Smoothing Reactor Effect on Harmonics and Power Quality for Modular Multilevel Converter

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Abstract— This paper presents the effect of changing arm inductor (smooth reactor for HVDC) on the modular multilevel converter (MMC) behavior in order to analysis the change on Total Harmonics Distortion (THD) for all MMC quantities including circulating current, upper arm current and voltage, lower arm current and voltage, and AC output voltage and current. For the reason that increasing arm inductor size could reduce the THD of the MMC, this effect will be investigated in this paper. The functions of smoothing reactor, are explained firstly. Secondly, size of arm inductor (Smooth reactor for HVDC systems) are discussed. Analysis of the smooth reactor value effect on MMC, is carried out from many simulation results in this paper. Finally, the hardware design and software design of the prototype are presented to verify the arm inductor value effect on MMC experimentally. The experimental results are also documented in this paper.

Index Terms— Arm inductance effect on MMC, Smoothing reactor effect on MMC.

1 Introduction

THIS One of the important parts of the MMC HVDC is the DC smoothing reactor. They are used in HVDC links and industrial applications such as rectifiers, traction systems, etc [3]. The smoothing reactor for MMC is connected in the way of the DC transmission and in series with the converter as in Figure 1 for single phase and Figure 2 for three phase. A part from smoothing the direct current, it also serves as a buffer between the converters and the DC line. the sizing of the reactor depends on various requirements including the reduction of ripple in the circulating current for MMC. Smoothing reactor – it is a static electromagnetic device designed to use its inductance in the electric circuit to surprise circulating current ripple to reduce higher harmonics. The ripple shall be within limits up to 10% of the direct current value [5]. The DC smoothing reactor was considered an essential requirement for HVDC operation [14]. Smoothing Reactors can be designed up to 1.5 H [6]. For transmission systems reactor values varying from 0.27mH to 1.5H, While for back-to-back systems values is varying from high of 200mH to a low of 12mH. HVDC Transformer Technology can be designed for Voltages up to ±1100KV [7].

The smoothing reactors have many functions as follow:-

1. They reduce the incidence of commutation failure in inverters caused by dips in the AC voltage at the converters bus [13].
2. They prevent consequent commutation failures in inverters by reducing the rate of rise of direct current in the bridge when the direct voltage of another series connected bridge collapses [1].
3. They smooth the circulating current by reducing the ripple in the direct current in order to prevent the current becoming discontinuous at light load.
4. They decrease harmonic output voltages and current in the MMC system.
5. They limit the crest current in the rectifier due to a short circuit on the DC line [1].
6. They limit the current in the valves during the converter bypass pair operation, due to the discharge of shunt capacitances of the DC line [1].
7. Smoothing reactors are used to reduce the harmonic all quantities either voltages or currents in the MMC system which will be proved by computer simulation and experimentally.

For systems with DC transmission lines, the inductors of value from 270 mH to 1.5 mH have been used. For back to back HVDC systems, the value ranges from 12 mH to 200 mH [1]..

inductance value must remain practically constant with variation in the direct current. This requires aircore construction [1].

The final reactor size is a matter of optimization with respect

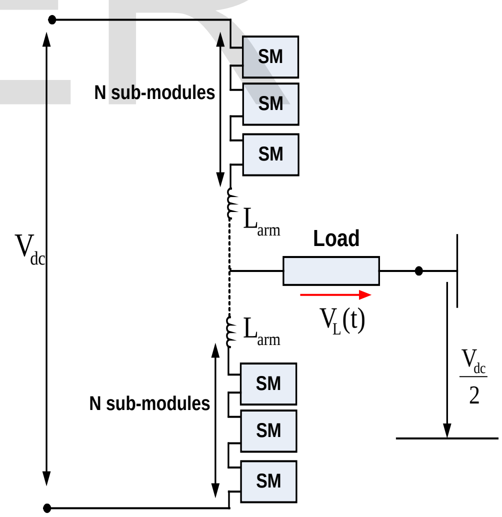

Figure 1 single phase MMC circuit

to several considerations such as [4]

1. Current extinction
2. Commutation performance
3. Harmonics current reduction
4. Cost and available sizes in the market, e. g., the cost from one manufacturer for a 50mH, 2000A air-core reactor would be approximately 3.6 times the cost of 10mH reactor; and
5. Surge current suppression

$$S_i = \frac{V_{dc}}{(L * I_{dc})} \quad (1)$$

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For the study in [9], a reactor size corresponding to an intermediate value of S (as defined in (1)) was chosen. (S = 0.45/ms with Vdc = 500 kV and Idc= 1100 A, L = 1 H). Table 1 shows some values for smoothing reactors for some HVDC systems.

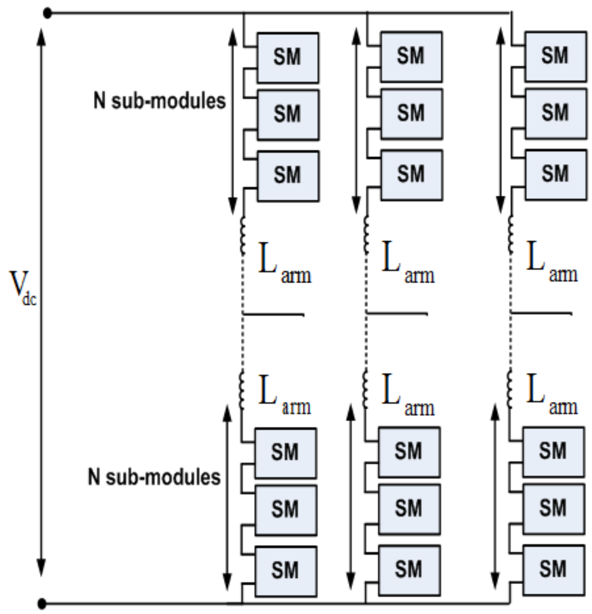

Figure 2 three phase MMC circuit capacitors

One of the major components an HVDC system is air-core dry-type reactors and they used for the purposes mentioned before. As an example the one-line diagram in Figure 3 shows a typical HVDC system. HVDC smoothing reactors (a) are connected in series with the HVDC transmission line or in the intermediate DC circuit of a back-to-back interconnector [2]. HVDC filter reactors are installed on the AC side (c) as well as on the DC side (b) of the converter station [2].

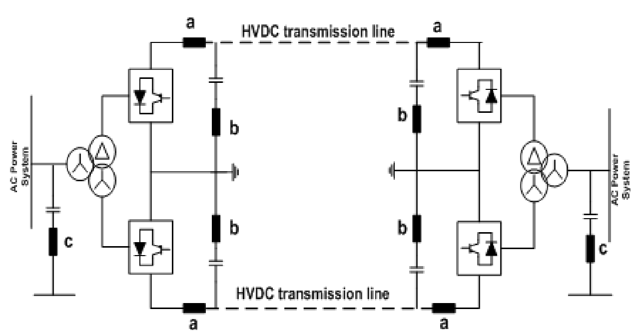

Figure 3 Smoothing reactor location for HVDC system [2]

2 REACTOR SIZE

According to table 1, there is a wide range of reactor sizes which will change the performance of MMC. There is a little information available on the choice of the optimum size of the DC smoothing reactor. One criterion used is the S_i factor is defined below [4]

TABLE I

SMOOTHING REACTOR OF SEVERAL HVDC SYSTEMS [9]

HVDC station	I_{dc}(A)	V_{dc} (KV)	L (H)	S (ms^{-1})
Cabora Bassa	1800	533	0.83	0.36
Pacific Intertie	1800	400	0.4	0.55
Nelson River II	1800	500	0.75	0.37
Hokkaido-Honshu	1200	250	1	0.21
Vancouver Is. II	1320	280	0.6	0.35
Inga Shaba	560	500	1.5	0.6
Skagerrak	1000	250	0.505	0.5
CU Project	1250	400	0.4	0.73
Itaipu	2625	600	0.27	0.85
Intermountain	1600	500	0.3	1.26

Where V_{dc} and I_{dc} are rated direct voltage (in KV) and direct current (in KA) respectively. L is the DC circuit inductance in mH which includes the transformer leakage inductance [4].

$$L = 3.5 * L_t + L_d \qquad (2)$$

where L_t is converter transformer inductance, and L_d smoothing reactor inductance. Since L_t so small compared to L_d for MMC, equation (1) can be re-written for MMC reactor inductance (arm inductance) as follow:-

The S_i factor for back to back HVDC links varies from 0.24 to 1.3 ms^{-1}. High the factor, lower is the rate of rise of the fault current [1]. According to the equation of arm inductor size in [10], For the minimum arm inductor size for medium voltage applications single

$$L_{arm} = \frac{3}{8 * \omega^2 \, C_{SM} \, V_C} \left(\frac{S}{3 \, I_{diff}} + V_{dc} \right) \qquad (4)$$

phase MMC can be calculated as follow:

Where ω radian fundamental frequency, C_{SM} submodule capacitor size, V_C submodule capacitor voltage, V_{dc} DC bus, I_{diff} maximum circulating current ($I_{diff} = I_{dc}$ for single phase system), and S apparent power (0.5 $V_m I_m$).

3 SIMULATION RESULTS

Since the smoothing reactor is used to suppress the circulating current, what is the effect of suppressing circulating current on output voltage and current THD?. With going up with the value of arm (reactor) inductance more and more, the circulating current is going to be flat more and more (has less fluctuation) that tends to be more stable. Stability of circulating current tends to stability of submodule voltage in the arm. Upper arm voltage and lower arm voltage will have less THD when the fluctuation of the capacitor voltage is going to be less and less. With case both upper and lower arm voltages have small THD; output voltage THD will be lost. Simulation results show that at certain case of large number of submodules there is no way to reduce THD less than 1% only by going up with the value of arm inductor or large number of submodules per arm. It is possible to say that smoothing reactor has another function beside the functions mentioned above which is output voltage and current THD control. 25-level MMC had been chosen to analyze the behavior of MMC with large values of arm inductors. Table II shows the simulation results for MMC 25-level at different values of arm inductor with the same DC bus and all parameters compared with calculated value(5mH).

Figures from 4 to 8 show the simulation results for MMC 25-level at calculated value of the arm inductor 5mh.

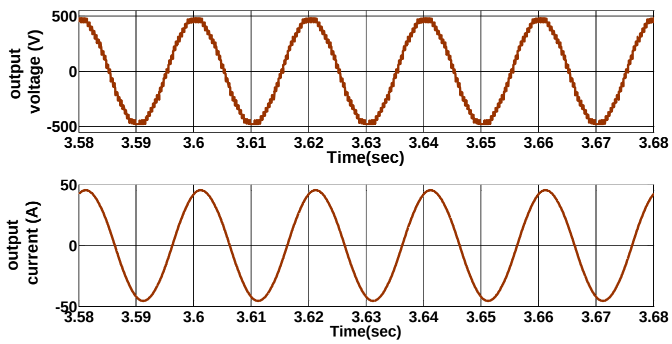

Figure 4 AC Output Phase Voltage and current for 25- level MMC at arm inductor 5 mH

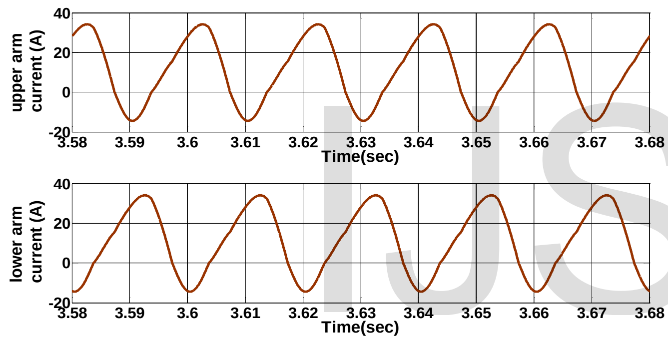

Figure 5 Upper and lower Arm Currents for 25- level MMC at arm inductor 5 mH

Figures 9 to 13 show the simulation results for MMC 25-level at eight times of inductance value of the arm inductor at 40mH.

Figure 14 shows the relationship between arm inductor and output voltage THD, figure 15 shows the relationship between arm inductor and maximum output voltage, figure 16 shows the relationship between arm inductor and circulating current ripple, and figure 17 shows the relationship between arm inductor and capacitor voltage ripple. As expected and can be seen from Table II, THD for output voltage and current, THD for upper and lower arms current, circulating current ripple, and capacitor voltage ripple can be reduced by increasing the value of arm inductor.

The output voltage THD will be decreased with increasing arm inductance as can be seen in the relationships in Figures 14.

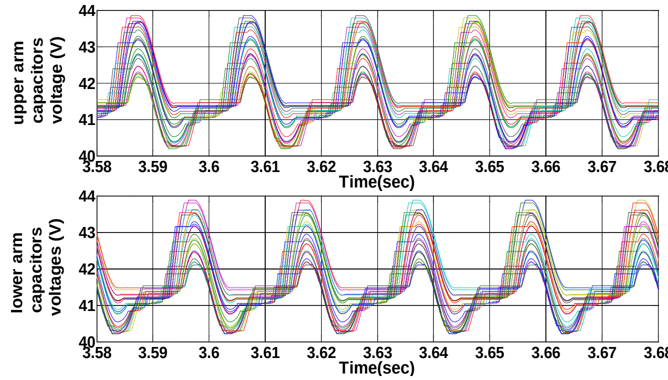

Figure 6 Intermediate capacitors voltages for 25- level MMC at arm inductor 5 mH

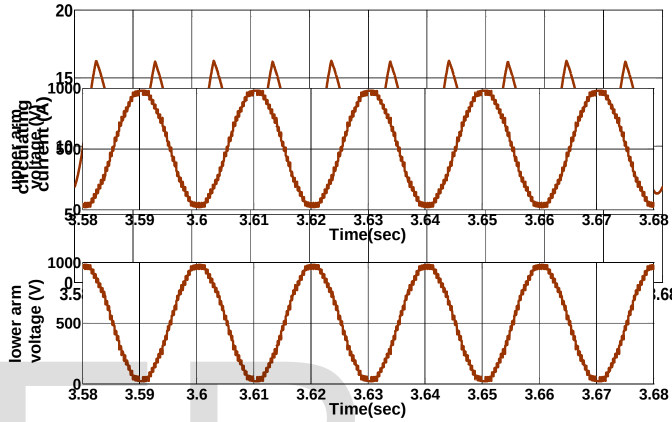

Figure 7 Circulating current for 25- level MMC at arm inductor 5 mH

Figure 8 Upper and lower Arm voltages for 25- level MMC at arm inductor 5 mH

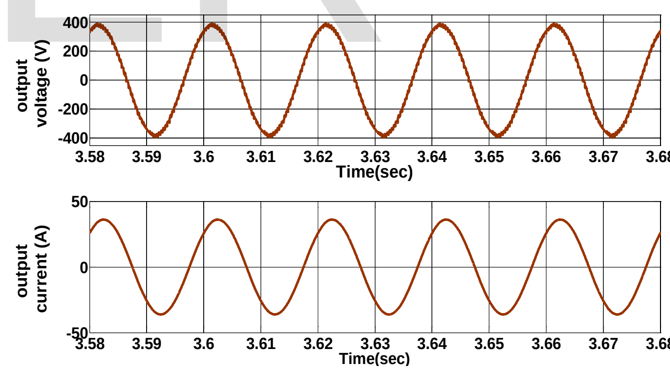

Figure 9 AC Output Phase Voltage and current for 25- level MMC at arm inductor 40 mH

TABLE II THE SIMULATION RESULTS FOR MMC 25-LEVEL AT
WITH THE SAME DC BUS AND ALL

Inductor size (mH) For 25 level at 24.1mF	Output Voltage		Output Current		Upper arm current		Lower arm current		Upper
	THD%	Max. Value (V)	THD%	Max. Value (A)	THD%	DC component	THD%	DC component	THD%
0.5	5.32	490	1.23	46.75	65.05	11.1	64.9	11.2	146.7
1	5.15	488.1	1.2	46.57	56.48	11.1	56.1	11.1	54.69
2	5.04	483.5	1.06	46.13	45.64	10.9	45.6	10.9	46.53
4	4.57	479.9	0.78	45.78	25.37	10.8	25.4	10.8	47.52
5	4.39	478.1	0.73	45.62	20.86	10.7	20.9	10.7	66.77

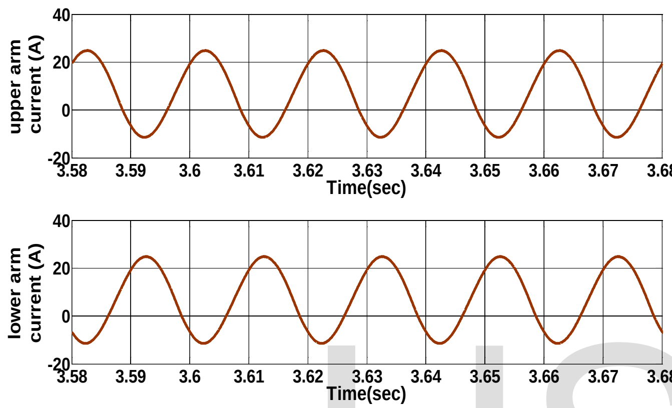

Figure 10 Intermediate capacitors voltages for 25- level MMC at arm inductor 40 mH

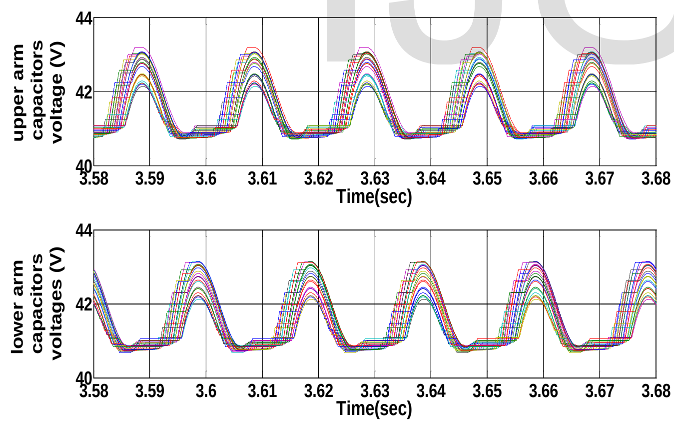

Figure 11 Upper and lower Arm Currents for 25- level MMC at arm inductor 40 mH

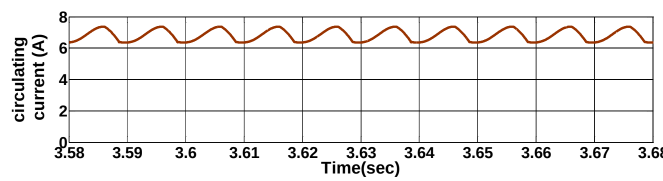

Figure 12 Circulating current for 25- level MMC at arm inductor 40 mH

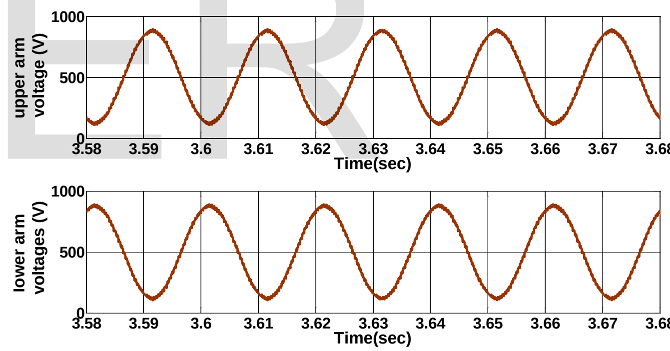

Figure 123 Intermediate capacitors voltages for 25- level MMC at arm inductor 40 mH

4 4 SIMULATION AND IMPLEMENTATION OF 50-LEVEL TO 1057-LEVEL

This part is concentrating on the complete analysis of the change in THD with increasing both DC bus voltage, number of submodules per arm, and smoothing reactor inductance for HVDC systems and simulation results are given in Table III. Figures 18 to 20 show simulation results for 529-levels.

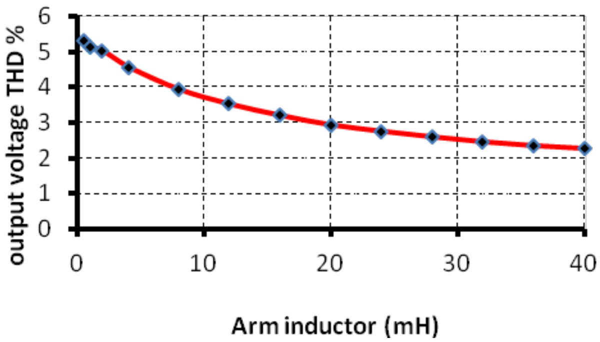

Figure 14 The relationship between arm inductor and THD

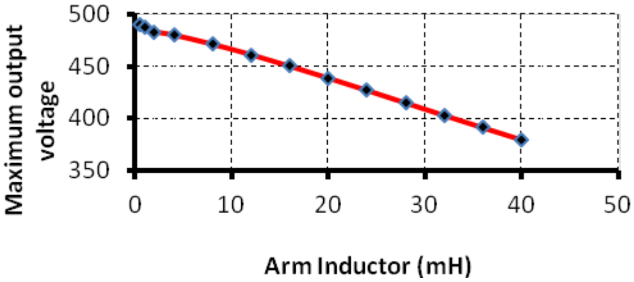

Figure 15 The relationship between arm inductor and maximum output voltage

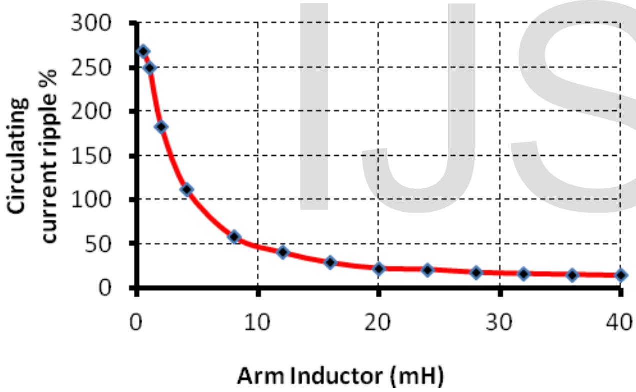

Figure 16 The relationship between arm inductor and circulating current ripple

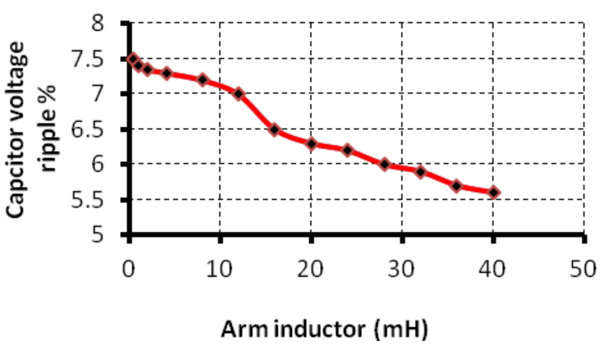

Figure 17 The relationship between arm inductor and capacitor voltage ripple

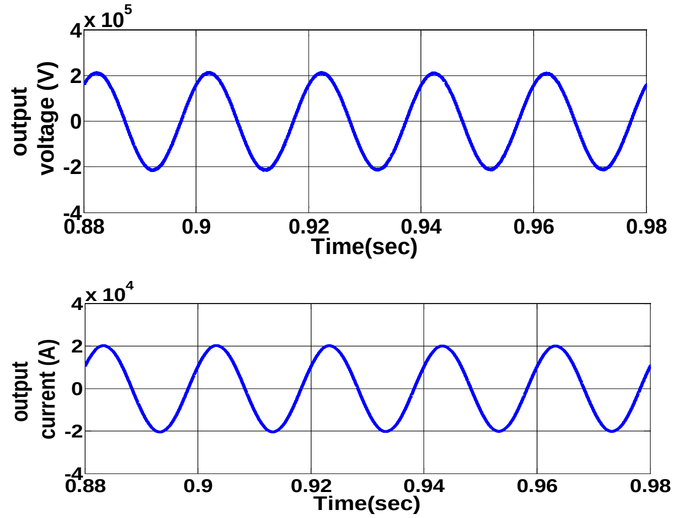

Figure 18 AC Output Phase Voltage and current for 529- level MMC by using MHMC

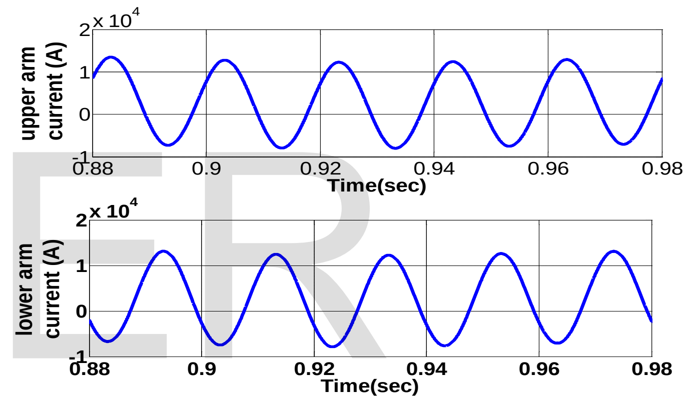

Figure 19 Upper and lower Arms Currents for 529- level MMC by using MHMC

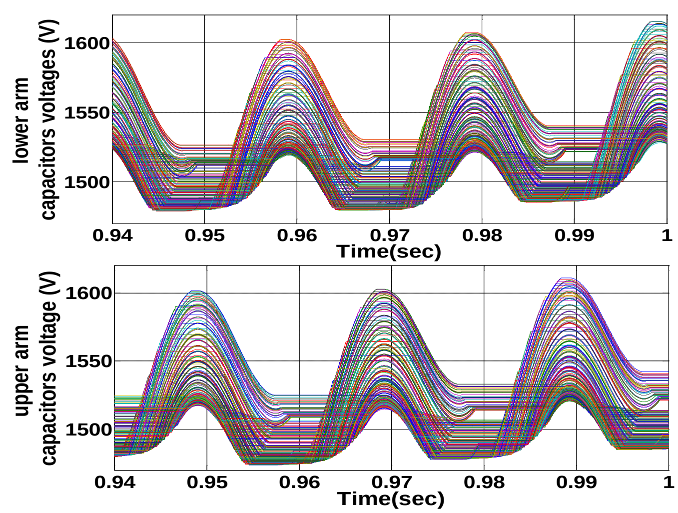

Figure 21 upper and lower arms Intermediate capacitors voltages for 529- level MMC by using MHM

TABLE III THE SIMULATION RESULTS FOR HIGH MULTILEVEL OUTPUT VOLTAGE AT DIFFERENT VALUESOF ARM INDUCTOR AND DIFFERENT VALUES OF DC BUSES.

Number of output voltage levels	Submodule capacitor mF	Arm inductor	DC bus (KV)	Output Voltage		Output Current		Upper arm current		Lower arm current		Upper arm voltage		Lower arm voltage		Circulating current	
				THD%	Max. Value (KV)	THD%	Max. Value (KA)	THD%	DC component (KA)	THD%	DC component (KA)	Voltage ripple %	DC0 component (KV)	Voltage ripple %	DC component (KV)	Current ripple %	DC component (KA)
49	48.4	9.6	400	2.13	190	0.28	18.13	6.81	4.148	6.76	4.16	8.9	8.29	9.8	8.26	26.4	4.16
		15	400	1.86	184	0.25	17.5	4.3	3.88	4.28	3.88	8.5	8.17	8.5	8.19	18	3.88
		25	500	1.55	214.6	0.21	20.48	2.55	4.218	2.52	4.218	7	10.35	7	10.25	13	4.218
97	96.77	9.6	400	1.53	189.4	0.13	18.1	7.48	4.14	7.48	4.15	9.9	4.118	9.9	4.13	30.2	4.14
		20	400	1.2	177.4	0.22	16.92	3.31	3.625	3.32	3.62	9.7	4.117	9.7	4.10	13.8	3.623
		25	500	1.1	214.1	0.2	20.42	2.61	4.224	2.61	4.221	9.8	5.085	9.8	5.148	12.3	4.223
145	145.1	9.6	400	1.45	188.9	0.3	18.02	7.54	4.126	7.53	4.135	11	2.727	11	2.74	30	4.132
		25	400	1.04	170.8	0.2	16.3	2.62	3.375	2.61	3.375	10	2.708	10	2.74	11.85	3.375
		25	500	1.04	213.5	0.2	20.37	2.62	4.218	2.61	4.218	10.2	3.418	10.2	3.439	12.6	4.218
193	193.5	9.63	400	1.38	188.3	0.3	17.96	7.64	4.122	7.65	4.118	6.1	2.057	6.1	2.02	31.6	4.12
		25	400	1	170.4	0.21	16.26	2.67	3.37	2.67	3.37	9.8	2.036	9.8	2.03	12	3.37
		25	500	1	213.2	0.21	20.32	2.66	4.213	2.66	4.211	11	2.582	11	2.567	13	4.212
217	217.7	25	500	0.98	213	0.26	20.29	2.69	4.232	2.67	4.238	10.7	2.343	10.7	2.26	12	4.235
		47	400	0.79	144.1	0.16	13.75	1.5	2.415	1.49	2.414	8	1.802	8	1.816	10	2.414
		100	400	0.6	98.57	0.07	9.404	0.67	1.043	0.67	1.04	6	1.826	6	1.828	7.1	1.041
241	241.9	9.6	400	1.3	187.7	0.3	17.91	7.85	4.109	7.58	4.11	10.8	1.664	10.8	1.66	32.8	4.109
		25	400	0.95	170	0.21	16.21	2.65	3.363	2.65	3.363	9	1.623	9	1.63	11.9	3.363
		25	500	094	212.4	0.2	20.37	2.62	4.218	2.61	4.218	10	3.402	10	3.378	11.9	4.218
		40	400	0.83	152	0.17	14.5	1.72	2.69	1.72	2.69	7.5	1.633	7.5	1.65	9	2.69
289	290.3	25	500	0.86	211	0.06	20.06	0.65	4.134	0.65	4.134	2.3	1.725	2.3	1.714	4.8	4.134
337	338.7	25	500	0.79	210.6	0.26	20.02	0.8	4.119	0.81	4.121	7	1.473	7	1.474	9.2	4.12
433	436.5	25	500	0.59	210.4	0.37	20.1	2.83	4.188	2.48	4.163	10.7	1.123	10.7	1.13	12	4.176
529	533.2	25	500	0.55	209.3	0.2	19.97	2.68	4.166	2.68	4.164	10	0.921	10	0.916	13	4.165
		50	800	0.42	277.8	0.15	26.5	1.42	4.594	1.42	4.591	8	1.466	8	1.494	9.7	4.592
1057	1064.5	73	1600	0.5	460.8	0.1	43.95	1.01	6.464	1.1	6.472	8.8	1.469	8.8	1.47	7.7	6.468
		80	1600	0.47	438.7	0.09	41.85	1.32	5.63	1.34	5.636	8	1.47	8	1.48	5.3	5.633

To achieve low THD for HVDC, smoothing reactor inductance should be increased in order to surprise second harmonic component for upper and lower arm current. From simulation processes for HVDC systems in Table III, it is possible that with high inductance for smoothing reactor, THD can be less than 1% compared to smaller inductance. Medium and large number of submodules had been simulated by Matlab Simulink. At different DC bus for different number of submodules per arm, the results were taken. Table III shows the simulation results for high multilevel output voltage at different values of arm inductor and different values of DC buses.

5 Experimental Rresults

The effect of arm inductor (smoothing reactor for HVDC) for the MMC is also verified on a phase-leg experimental prototype with two submodules per arm as shown in figure 22. The modulation, voltage sorting, and balancing algorithms are implemented using the DSP F2812 board in order to verify the simulation results. The final form of a prototype MMC board is shown on Figure 22. It is equipped with eight switches on a heat sink, as depicted. Each submodule needs the blocking ability of about of voltage range from 5 to 30 volt. For the rating of this prototype, MOSFETs were chosen, since they have the necessary blocking voltage up to 35V. The MOSFET that is used is the DMN4036LK3-13 from ZETEX, which has a RDSon value of only 36 mΩ, and can handle voltages of more than 30 V and currents of 8A. The MOSFETs are driven by a dual driver of type IR2110, This driving unit controls both MOSFETs with only one control signal. A dead time of approximately 1 µs. The

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modulation control scheme was tested first, as a final MMC control validation approach. The results, which are given below, correspond to single-phase operation with 10kHz switching frequency. Figure 23 shows the output voltage of the 3-level modulation concept , consisting of three levels as expected and output phase current.

Also Figure 24 shows the resultant of upper (at top) and lower (at bottom) arms voltages are giving the output voltage (at middle). Figure 25 shows the resultant of upper (at top) and lower (at bottom) arms currents are giving the output current (at the middle). The waveforms in Figures 26 to 29 show the change in circulating current with increasing the arm inductance I_{diff} of a 10 ms period from 250 µH to 1000 µH.

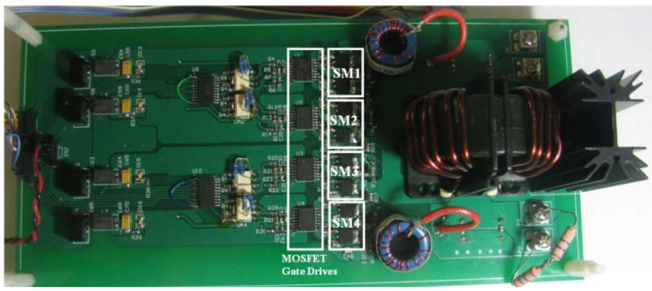

Figure 22 Laboratory prototype modular multilevel converter phase-leg

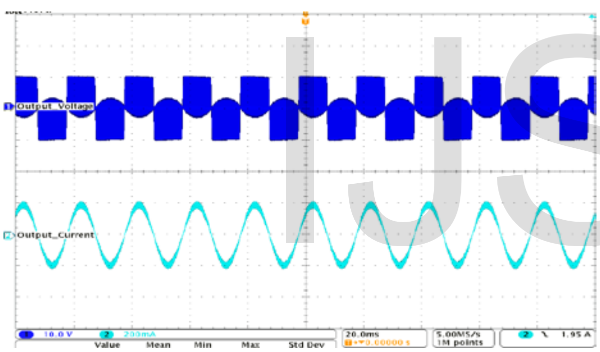

Figure 23 Experimental results: three-level phase-voltage and load current

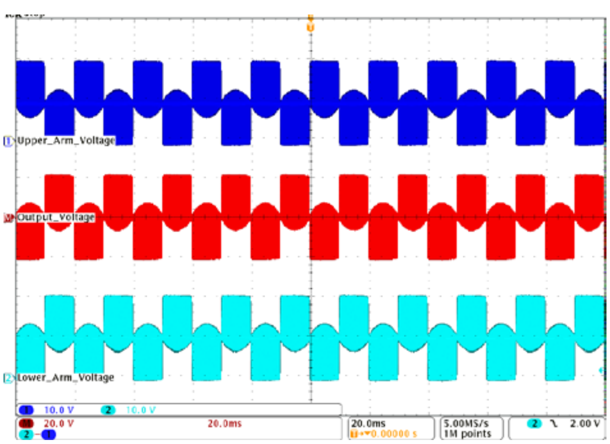

Figure 24 Experimental results: Upper arm voltage (top),
lower arm voltage (bottom) and output voltage (middle) of the MMC

Since the initial aim of the experimentation is the validation of the effectiveness of arm inductor on MMC behavior and the comparison with the simulation results, the converter is run on a single-phase only. The arm currents (upper arm current at the top and lower arm current at the bottom) and circulating current at the middle, which are depicted in Figures 21, 22, 23, and 24 at different values of arm inductance and they prove the effectiveness of arm inductance on MMC.

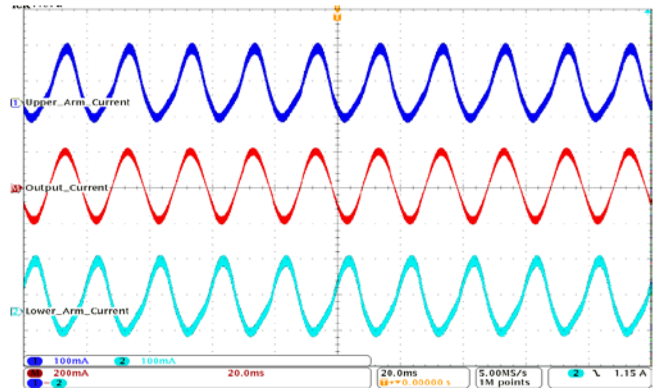

Figure 25 Experimental results: Currents through the upper (top) arm,
lower (bottom) arm and output current (middle) of the MMC

Figures 21, 22, 23, and 24 show some distortion and contain a strong second harmonic component with low arm inductance. Since the second-order harmonic of the arm currents is almost eliminated and has been sufficiently suppressed, leading to a smaller AC component of the circulating current to be almost pure DC circulating current. Therefore, the arm currents and the circulating current are less distorted with large amount of arm inductance. From Table II and The experimental results, it is obvious that both results experimentation and simulation agree each other.

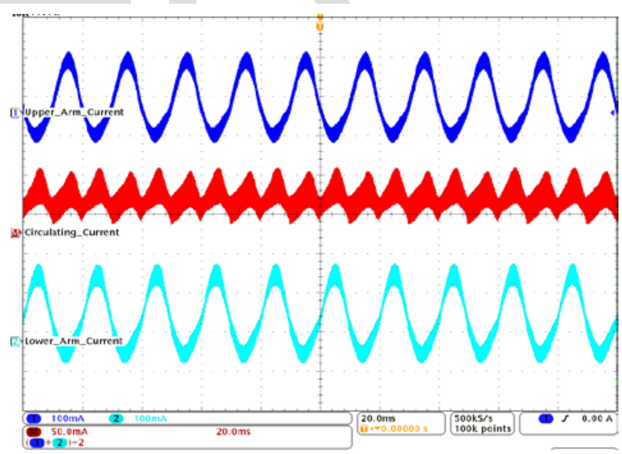

Figure 26 Experimental Results at 250 µH arm inductor

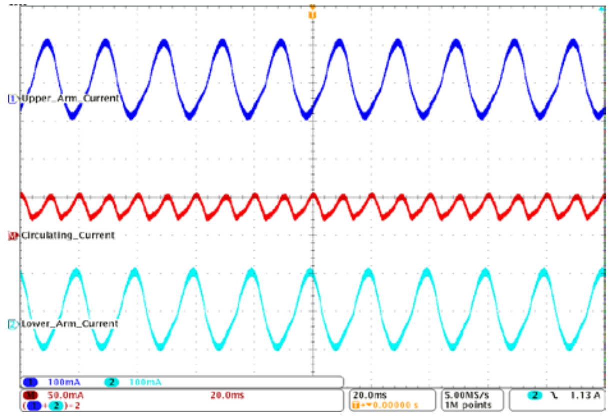

Figure 28 Experimental Results at 750 µH arm inductor

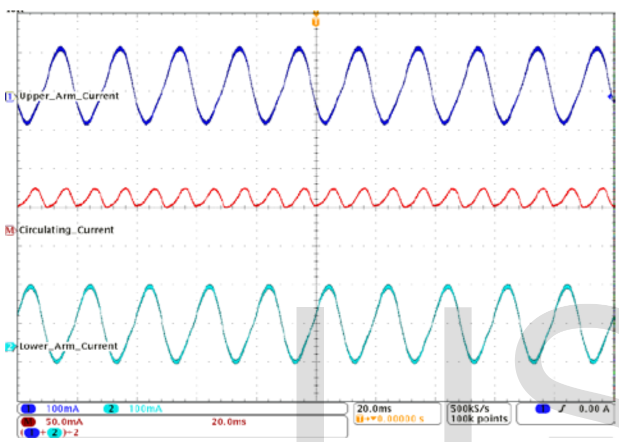

Figure 29 Experimental Results at 1000 µH arm inductor

6 CONCLUSION

This paper described the effectiveness of MMC arm inductor (smoothing reactor for HVDC), and the behavior of MMC with changing the values of this component. Moreover, this paper analyzed the effectiveness of Arm inductor on MMC THD for all quantities, maximum output voltage and current, circulating current ripple, capacitor voltage ripple, and upper and lower arms current.

Also, 50-level to 1057-level MMC were simulated and implemented in order to show the approximated values of MMC smoothing reactor for high, extra and ultra voltages. Not only the relationship between Number of output voltage levels at same DC bus and arm inductance and THD was implemented, but also the relationship between Number of output voltage levels at same DC bus and arm inductance and maximum output voltage was also presented. On one hand, it is obvious that increasing the arm inductance leads to stabilize the circulating current and capacitor voltage which leads to reduce THD for the output voltage and current. On the other hand, increasing arm inductance lead to decrease the maximum output voltage which is indicating that increasing arm inductor is acting as modulation index. In this paper, the prototype hardware, the implementation and experimental results of the effectiveness of arm inductor on MMC behavior is discussed and evaluated in order to bring agreement with simulation results.

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