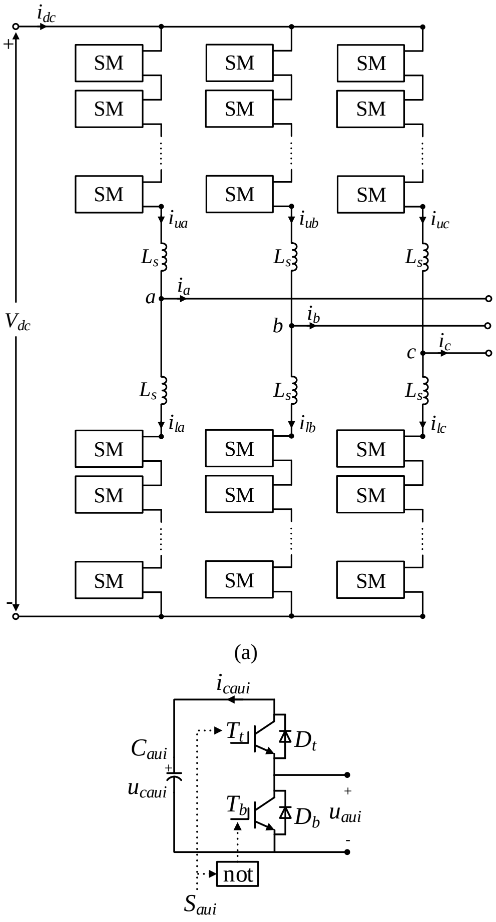
A three-phase MMC is shown in Fig. 1(a), which contains six arms. Each arm consists of *n* identical SMs and an arm inductor L_s. Fig. 1(b) shows the *i*-th SM (i=1, 2……n) in the upper arm of phase A, which contains the switch/diode T_t/D_t, T_b/D_b and a dc capacitor C_{aui} [26]. The SM is normally controlled with a switching function S_{aui} as

$$S_{aui}=\begin{cases}1, & T_t \text{ is on and } T_b \text{ is off}\\ 0, & T_t \text{ is off and } T_b \text{ is on}\end{cases} \tag{1}$$

The SM output voltage u_{aui} is

$$u_{aui}=S_{aui}\cdot u_{caui} \tag{2}$$

where u_{caui} is the capacitor voltage. Table I shows the two states of the SM. One is "On" state under S=1, where u_{aui} equals u_{caui}. The other one is "Off" state under S=0, where u_{aui} equals 0. In the "On" state, the charge and discharge of the capacitor C_{aui} depends on the arm current flow direction. If the arm current i_{ua} is positive, as shown in Fig. 1(a), the capacitor in the on-state SM would be charged and u_{caui} is increased. If the arm current i_{ua} is negative, the capacitor in the on-state SM would be discharged and u_{caui} is decreased. In the "Off" state, the SM capacitor would be bypassed and u_{caui} is unchanged, irrespective of the arm current flow direction [27].



(a)

(b)

Fig. 1. (a) Block diagram of a three-phase MMC. (b) SM unit.

TABLE I

OPERATION OF THE SM

SM state	S_{aui}	T_t	T_b	u_{aui}	Arm current i_{ua}	C_{aui}	u_{caui}
On	1	On	On	u_{caui}	u_c	Charge	Increased
					0	Bypass	Unchanged
Off	0	Off	Off	0	u_c	Discharge	Decreased

In Fig. 1, the upper and lower arm current i_{uj} and i_{lj} (j=a, b, c) can be described as

$$\begin{cases} i_{uj}=\dfrac{i_j}{2}+i_{diff\_j}\\ i_{lj}=-\dfrac{i_j}{2}+i_{diff\_j}\end{cases} \tag{3}$$

with

$$i_{diff\_j}=\frac{i_{dc}}{3}+i_{2f\_j} \tag{4}$$

where i_j is the ac grid current of phase j. i_{diff_j} is the inner difference current of phase j, which contains two parts and can be expressed as (4) [28]. One part is the dc component, $i_{dc}/3$. The other part is the circulating current i_{2f_j} of phase j.

B. *Voltage-Balancing Control of MMCs*

The conventional voltage-balancing control (C-VBC) of the MMC is shown in Fig. 2 (a). Under the modulation schemes, through the comparison between the reference signal and the carriers, the number n_{on} of the on-state SMs can be obtained.

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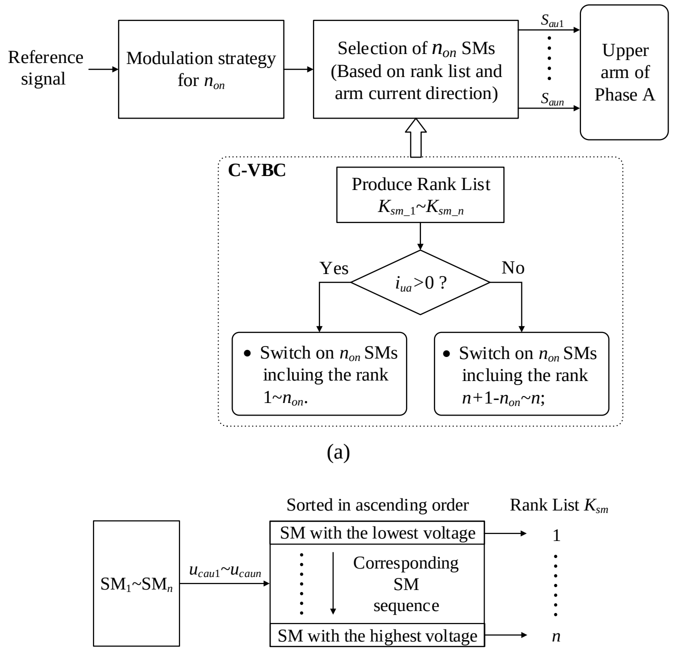


(a)

(b)

Fig. 2 (a) C-VBC for MMCs. (b) Rank list production.

The switching function for each SM can be decided based on n_{on}, the rank list and the arm current. Fig. 2(b) shows the production of the rank list. The capacitor voltage u_{cau1}~u_{caun} in the arm is measured and the SMs in the arm are ordered according to their capacitor voltage in ascending order. And then, the rank K_{sm_i} (i=1, 2…n) corresponding to the SM$_i$ in the arm can be produced, where the K_{sm} for the SM with the lowest voltage is 1 and the K_{sm} for the SM with the highest voltage is n. If the arm current is positive, the n_{on} SMs with the lowest voltage corresponding to the rank 1~n_{on} will be switched on. If the arm current is negative, the n_{on} SMs with the highest voltage corresponding to the rank n-n_{on}+1~n will be switched on, which ensures the capacitor voltage balancing in the arm [29].

III. PROPOSED RSM-BASED CAPACITOR MONITORING STRATEGY

A. Conventional Capacitor Monitoring Method

In the conventional capacitor monitoring for the MMC [22, 23], the capacitance C_{aui} shown in Fig. 1(b) can be directly estimated based on the arm current i_{ua}, capacitor voltage u_{caui} and the switching function S_{aui} as

$$C_{aui} = \frac{1}{u_{caui}}\int S_{aui}\cdot i_{ua}dt \tag{5}$$

The capacitance estimation in the conventional method can be achieved with very high accuracy, and the error is less than about 1%. However, the conventional method not only needs the information of all capacitor voltage and current, but also relies on the complex integral computation. If all capacitances in the arm are estimated by the conventional monitoring method, it would complicate the algorithm and increase the computation burden.

B. Proposed RSM-Based Capacitor Monitoring Method

In order to simplify capacitor monitoring algorithm, the RSM-based capacitor monitoring method is proposed for the capacitance estimation in the arm, as shown in Fig. 3. In the proposed RSM-based capacitor monitoring method, some SM is selected as the RSM and the capacitances in the other SMs can be estimated based on the capacitance in the RSM.

Suppose that the capacitance in the RSM has been estimated, in order to monitor the capacitance C_{aui} in the SM$_i$, $i \in (1, 2,\ldots n)$, the switching function S_{rsm} for the RSM must be the same to S_{aui} for the SM$_i$, as S_{rsm}=S_{aui}. In this situation, the RSM capacitor voltage u_{rsm} and the SM$_i$ capacitor voltage u_{caui} can be expressed as

$$\begin{cases} u_{rsm} = \dfrac{1}{C_{rsm}}\int S_{rsm}\cdot i_{ua}dt \\ u_{caui} = \dfrac{1}{C_{aui}}\int S_{rsm}\cdot i_{ua}dt \end{cases} \tag{6}$$

According to (6), the relationship between the capacitance C_{rsm} and C_{aui} can be obtained as

$$C_{aui} = C_{rsm}\frac{\Delta u_{rsm}}{\Delta u_{caui}} \tag{7}$$

where Δu_{rsm} and Δu_{caui} are the peak-to-peak values of the voltage u_{rsm} and u_{caui}, respectively, as shown in Fig. 3.

According to (7), the capacitance C_{aui} can be estimated in one fundamental period based on the measured RSM capacitor voltage u_{rsm}, the measured SM$_i$ capacitor voltage u_{caui} and the estimated RSM capacitance C_{rsm}, as shown in Fig. 3.

C. Proposed CM-VBC

To realize the proposed RSM-based capacitor monitoring shown in Fig. 3, a capacitor monitoring-based voltage-balancing control (CM-VBC) is proposed to select n_{on} on-state SMs, as shown in Fig. 4. The proposed CM-VBC not only balances the capacitor voltages in the arm for ensuring the normal operation of the MMC, but also ensures that the S_{rsm} for the RSM follows the S_{aui} for the monitoring SM$_i$, so as to complete the proposed RSM-based capacitor monitoring.

In Fig. 4, the n-1 SMs in the arm except RSM are sorted based on their capacitor voltages in the ascending order, so as to produce the rank K_{sm} for the corresponding SM. Suppose that the SM$_i$ corresponding to the rank K_{sm_i} is to be monitored, the selection of n_{on} on-state SMs will be decided based on the arm current i_{ua} and the ranks of the n-1 SMs, as follows.

1) $i_{ua} > 0$ & $K_{sm\_i} < n_{on}$: the n_{on}-1 SMs corresponding to the rank 1~n_{on}-1 are switched on. In addition, the RSM is also switched on. In this situation, SM$_i$ and RSM are both switched on.
2) $i_{ua} > 0$ & $K_{sm\_i} = n_{on}$: the n_{on}-1 SMs corresponding to the rank 1~n_{on}-2 and n_{on} are switched on. In addition, the RSM is also switched on. Here, SM$_i$ and RSM are both switched on.
3) $i_{ua} > 0$ & $K_{sm\_i} > n_{on}$: the n_{on} SMs corresponding to the rank 1~n_{on} are switched on. In this situation, SM$_i$ and RSM are both switched off.

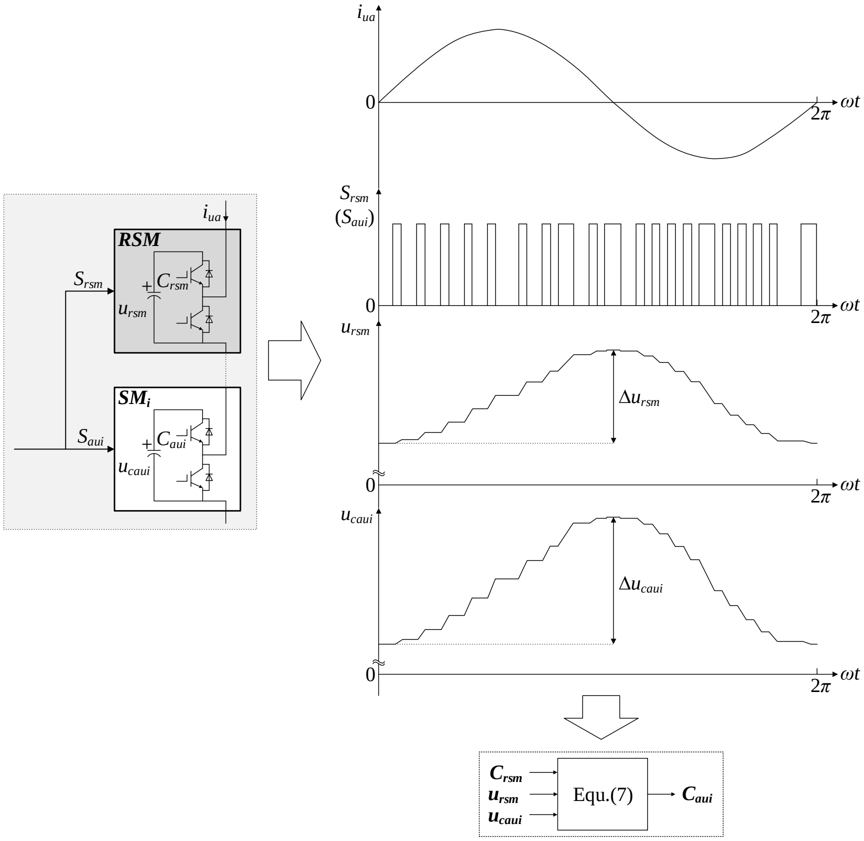


Fig. 3. Proposed RSM-based capacitor monitoring method.

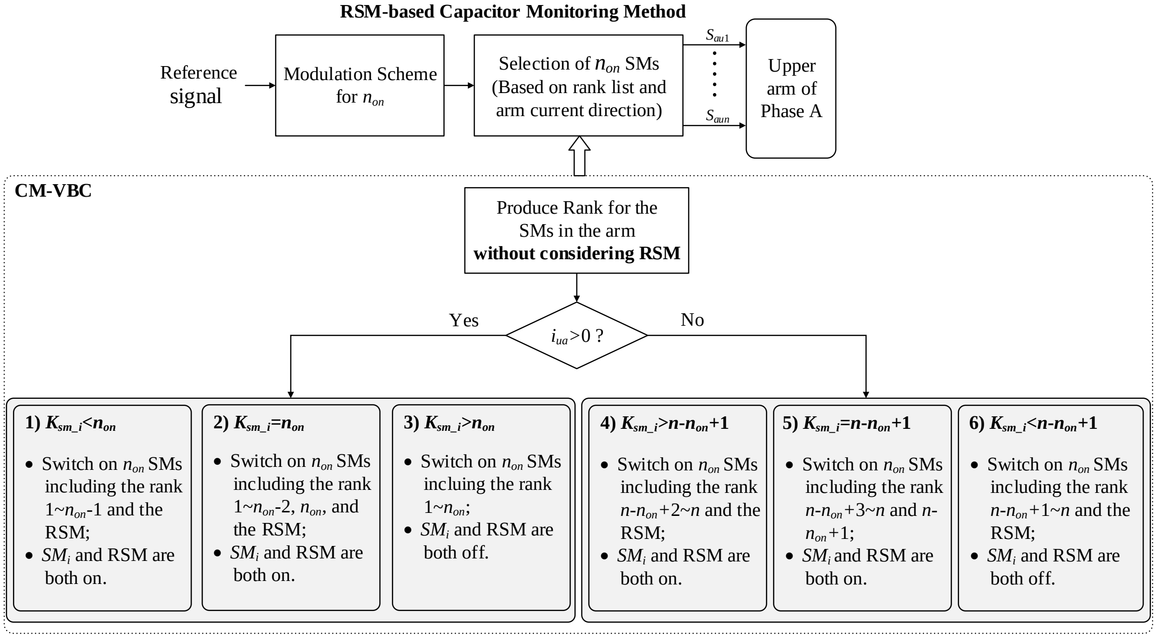


Fig. 4. Proposed CM-VBC for RSM-based capacitor monitoring.

4) i_{ua} < 0 & K_{sm_i} > n-n_{on}+1: the n_{on}-1 SMs corresponding to the rank n-n_{on}+2~n are switched on. In addition, the RSM is also switched on. Here, SM_i and RSM are both switched on.

5) i_{ua} < 0 & K_{sm_i} = n-n_{on}+1: the n_{on}-1 SMs corresponding to the rank n-n_{on}+3~n and n-n_{on}+1 are switched on. In addition, the RSM is also switched on. In this situation, SM_i and RSM are both switched on.

6) i_{ua} < 0 & K_{sm_i} < n-n_{on}+1: the n_{on} SMs corresponding to the rank n-n_{on}+1~n are switched on. Here, SM_i and RSM are both switched off.

D. Selection of RSM

In the proposed CM-VBC, although the capacitor voltages in the arm are kept balanced, the peak-to-peak value Δu_{rsm} in u_{rsm} would be variable, as shown in Fig. 3, which depends on the relationship between C_{rsm} and C_{aui} shown in (7). If C_{rsm} is bigger than C_{aui}, Δu_{rsm} is smaller than Δu_{caui}. In addition, the bigger of C_{rsm}, the smaller of Δu_{rsm}. If C_{rsm} is smaller than C_{aui}, Δu_{rsm} is bigger than Δu_{caui}. The smaller of C_{rsm}, the bigger of Δu_{rsm}, as shown in Table II.

TABLE II
VOLTAGE RIPPLE IN RSM

RSM's Capacitance C_{rsm}	RSM's voltage ripple Δu_{rsm}
$> C_{aui}$	$< \Delta u_{caui}$
$< C_{aui}$	$> \Delta u_{caui}$

Based on above analysis, the RSM should be selected with the SM, whose capacitance is the biggest one among C_{au1}~C_{aun}. It ensures that the Δu_{rsm} is always not bigger than the peak-to-peak value of the other SMs' capacitor voltages, which reduces the capacitor voltage ripple in the RSM.

Suppose that the electrolytic capacitor is used in the MMC and the capacitor needs to be replaced when its capacitance drops to 80% of the rated value, the RSM's Δu_{rsm} would be reduced by 0.2 p.u. at most. On the other hand, the capacitor voltages in the arm are kept balanced with the CM-VBC. Although the peak-to-peak value Δu_{rsm} of the RSM's capacitor voltage is less than that of the other SMs' capacitor voltages during the capacitor monitoring period, the capacitor voltage's peak-to-peak value is far less than the capacitor voltage [1-10], and therefor the impact of the variable RSM's Δu_{rsm} on the MMC performance during the capacitor monitoring period can be omitted.

E. Proposed Capacitor Monitoring Strategy

Based on above analysis, the capacitor monitoring strategy is proposed, as shown in Fig. 5, which estimates the SM's capacitances in the sequence from SM1 to SM*n* round. Firstly, the SM1 is selected as the RSM, and the RSM capacitance is estimated based on the conventional method as (5). Based on the RSM, the capacitance in the SM2 is estimated with the RSM-based monitoring method as shown in Fig. 6.

In Fig. 6, the selection signal (*SS*) is initially "0" and the C-VBC is enabled, where u_{cau1}~u_{caun} are kept the same with each other. When the capacitor in the SM2 is demanded to be monitored, the *SS* is switched to "1" and the RSM-based CM-VBC is enabled for one fundamental period. Here, the RSM's Δu_{rsm} would be changed, which is used for the SM2 capacitor monitoring based on (7). Afterwards, the *SS* is switched back to "0" again to keep the u_{cau1}~u_{caun} the same with each other, which waits for the next command to monitor the capacitance in the other SMs.

After the capacitance in SM2 is estimated, the RSM will be updated. Among the estimated SMs, the SM with the biggest capacitance is selected as the RSM. Afterwards, the SM3, SM4……will be monitored with the same method, which is not repeated here.

Although, the capacitor voltage ripple of the RSM is a little smaller than those of the other SMs in the CM-VBC, the capacitor voltage ripple is far less than the capacitor voltage, which makes that the proposed capacitor monitoring has little effect on the performance of the MMC. In addition, due to the chemical process and aging effect, the speed of the capacitance drop is quite slow. Therefore, the SM capacitors in the arm can be monitored in the sequence from SM1 to SM*n* round with some short interval such as one fundamental period.

One thing to be mentioned is that, the capacitor monitoring in the proposed strategy is indirectly realized based on the SM1's capacitance, as shown in Fig. 5. Hence, the estimation accuracy of the SMs' capacitor depends on that of the SM1's capacitance. According to [22, 23], the SM1's capacitance can be estimated by (5) with very high accuracy, and the error is less than about 1%, which guarantees the capacitance estimation accuracy in the proposed strategy. On the other hand, in order to ensure the high estimation accuracy, the selected RSM's capacitor will be estimated by (5) at an interval of time *T*, as shown in Fig. 5.

From Fig. 5, it can be observed that the proposed capacitor monitoring method does not rely on the information of all capacitors' voltage and current for the complicated integral computation, which effectively simplifies the capacitor monitoring algorithm.

IV. SIMULATION STUDIES

To verify the proposed strategy, a three-phase MMC system shown in Fig. 7 is simulated with the time-domain simulation tool PSCAD/EMTDC. In the simulation, the active power *P* and the reactive power *Q* is 100 MW and 0 MVar, respectively. The capacitances C_{au2}~C_{au6} drop, where C_{au2}=13.5 mF, C_{au3}=12 mF, C_{au4}=10.5 mF, C_{au5}=9 mF, C_{au6}=7.5 mF, respectively. The other system parameters are shown in the Table III.

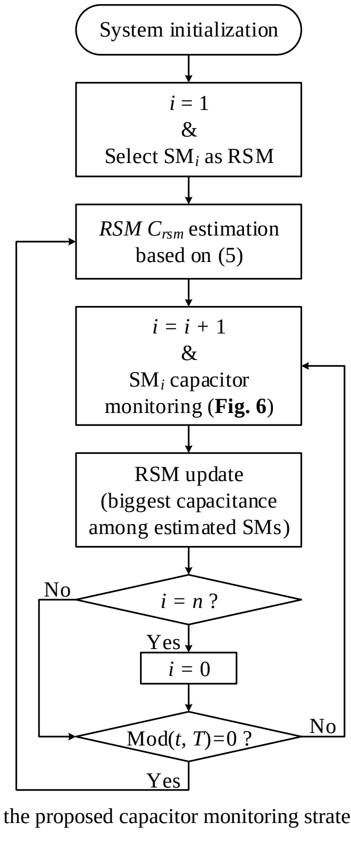


Fig. 5. Flowchart of the proposed capacitor monitoring strategy for MMCs.

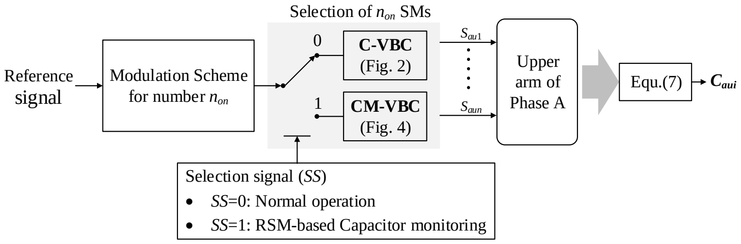


Fig. 6. Proposed capacitor monitoring.

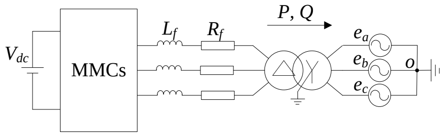


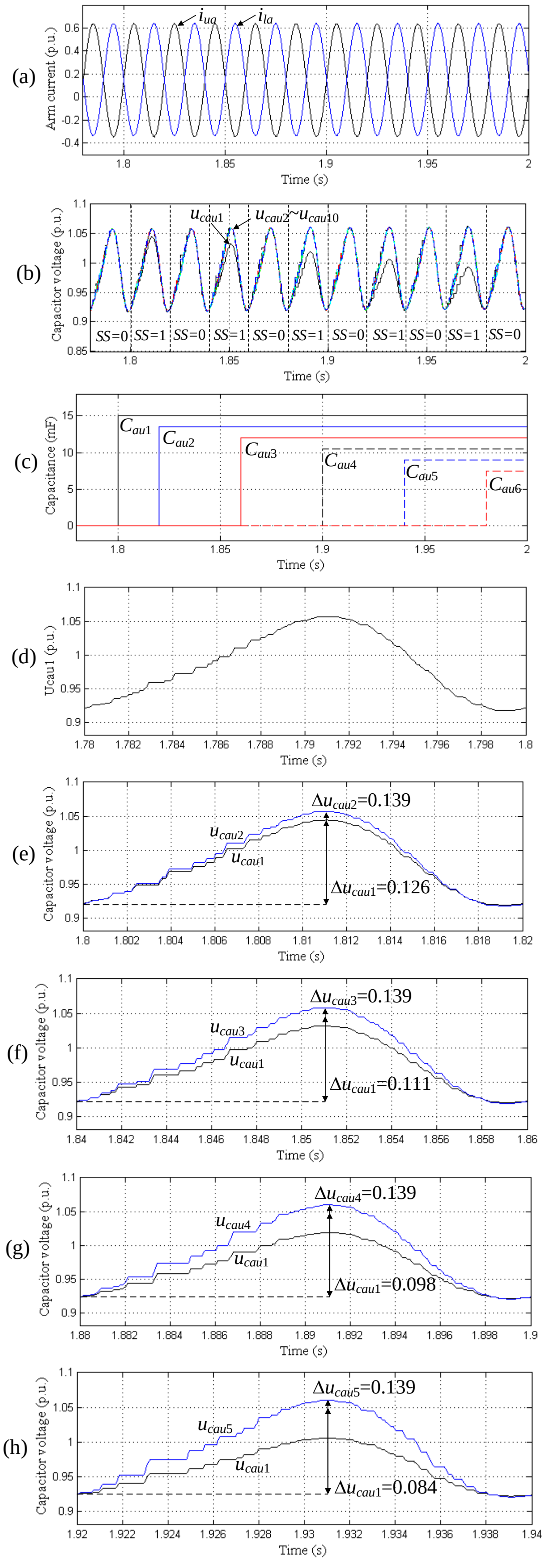
Fig. 7. Block diagram of the simulation system.

TABLE III
SIMULATION SYSTEM PARAMETERS

Parameters	Value
DC-link voltage V_{dc} (kV)	100
Grid line-to-line voltage (kV)	220
Grid frequency (Hz)	50
Transformer voltage rating	50 kV/220 kV
Transformer leakage reactance	10%
Number of SMs per arm n	100
Nominal SM capacitance C (mF)	15
Inductance L_s (mH)	10
Load inductance L_f (mH)	2

Fig. 8 shows the performance of the MMC with the proposed capacitor monitoring strategy, where the average switching frequency is about 2.5 kHz. Fig. 8(a) shows the arm current i_{ua} and i_{la}. Fig. 8(b) shows capacitor voltage u_{cau1}~u_{cau10}. Before 1.8 s, the C-VBC is used with "SS=0". With the conventional capacitor monitoring method, the C_{au1} is estimated as 15 mF, as shown in Fig. 8(c). And then, the SM$_1$ is selected as the RSM. Between 1.8 s and 1.82 s, the C_{au2} is monitored with "SS=1", where the switching function for SM$_1$ is the same to that for SM$_2$. The different C_{au1} and C_{au2} result in the different capacitor voltage u_{cau1} and u_{cau2}, as shown in Fig. 8(e), where Δu_{cau1} and Δu_{cau2} are 0.126 and 0.139, respectively. According to (7), the capacitor C_{au2} is monitored as 13.5 mF shown in Fig. 8(c). And then, the MMC goes back to the C-VBC with "SS=0", where all capacitor voltage are kept the same again between 1.82 s and 1.84 s. Similarly, the C_{au3}, C_{au4}, C_{au5} and C_{au6} are monitored with "SS=1" one after another. In Fig. 8(f), C_{au3} is monitored as 12 mF with Δu_{cau1}=0.111 and Δu_{cau3}=0.139. In Fig. 8(g), C_{au4} is monitored as 10.5 mF with Δu_{cau1}=0.098 and Δu_{cau4}=0.139. In Fig. 8(h), C_{au5} is monitored as 9 mF with Δu_{cau1}=0.084 and Δu_{cau5}=0.139. In Fig. 8(i), C_{au6} is monitored as 7.5 mF with Δu_{cau1}=0.07 and Δu_{cau6}=0.139. Owing to that C_{au1} is the biggest among C_{au1}~C_{au6}, the SM$_1$ is always selected as the RSM and Δu_{cau1} is less than Δu_{cau2}~Δu_{cau6}, as shown in Fig. 8(b).

Fig. 9 shows the THD of the arm current i_{ua} when the proposed strategy is employed to estimate the capacitances in the SM1~SM6, respectively, where the average switching frequency is about 2.5 kHz. In Fig. 9, the THDs of i_{ua} are almost the same with each other. It shows that the variable RSM capacitor voltage ripple has little impact on the MMC performance in the proposed capacitor monitoring strategy.



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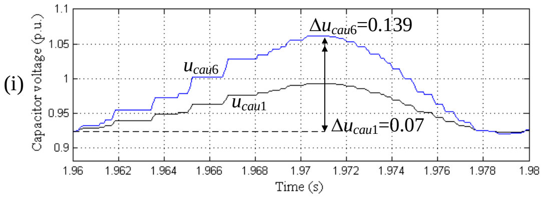


Fig. 8. (a) i_{ua} and i_{la}. (b) Upper arm capacitor voltage u_{cau1}~u_{cau10}. (c) Calculated capacitance C_{au1}~C_{au6}. (d) u_{cau1}. (e) u_{cau1} and u_{cau2}. (f) u_{cau1} and u_{cau3}. (g) u_{cau1} and u_{cau4}. (h) u_{cau1} and u_{cau5}. (i) u_{cau1} and u_{cau6}.

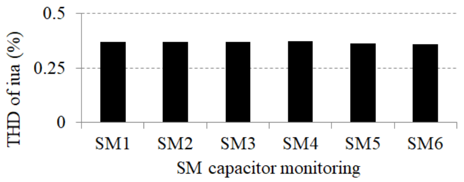
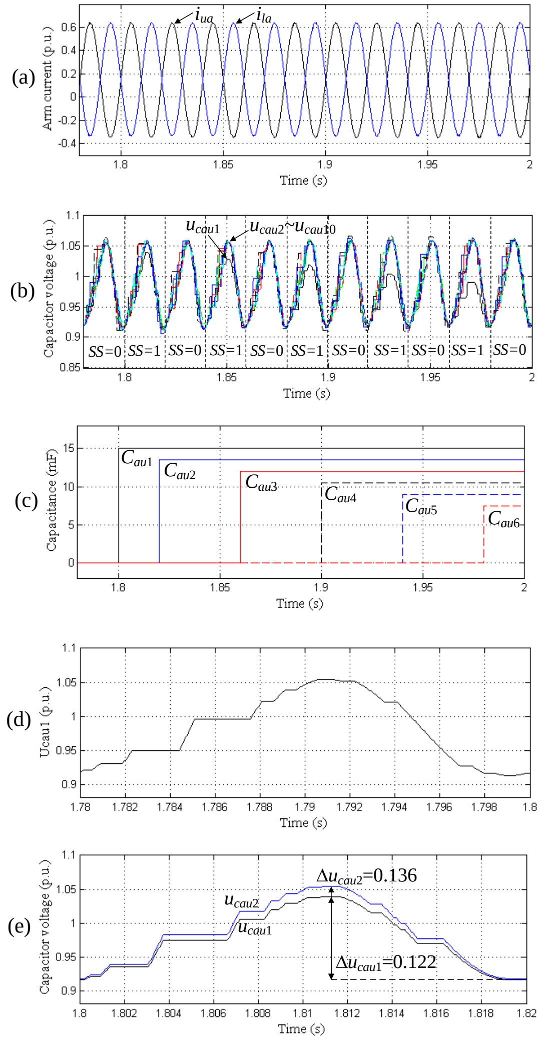


Fig. 9. THD analysis of i_{ua}.

Fig. 10 shows the performance of the MMC with the proposed capacitor monitoring strategy, where the average switching frequency is about 600 Hz. Fig. 10(a) shows the arm current i_{ua} and i_{la}. Fig. 10(b) shows capacitor voltage u_{cau1}~u_{cau10}. With the proposed capacitor monitoring method, the capacitors C_{au1}, C_{au2}, C_{au3}, C_{au4}, C_{au5} and C_{au6} are monitored as 15 mF, 13.5 mF, 12 mF, 10.5 mF, 9 mF and 7.5 mF, respectively, as shown in Figs. 10(c)~(i).



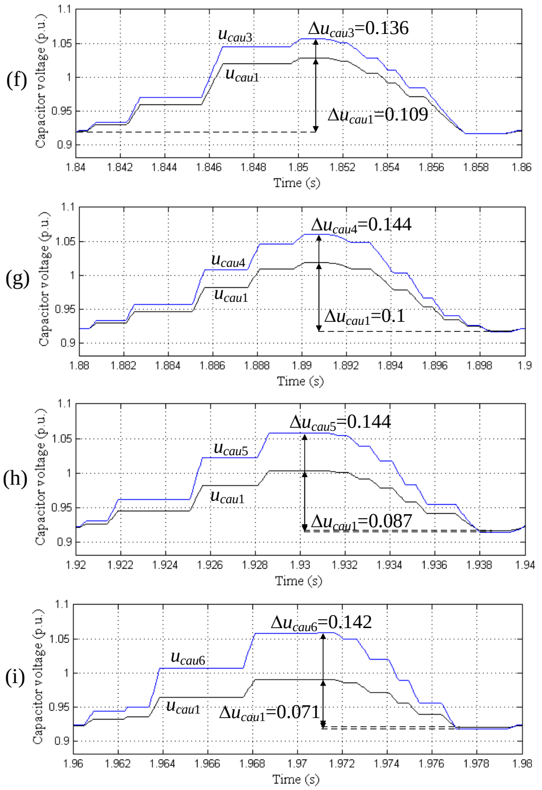


Fig. 10. (a) i_{ua} and i_{la}. (b) Upper arm capacitor voltage u_{cau1}~u_{cau10}. (c) Calculated capacitance C_{au1}~C_{au6}. (d) u_{cau1}. (e) u_{cau1} and u_{cau2}. (f) u_{cau1} and u_{cau3}. (g) u_{cau1} and u_{cau4}. (h) u_{cau1} and u_{cau5}. (i) u_{cau1} and u_{cau6}.

Fig. 11 shows the THD of the arm current i_{ua} when the proposed strategy is employed to estimate the capacitances in the SM1~SM6, respectively, where the average switching frequency is about 600 Hz. It can be observed that the THDs are almost close to each other, which shows that the variable RSM capacitor voltage ripple has little impact on the MMC performance in the proposed capacitor monitoring strategy.

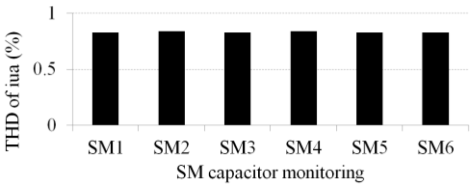


Fig. 11. THD analysis of i_{ua}.

V. EXPERIMENTAL STUDIES

A single-phase MMC prototype with 7 SMs per arm, as shown in Fig. 12(a), is built in the laboratory to confirm the proposed scheme. Fig. 12(b) shows the photo of the experimental setup. A three-phase uncontrolled rectifier with electrolytic capacitors constitutes the dc bus voltage. The IXFK48N60P is used as the switch/diode in each cell. The system control algorithm is implemented in dSPACE DS1005 and the pulse signals from the dSPACE are transferred to the driving panel of each SM by optical fiber. The system parameters are shown in the Table IV. To verify the proposed capacitor monitoring strategy, the small capacitor C_{au2} and C_{au3} are used, whose manufacture parameters are 1.88 mF and 1.41 mF, respectively.

TABLE IV
EXPERIMENTAL SYSTEM PARAMETERS

Parameters	Value
DC-link voltage V_{dc} (V)	280
Rated frequency (Hz)	50
Capacitor C_{in} (mF)	2.2
Nominal capacitor C_{sm} (mF)	2.35
Inductor L_s (mH)	3
Load inductor L (mH)	1.8
Load resistor R (Ω)	10
Switching frequency (kHz)	5

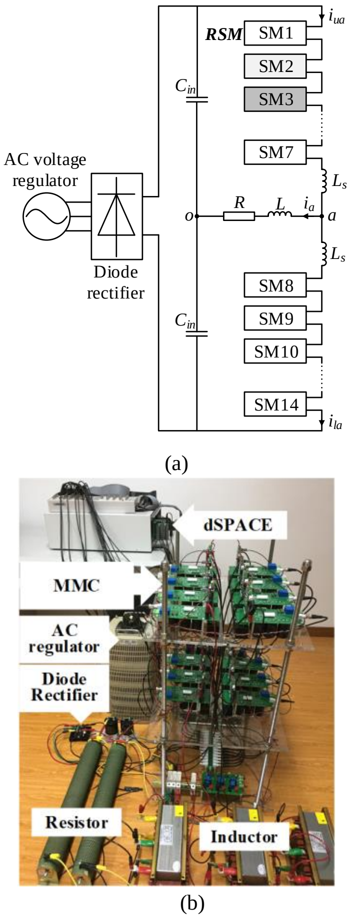


Fig. 12. (a) Experimental circuit. (b) Photo of the experimental system.

Fig. 13 shows the performance of the MMC under the proposed capacitor monitoring strategy. Fig. 13(a) shows the arm current i_{ua}. Fig. 13(b) shows the capacitor voltage u_{cau1}, u_{cau2} and u_{cau3} in SM1, SM2 and SM3, respectively. Before 0.02 s, the C-VBC is used with "SS=0". With the conventional capacitor monitoring method, the C_{au1} in SM1 is obtained as 2.22 mF. And then, the SM1 is selected as the RSM. Between 0.02 s and 0.04 s, the capacitor C_{au2} in SM2 is monitored with "SS=1", as shown in Fig. 13(c), where Δu_{cau1}=4.01 V and Δu_{cau2}=5.03 V. Consequently, the C_{au2} in SM2 is obtained as 1.77 mF based on (7). Between, 0.04 s and 0.06 s, the C-VBC is enabled to keep the capacitor voltage the same with "SS=0". Afterwards, the capacitor C_{au3} in SM3 is monitored with "SS=1" between 0.06 s and 0.08 s, as shown in Fig. 13(d), where Δu_{cau1}=3.09 V and Δu_{cau3}=5.13 V. As a result, the C_{au3} in SM3 is obtained as 1.34 mF based on (7). Owing to that C_{au1} is the biggest among C_{au1}~C_{au3}, the SM$_1$ is always selected as the RSM and Δu_{cau1} is less than Δu_{cau2} and Δu_{cau3}, as shown in Figs. 13(b)~(d).

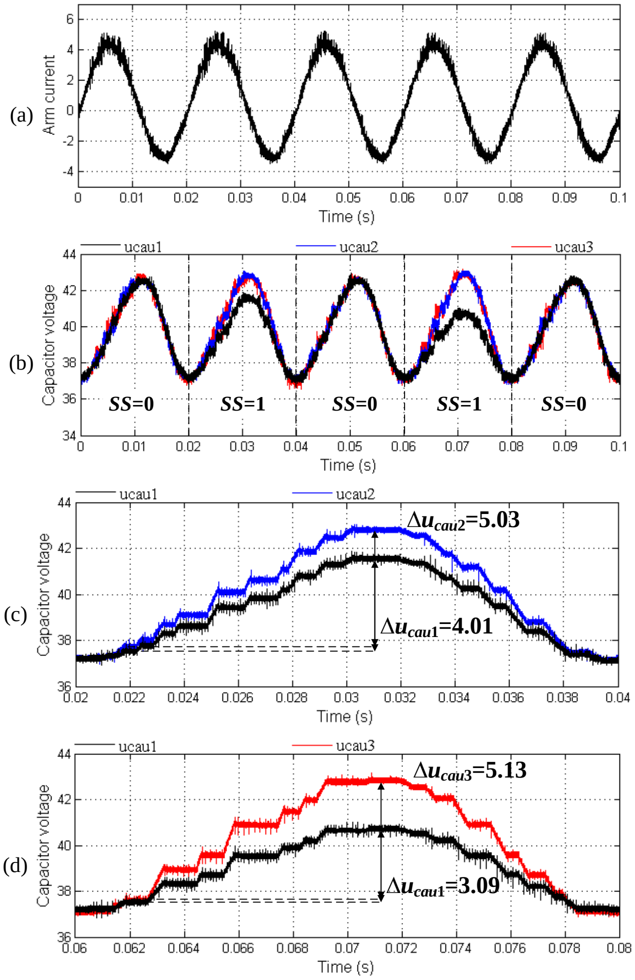


Fig. 13. (a) i_{ua}. (b) u_{cau1}~u_{cau3}. (c) u_{cau1} and u_{cau2}. (d) u_{cau1} and u_{cau3}.

Fig. 14(a) shows the monitored capacitance with the proposed strategy and the measured capacitance with the UNI-T UT612 LCR meter at 100 Hz and 25^{o}C. Fig. 14(b) shows the errors between the estimated capacitance and the measured capacitance. It shows small error, where the maximum error is less than 0.52%.

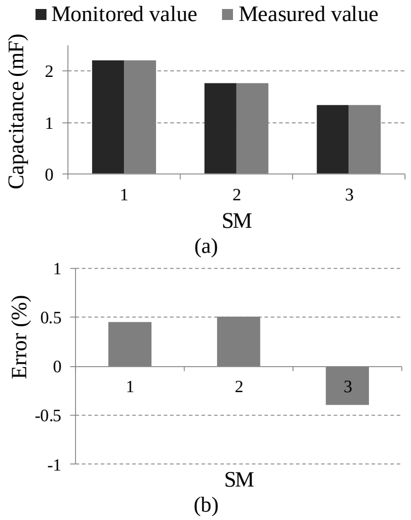


Fig. 14. (a) Monitored capacitance and measured capacitance. (b) Error.

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Fig. 15 shows the THD of the arm current i_{ua} when the proposed strategy is employed to estimate the capacitances in the SM1~SM3, respectively, where the THDs are almost the same with each other. It shows that the variable RSM capacitor voltage ripple has little impact on the MMC performance in the proposed capacitor monitoring strategy.

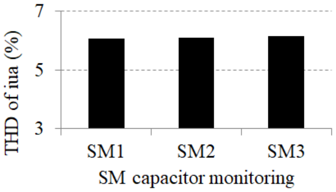

Fig. 15. THD analysis of i_{ua}.

VI. CONCLUSIONS

In this paper, a RSM-based capacitor monitoring strategy is proposed for the MMC. The SM with the biggest capacitance is selected as the RSM. Under the proposed capacitor monitoring-based voltage-balancing control, the peak-to-peak value of the RSM's capacitor voltage would be variable. Based on the capacitor voltage relationship among the RSM and the monitoring SMs, the SMs' capacitances can be estimated based on the RSM's capacitance. The proposed RSM-based capacitor monitoring strategy does not rely on the information of all capacitor voltage and current, which realizes the capacitor monitoring with simple algorithm and simplify the computation. The simulation and experiment studies are conducted to verify the proposed strategy, and the results show the effectiveness of the proposed RSM-based capacitor monitoring strategy.

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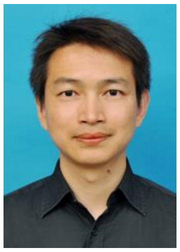

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