

Spatial Repetitive Controller for Improved Steady State Performance of Droop Regulated Modular Multilevel Converter in Wind Farm Application

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Abstract—Modular Multilevel Converters (MMC) are emerging as a promising technology for high power conversion at high voltage levels. When frequency droop regulated MMC is used as a front-end converter to integrate wind farm into HVDC grid, variation in the fundamental operating frequency results in the change of circulating current harmonic frequencies. Due to this variation in harmonic frequencies, conventional time-domain based repetitive controller with fixed sampling frequency will fail to alleviate the circulating harmonic currents. In this paper, a spatial repetitive controller (SRC) based circulating current controller is proposed to effectively attenuate the harmonics in the circulating currents even under variable frequency operation of MMC, to improve its steady-state performance. SRC has a strong periodic disturbance rejection capability, therefore, can effectively alleviate the circulating harmonic currents and is independent of the fundamental AC line frequency of the MMC. A scaled-down laboratory prototype of a single phase, 5-level MMC is developed to experimentally validate the performance of the proposed control strategy. Experimental results are presented to substantiate the improvement in steady-state performance of the MMC with the proposed spatial repetitive based circulating current controller.

I. INTRODUCTION

Modular multilevel converter (MMC) has become an attractive alternative to the conventional multilevel power converter topologies due to its superior properties [1], [2], especially in high and medium voltage applications. These applications range from high voltage direct current (HVDC) transmission, split battery energy management systems to offshore renewable energy integration. Features like modularity, which in turn brings in scalability, fault tolerant operating capability and distributed capacitance, which avoids catastrophic failure, made MMC more popular than its counterparts [3]. But, due to the inherent structure of the MMC, there are some control issues to be addressed for it to deliver optimum performance. One of the issue is internal circulating harmonic current in this MMC, where lot of research has been done to deal with it.

Even order harmonics in the circulating current distorts the shape of the arm current, in addition bring in higher current stress to the devices and increases the power loss in the converter, resulting in low efficiency [4]. If the second order harmonic component of the circulating current is allowed to propagate, it can result in series of higher, even-order harmonic currents. Conventional controller like proportional and integral

controller has limited harmonic rejection capability due to lower gains at harmonic frequencies and fails to attenuate circulating harmonic currents. This results in poor steady state performance of the converter. Where as, the resonant controllers exhibit better attenuation capability compared to PI controller due to their high gains at the designed frequency. As discussed, the second order harmonic in the the circulating current can trigger a series of higher order harmonics. This asks for multiple resonant controllers to be connected in parallel to effectively dampen out the harmonics. But, use of multiple resonant controllers might complicate the design process and also might compromise the system stability. On the other hand a single repetitive controller can attenuate multiple harmonics and has high periodic disturbance rejection capability. In [5] and [6] authors have demonstrated the improvement in steady state performance with the use of repetitive controller (RC) in conjunction with the PI controller. This is due to the fact that RC offers a high gain at a designed specific frequency and at all corresponding harmonic frequencies.

In the case of MMC, which is used to integrate the AC grid formed by the offshore wind farm into the HVDC grid (Fig. 1), the AC line frequency droop control will be employed to vary the active power set points of each turbine equipped with full back-to-back voltage source converters in the wind farm [7]. Generally, wind farms with large number of turbines often uses droop control architecture for control of power flow from each turbine. Droop control enables decentralized control, which eliminates the requirement for intercommunication between the MMC and the back-to-back converters. Centralized control requires high bandwidth communication infrastructure which increases the cost and also reduces the reliability. In decentralized control the control of power flow from each turbine is enabled by local measurements available to each back-to-back converter. MMC which is integrating the wind farm into HVDC transmission will have control over voltage and frequency of the AC grid, to which all the back-to-back converters are connected. Therefore to control the active power flow fed by the individual turbines, MMC will vary the line frequency, which varies the power fed by back-to-back converters according to their designed droop characteristics. In this case, the fundamental AC line frequency of MMC can vary over a significant range and same with the harmonics frequen-

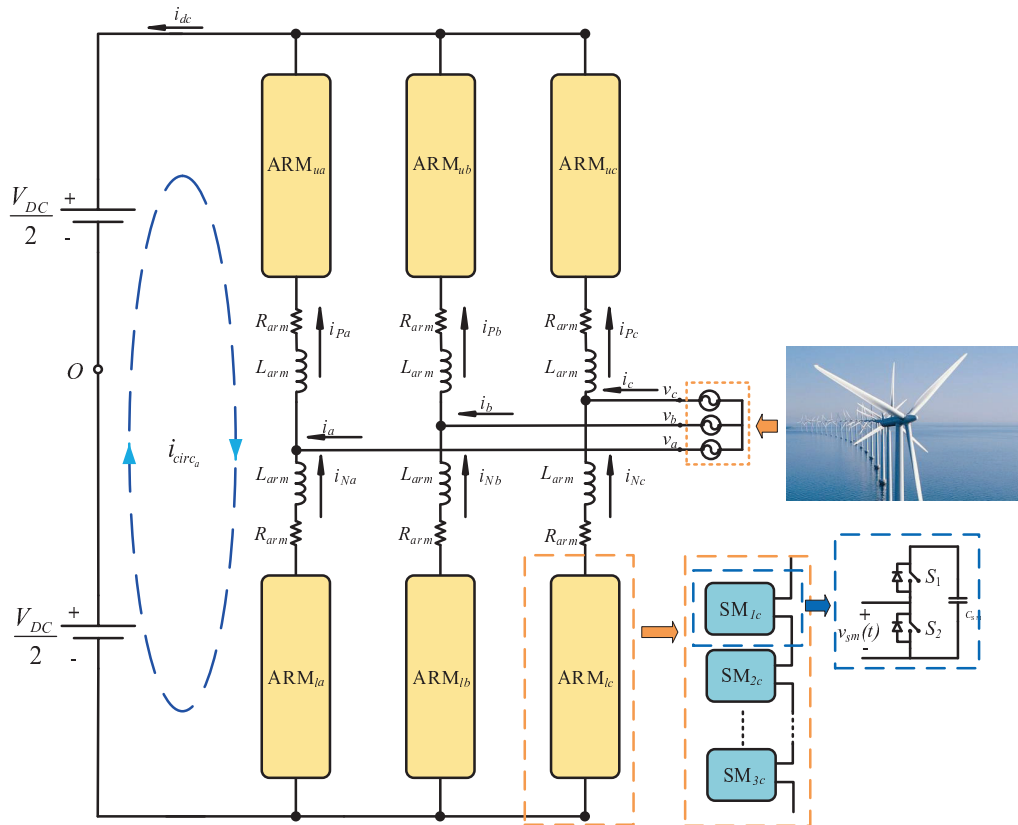


Fig. 1. Circuit configuration of a three phase MMC integrating AC grid of an offshore wind farm into HVDC transmission system

cies in the circulating current. Therefore resonant controllers which are tuned for specific frequencies and time-domain based repetitive controller with fixed sampling frequency fails to alleviate the circulating harmonic currents.

To overcome the above mentioned issue, a new control approach is proposed in this paper to mitigate circulating harmonic currents in frequency droop regulated MMC used for wind farm integration in to HVDC grid. The proposed circulating current controller comprises of spatial repetitive controller (SRC) in conjunction with the PI controller. SRC is implemented based on the line voltage space phase angle sample position ($\theta = \int \omega dt$) domain [8]–[10]. As the controller is implemented in space phase (θ) domain it is independent of fundamental AC line frequency and can effectively attenuate the harmonics in the circulating currents even under variable frequency operation of MMC.

II. SPATIAL REPETITIVE CONTROLLER BASED CIRCULATING CURRENT CONTROL SCHEME

Conventional circulating current controller based PI control is shown in Fig. 2, but it has limited periodic disturbance rejection capability. This is due to lower gains of PI controller at harmonic frequencies.

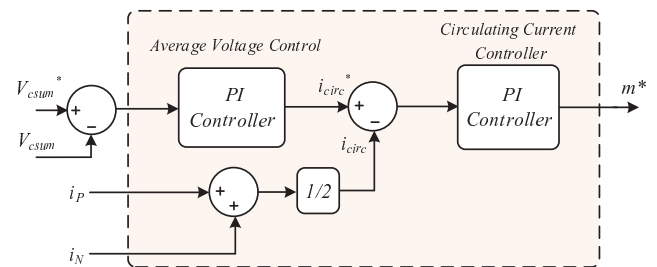


Fig. 2. Existing control architecture of circulating current control with PI controller

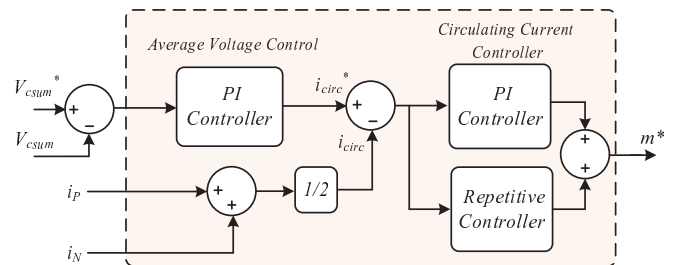


Fig. 3. Existing control architecture of circulating current control with PI and repetitive controllers

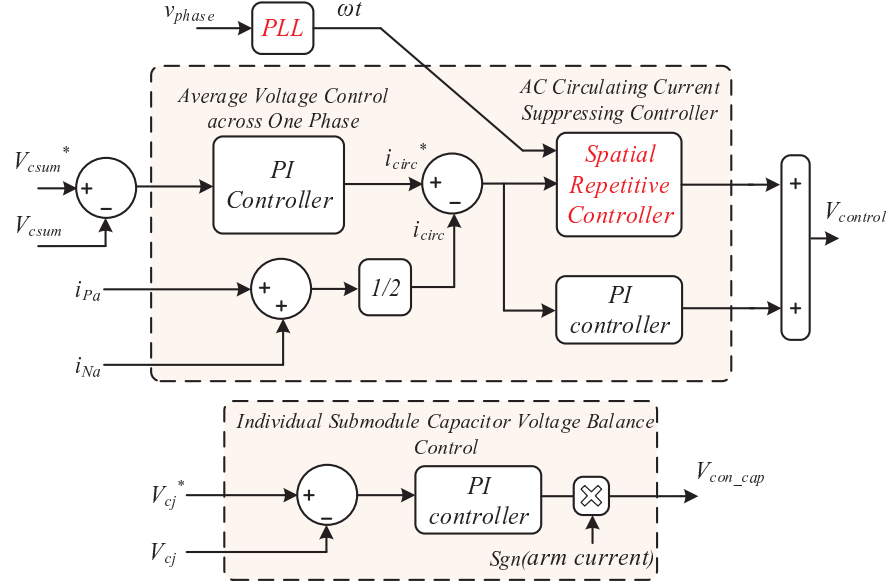


Fig. 4. Control architecture with AC circulating current suppression using spatial repetitive controller and submodule capacitor voltage balance control

High gain at DC or zero frequency, makes PI controller suitable only for step disturbance rejection but not for periodic disturbances. Where as the repetitive controller shown in Fig. 3, is especially used to deal with periodic disturbances in the system. Its ability to reject disturbance at multiple harmonic frequencies makes it an ideal controller for circulating harmonic current elimination.

The proposed circulating current control is shown in Fig. 4, where v_{csum} is the sum of upper and lower arm submodule capacitor voltages. The control input $V_{control}$ generated by inner loop circulating current controller needs to counteract the periodic disturbances caused by the voltage ripple across the submodule capacitors to alleviate circulating circulating harmonic currents.

Without spatial repetitive controller, the limited gain of the PI controller at harmonic frequencies makes it inefficient in alleviating the circulating harmonic currents, therefore resulting in poor steady state performance.

For repetitive controller to be effective the frequency of the second order component in circulating current should be an integral fraction of sampling frequency, i.e $\frac{f_s}{f_f} = N$, where N is a large integer. But in the case of MMC which is used to integrate wind farm into the HVDC grid will be employed with frequency droop control to vary active power set points of each turbine in the wind farm. But, if the frequency of the second order component varies the time-domain based repetitive controller with fixed sampling frequency will become ineffective in alleviating the harmonics. Therefore the sampling frequency must be varied according to the second order component frequency, such that the number of samples N in a cycle are constant. But, varying the sampling frequency in accordance with the second order component frequency is a complex task. At steady state, the discrete complex frequency

at the fundamental AC line frequency, f_f can be given as $Z = e^{j\omega T_s}$, where $\omega = 2\pi f_f$ and $T_s = \frac{1}{f_s}$. If the number of samples per cycle N , can be maintained constant with the relation $\frac{f_s}{f_f} = N$, at steady state Z can be given as $Z = Z_\theta = e^{j\frac{2\pi}{N}} = e^{j\Delta\theta}$. So this explains, that dynamic change in sampling frequency can be achieved by sampling the system at multiples of fundamental space phase $\Delta\theta = \frac{2\pi}{N}$. Therefore, in a spatial repetitive controller system is sampled at fundamental space phase $\Delta\theta = \frac{2\pi}{N}$ and the SRC takes control action at discrete samples of fundamental space phase $\Delta\theta = n\frac{2\pi}{N}$, where $n = 1, 2, 3, \dots, N$. Hence, the SRC can attenuate the harmonic components of the circulating current without being affected by the variation in the fundamental AC line frequency.

Block diagram of the spatial repetitive control scheme for suppressing circulating current is shown in Fig. 5. The transfer function of the spatial repetitive controller [8] is given by:

$$G_{src}(z_\theta) = \frac{U_{src}(z_\theta)}{E(z_\theta)} = K_{src} \frac{z_\theta^{-(N-N_1)}}{1 - z_\theta^{-N}} \quad (1)$$

where, $U_{src}(z_\theta)$ is the control output of SRC, $E(z_\theta)$ is the tracking error, K_{src} is the positive gain of spatial repetitive controller and $N_1(N_1 < N)$ is the number of advancement samples given to compensate the phase delay of the plant. The discrete plant transfer function $G_p(z_\theta)$ for the circulating current model is given by:

$$G_p(z_\theta) = \frac{\Delta\theta}{(z_\theta - 1)L_{arm}} \quad (2)$$

where the resistance of the arm inductor is neglected, $\Delta\theta$ is the fundamental space phase angle.

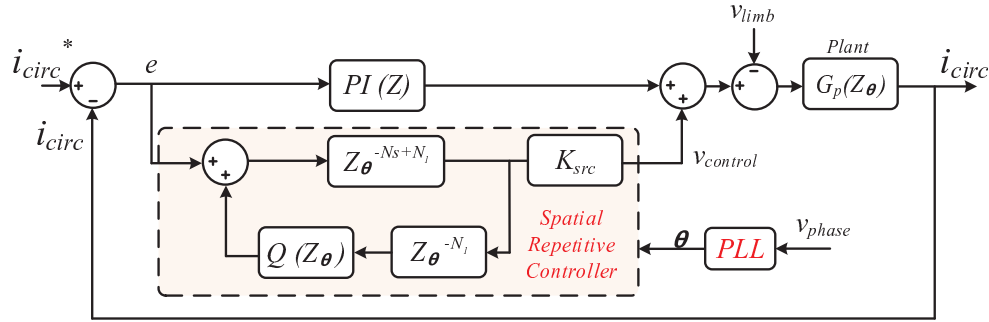


Fig. 5. Block diagram of the spatial repetitive control scheme for circulating current

TABLE I
PARAMETERS OF SINGLE-PHASE MMC

Parameter name	Symbol	Value
DC link voltage	V_{dc}	100 V
Number of submodules in each arm	N	2
submodule capacitor	C	1 mF
Rated capacitor voltage	V_C	200 V
Arm Inductor	L_{arm}	2.5 mH
Arm equivalent resistance	R_{arm}	0.1 Ω
PWM strategy		Carrier phase shift PWM
submodule switching frequency	f_{sm}	20 kHz
MMC equivalent switching frequency	f_{eff}	40 kHz

TABLE II
CONTROLLER PARAMETERS

Controller	Parameter	Value
Average voltage controller	Proportional Gain & Integral Gain	0.01 & 1
Circulating current controller	Proportional Gain & Integral Gain	0.1 & 1
Repetitive controller	K_{rc}, N, N_1	0.03, 100, 2
Spatial Repetitive controller	K_{rc}, N, N_1	0.03, 100, 2

III. EXPERIMENTAL RESULTS AND DISCUSSION

A scaled-down laboratory prototype of 5-level single phase MMC is developed for experimental validation of the proposed control strategy. The developed prototype of MMC consists of 2 arms, each arm consists of two half bridge submodules. The IGBT based half bridge submodule shown in Fig. 6 acts as a basic building block of the MMC. Four such submodules are used to realise the 5-level single phase MMC. An arm inductance of 2.5 mH and a submodule capacitance of 0.96 mF are used. Phase shifted carrier modulation is implemented for generating the multilevel voltage across the load. Upper arm is modulated with two triangular carrier waves, those are 180 deg (360 deg/ k) phase shifted, k is the number of submodules per arm. The submodule switching frequency is 20 kHz. PLECS RT Box is used to develop the proposed circulating current controller. Parameters of the experimental prototype and the controller are given in Table. I and Table. II respectively.

The performance of the proposed control strategy is compared with the conventional cascaded PI controller and PI-repetitive controller. The multilevel output voltage, upper and lower arm currents and the circulating current of the single phase MMC with conventional PI control based circulating current controller are shown in Fig. 7. Due to the dominant second order harmonic in the circulating current, arm currents are non-sinusoidal. The second order harmonic in circulating current results in increase of its rms value, which in-turn

increases the conduction loss in the devices. Therefore to attenuate the 100 Hz component in the circulating current, a repetitive controller which is tuned to 100 Hz has been added in parallel with the PI controller. With the use of repetitive controller in conjunction with the PI controller, the second-order harmonic has been alleviated and the arm currents became sinusoidal as shown in Fig. 8. This due to high gain of repetitive controller at designed frequency of 100 Hz and at respective harmonic frequencies. However, with a change in fundamental AC line frequency from 50 Hz to 52 Hz, the PI+repetitive controller failed to attenuate the second-order harmonic in the circulating current. As shown in the result Fig. 8, one can observe that with the change in fundamental line frequency to 52 Hz, the second order harmonic which is at 104 Hz has propagated and as a result the arm currents became non-sinusoidal. This is because of the shift in the frequency of circulating current to 104 Hz with change in the fundamental frequency to 52 Hz. As the repetitive controller is designed to have high gain at 100 Hz and its corresponding harmonic frequencies, it failed to attenuate harmonic component at 104 Hz in the circulating current.

Now the same experiment has been conducted with the proposed spatial repetitive controller. Fig. 9 shows the performance of the proposed SRC based circulating current control scheme. It is evident from the results that the even-order harmonics in the circulating current are alleviated by the proposed controller even with varying fundamental AC line frequency. This is due to the space phase domain sampling and strong harmonic suppression capability of the spatial

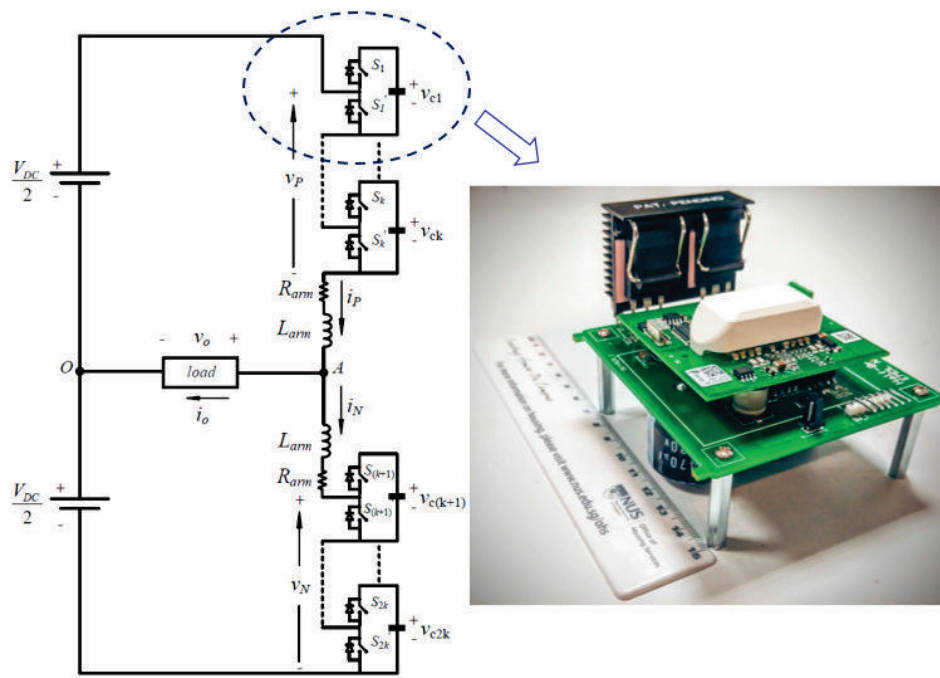


Fig. 6. Schematic diagram of single phase MMC and laboratory prototype of a half bridge submodule

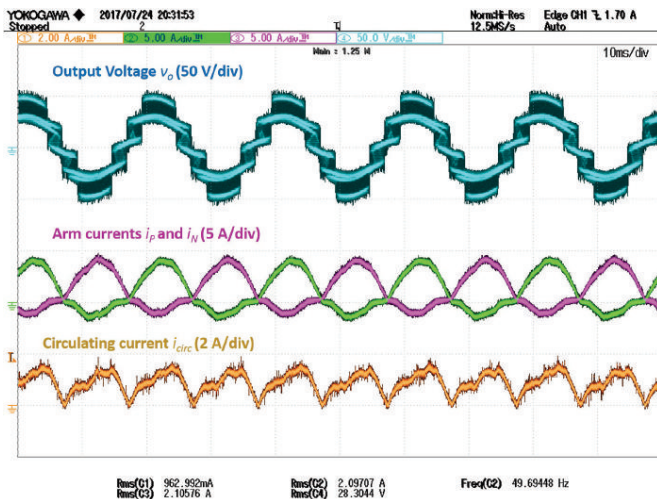


Fig. 7. Experimental results for output voltage, arm currents and circulating current under steady state with cascaded PI controller

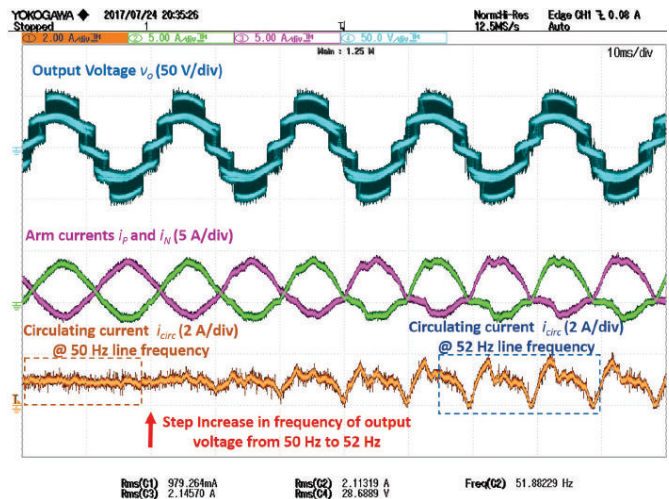


Fig. 8. Experimental results for output voltage, arm currents and circulating current with PI + repetitive controller

repetitive controller irrespective of variation in fundamental operating frequency. In the case of repetitive controller, fixed time-domain sampling is used. Therefore with the change in frequency the number of samples per cycle is not constant. This results in poor performance of repetitive controller. If the sampling frequency can be changed, such that the number of desired samples N_s per period is an integer and constant. But it could be complex to change sampling frequency online to keep N_s as an integer. Whereas, in spatial repetitive controller the phase of line voltage is sampled. As the phase varies always from 0 to 2π irrespective of frequency, the number of samples remain constant and variable sampling frequency is achieved.

IV. CONCLUSIONS

In this paper, a new control structure comprising of a spatial repetitive controller in addition to the PI controller in the circulating current loop is proposed to improve the steady state performance of the frequency droop regulated MMC used for integration of wind farm into HVDC grid. A scaled-down laboratory prototype of a single phase, 5-level MMC is built to experimentally substantiate the performance of the proposed control scheme. The steady state performance of the MMC with the proposed control structure is compared with that of the conventional circulating current controllers. Time-domain

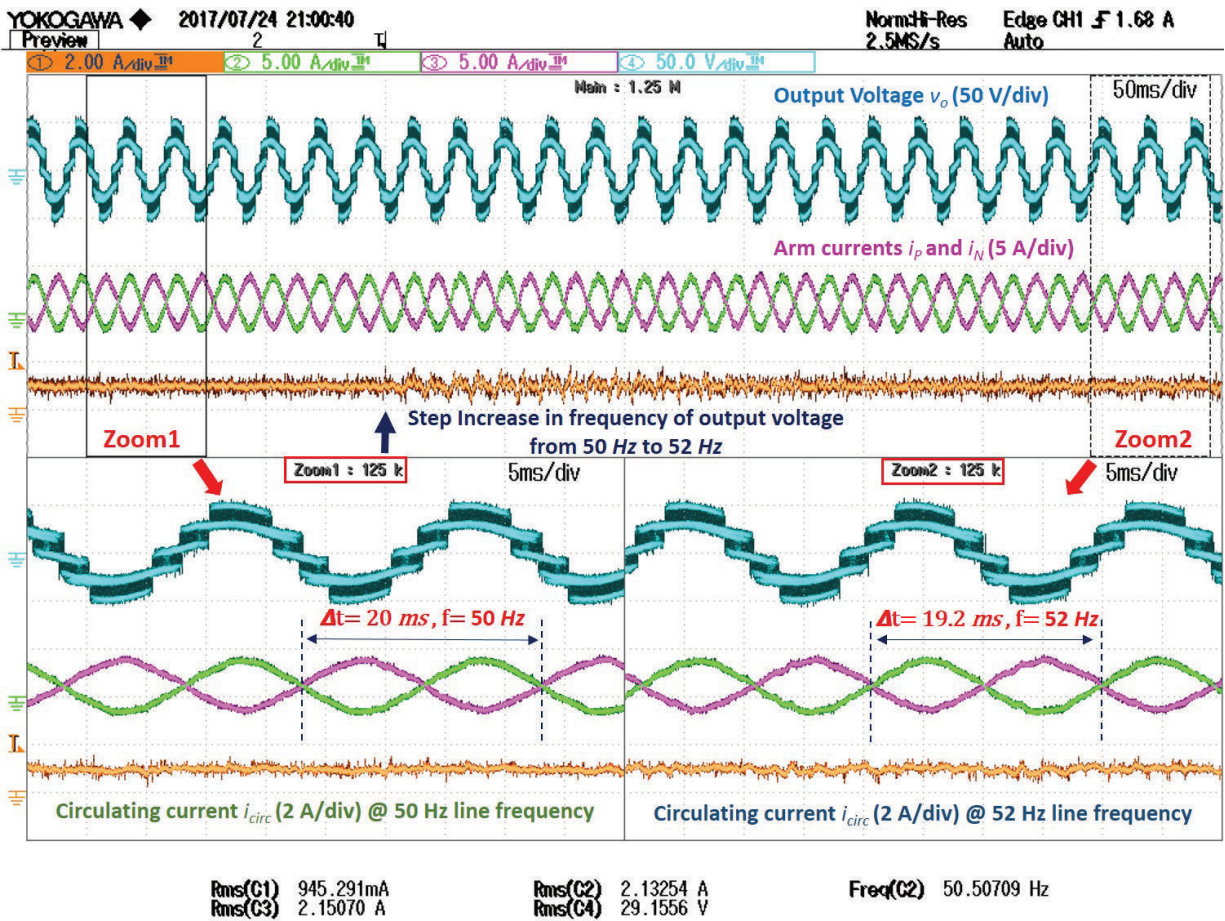


Fig. 9. Experimental results for output voltage, arm currents and circulating current with PI + spatial repetitive controller

based repetitive controller has limited harmonic rejection capability at variable frequencies and thereby failed to attenuate the dominant second-order harmonic in the circulating current when the fundamental AC line frequency is changed from 50 Hz to 52 Hz. On the other hand, results show that the proposed control scheme with a spatial repetitive controller in the circulating current loop effectively eliminates the circulating harmonic currents even under variable frequency operation of MMC, thereby improving the steady state performance compared to its counter part.

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