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HARMONIC SUPPRESSION OF CIRCULATING CURRENT IN MODULAR MULTILEVEL CONVERTER USING REPETITIVE CONTROLLER

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Abstract— A plug-in repetitive control scheme is used here. It combines the high dynamics of PI controller and good steady-state harmonic suppression of the repetitive controller, and minimizes the interference between the two controllers. It is suitable for multiple harmonic suppression

Index Terms— Circulating current,Harmonics,Repetitive controller,Modular multilevel converter,.

1 INTRODUCTION

Multilevel converters have increased attention in industries and also it is preferred choices of electronic power conversion for high power applications. Currently they are commercialized in standard and customized products that power a wide range of applications, such as compressors, grinding mills, crushers etc. Converters for this applications are commercially offered by a growing group of companies in the field. Among the multilevel topology family, the modular multilevel converter is attracting increasing interest for the advantages of modular structure ,inherent reduntancy ,improved power quality etc.The modular multilevel converter consists of submodules which have capacitors in it. These capacitors produce ripples. These ripples produce second order harmonic in the circulating current that flows through the dc source and the phase leg. If proper control is not given, the amplitude of the second order harmonics can be significant and this will cause to produce higher even order harmonics. The harmonics in the circulating current increases power losses and reduce service life of the power devices. If it is not controlled properly they may cause instability during transients.

In [1],[2] a detailed explanation of many open-loop methods for circulating current control are given. These methods are also used for the suppression of harmonics in the circulating current. But the main disadvantage was the parameter sensitivity which affects the stability. Another method is proposed in [3] where PI controller is used for suppression. But it cannot totally remove the harmonics because of its limited gains at those harmonic frequencies .In [4],a pair of PI controller based on double line frequency, negative-sequence rotating frame, are utilized to eliminate the second-order harmonics. Disadvantage is that the rotating frames are difficult to define in single phase systems.

In [5],a repetitive plus PI control scheme is proposed. It is applicable to the both single-phase and three phase systems. it can eliminate multiple harmonics in the circulating current with a single repetitive controller. However, the repetitive controller and PI controller are paralled in this paper. But this imposes unnecessary limitation on the PI controller design and also complicates the repetitive controller designSince the second order and higher order harmonics affect the stable operation of the MMC ,we have to eliminate it. Here a unified model of circulating current is built, which is applicable to both single and three phase MMCs. The entire control structure is done here. The harmonics is produced in circulating current .So we have to control the circulating current for the harmonics reduction. For this we have to model the circulating current.

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2 Modelling and Analysis of Circulating Current

2.1 Mathematical model of circulating current

For the mathematical modeling ,firstly the total output voltages of the SMs in the upper and lower arm of each phase can be modeled as controlled voltage sources v_{px} and v_{nx} respectively. From the fig.2(a) the circulating current(i_{zx}) can be defined as

$$i_{zx} = (i_{px} + i_{nx})/2 \quad (1)$$

Differential equations of arm currents are given as follows:

$$v_{px} = \frac{V_{dc}}{2} - v_x - L\frac{di_{px}}{dt} - Ri_{px}$$

$$v_{nx} = \frac{V_{dc}}{2} + v_x - L\frac{di_{nx}}{dt} - Ri_{nx} \quad (2)$$

$$i_{px} = i_{zx} + \frac{i_x}{2}$$

$$i_{nx} = i_{zx} - \frac{i_x}{2} \quad (3)$$

Substituting (3) into (2) yields

$$2L\frac{di_{zx}}{dt} - 2Ri_{zx} = V_{dc} - (v_{px} + v_{nx}) \quad (4)$$

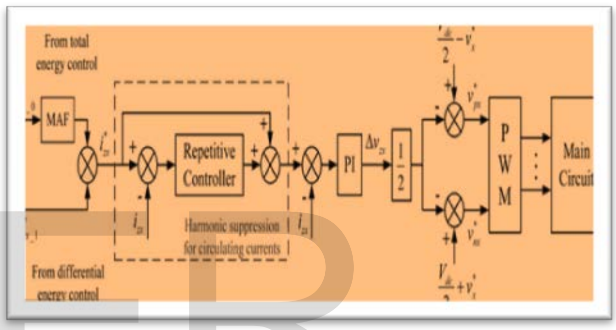
By looking through the equation [4] ,it is noted that all variables other than (v_{px} + v_{nx}) i.e the common mode component of the arm voltages ,defined as v_z is constant. Therefore control of i_{zx} is realized adjusting v_{zx}.
According to [5] and [6] , if the modulating signals for SMs are purely sinusoidal (with dc offfset) ,i_{zx} should consists of a dc component $I_{zx\text{-}0}$ and even order harmonics I $_{zx\text{-}k}$(k=2,4,6….). Eliminating these harmonics is the purpose of this study.

The dc component $I_{zx\text{-}0}$ in the circulating current represents the average power supplied by the dc source, which is to be consumed by the load and the SM capacitors. This component can be used for total energy control ,i.e. the control of average voltages of all the SM capacitors in one-phase leg. The fundamental component in the circulating current can transport energy between the upper and lower arm capacitors. Therefore $i_{zx\text{-}1}$ can be utilized in differential energy control between the upper and lower arms.

2.2 Control of circulating current

The proposed control system consists of the basic PI controller and a repetitive controller. For a three phase MMC inverter, three such control systems are needed. The circulating current reference ,i^*_{zx} consists of a dc component coming from total energy control and fundamental component coming from differential energy control. Since the dc component ,$i^*_{zx\text{-}0}$ in the current reference can be easily corrupted by the harmonics in the capacitor voltages, a moving average filter(MAF) is inserted in the ,$i^*_{zx\text{-}0}$ path. The time span of the MAF is chosen as half the fundamental period, since the lowest order ripple in the summed capacitor voltages of one-phase leg is the second order one.

The output of the circulating current control system Δv_{zx} is halved and then added to the



normal components of the arm voltage references() to form the final references$'^*_x$ is the desired ac output voltage of phase x:

$$v_x^* = M\frac{V_{dc}}{2}\sin(\omega t + \psi_x)\ ,\quad M \text{ € } [0,1] \quad (5)$$

3.Design and Analysis of the Proposed Repetitive Controller

The harmonic suppression, the preliminary measure, we can take is to add a PI control in system for better transient performance.

The transfer function of the PI controller is

$$PI(s) = \frac{K_p s + K_i}{s} \quad (6)$$

According to (3), the transfer function of plant *G*(*s*) is

$$G(s) = \frac{1}{2Ls + 2R} \quad (7)$$

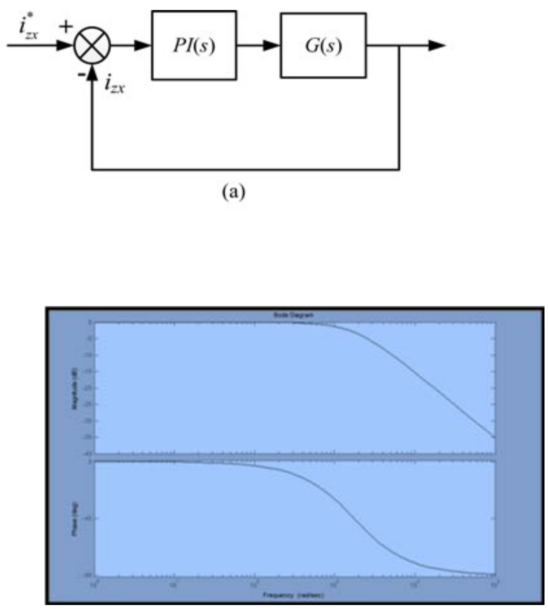


Fig. 4. (a) Block diagram and (b) Bode plot of the PI controlled circulatingcurrent loop.

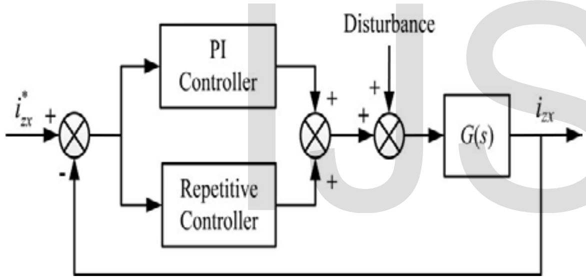


Fig. 5. Control structure proposed in [10].

In ,the PI controller is paralled with the repetitive controller to improve harmonic suppression. The resulted control structure is shown in fig 5.Such a parallel configuration of a repetitive controller and the existing high-dynamic controller can also be found in .An important consideration behind a parallel structure is perhaps the transient performance .It seems that by paralleling the two controllers instead of cascading them, the quick response of PI controller will not be affected by the slow repetitive controller. Since the repetitive controller has a small delay of operation.

But the cascaded structure ie series connection of PI controller and repetitive controller,will avoid this delay. With the feedforward path of current reference, the control structure in Fig. 6 is equivalent to the classical "plug-in" structure [18] as shown in Fig. 7. It is easier to see from Fig. 7 that the plug-in repetitive controller is more separated from the PI controlled circulating current loop. Therefore, the PI controller can be designed independently, and the dynamics of the whole system will not be hold back by the repetitive controller. The plug-in repetitive controller only deals with the residual, repetitive error left by the PI controller

The proposed control structure also provides a more friendly "plant" for the repetitive controller. In Fig. 6 or Fig. 7, the plant (i.e., all the dynamics from y_{rp} to i_{zx}) as seen from the repetitive controller is the PI-controlled circulating current loop, with the transfer function.

$$P(s) = \frac{PI(s)G(s)}{1+PI(s)G(s)} \qquad (8)$$

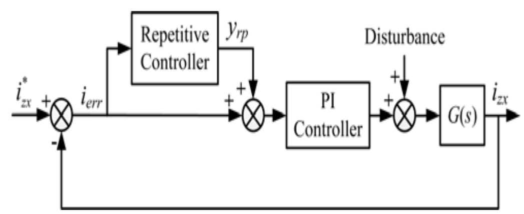
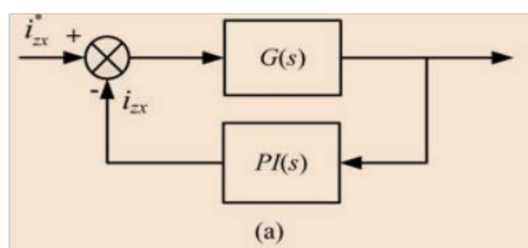


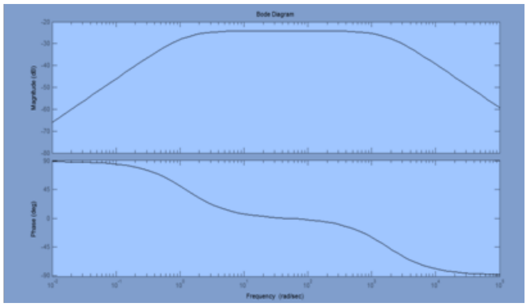
Fig. 6. Proposed plug-in repetitive control structure

The frequency characteristics of $P(s)$ has already been given in Fig. 4(b). It exhibits unity gain from zero frequency up tothe break frequency, and then a monotonically decreasing gain after the break frequency. This is a frequency characteristic that is most desirable for the repetitive controller design [23].

With the parallel structure, the plant of the repetitive control is

$$P'(s) = \frac{G(s)}{1+PI(s)G(s)} \qquad (9)$$





(b)

Fig. 7(a) Block diagram and (b) Bode plot of the plant of RP controller for parallel control structure

The difference between (9) and (8) is the transfer function of the PI controller. Shown in Fig. 8 are the equivalent block diagram and the Bode plot of P′(s). The gain curve of P′(s) becomes a trapezoid. The constant-gain region (where it is convenient for the repetitive controller to achieve good command following and disturbance rejection) greatly narrows. As indicated in [23], slope sections in the gain curve pose potential threats for stability of the repetitive control system. With a gain curve like Fig. 7(b), the design of the repetitive controller becomes difficult, since the designer now faces two instead of only one such slop section.

It also should be noted that in order for the fundamental frequency to remain in the flat-top region of the gain curve, the break frequency f_{PI} of the PI controller has to be kept well below the fundamental frequency. This is clearly an unwelcome limit imposed on PI controller design, which may affect the optimization of PI parameters

3.2 DESIGN OF PROPOSED REPETITIVE CONTROLLER

Fig. 6 is redrawn in *z*-domain and with more detail in Fig. 8, which shows the inner structure of the repetitive controller. For convenience, the disturbance has been equivalently moved to the output side of G(z). The design process of the repetitive controller is based on the parameters listed in Table I.

The sampling frequency f_s of the control system equals the carrier frequency (which is also the equivalent switching frequency of the MMC); therefore, f_s = 4 kHz. Since odd-order harmonics may also arise due to imperfections in practical applications, and the current reference contains fundamental component, the base frequency of the repetitive controller is chosen as the fundamental frequency (50 Hz) of the MMC. Therefore, there are N_s = 80 error samplings within one repetitive control cycle. Note that although phase disposition PWM (PDPWM) is employed here, other PWM techniques, e.g., carrier phase-shifted PWM (CPSPWM), can also be used with the proposed control method, provided that the equivalent switching frequency is the same.

As the core of the repetitive controller, the modified internal model $1/(1 - Q(z)z^{N_s})$ integrates the error on a cycle basis. The $Q(z)$ filter, which enhances robustness by slightly attenuating the integration action, can be a constant close to 1, or a low-pass filter. $Q(z) = (z + 4 + z^{-1})/4$ is adopted here. It is a low-pass filter with zero-phase shift at low frequencies. The time delay unit z^{-N_s} postpones control action by one repeating period so that the time advance unit z^k(for phase compensation purpose) as well as the non causal $Q(z)$ filter can be realized.

In the repetitive compensator $K_r S(z) z^k$, the filter $S(z)$ provides magnitude compensation for the plant $P(z)$. Since the low-frequency gain of $P(z)$ is already a constant 0 dB, $S(z)$ is chosen as a simple second-order low-pass filter with natural frequency $\omega_n = 10\omega_1$ and damping ratio $\zeta = 1$. It provides a steeper descending slope of the gain curve at high frequencies, which is helpful to system stability.

Time advance unit z^k performs phase compensation for $S(z)P(z)$. Fig. 10 shows that z^4 can perfectly cancel out the phase delay of $S(z)P(z)$ up to$10\omega_1$.

Repetitive gain K_r $(0 < Kr \leq 1)$ ultimately determines the amplitude of controller output y_{rp} . A smaller Kr brings larger stability margin but slower error convergence speed.

The transfer function from the error signal $i_{err}(z)$ to reference $i^*_{zx}(z)$ in Fig. 8 is:

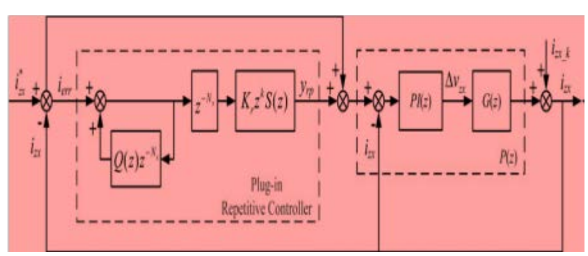


Fig. 8. Detailed block diagram of the proposed repetitive control scheme for circulating current

The characteristic equation of the repetitive control system is

$$z^{N_s} - [Q(z) - K_r S(z) z^k P(z)] = 0$$

(11)

The necessary and sufficient condition for system stability is that N_s roots of (11) are inside the unity circle centered at the origin of the *z*-plane. To simplify the design process, a sufficient condition for system stability can be derived by small gain theorem [25]:

$$\left| Q(e^{j\omega t}) - K_r S(e^{j\omega t}) e^{jk\omega t} P(e^{j\omega t}) \right| < 1,\ \omega \in [0,\ \pi/T_s]$$

(12)

Items	Values
Rated active power	**1kw**
Load Resistor,L	**14Ω**
Modulation Index	**0.9**
DC link voltage	**400V**
Rated frequency,f_i	**50Hz**
SM capacitor	**560uF**
Arm inductance	**4.6mH**
SM switching frequency	**1kHz**
Arm equivalent resistance,R	**0.05 Ω**
Rated Capacitor voltage	**100V**
Parameters of circulating current	**K_p=16 K_i=20**

TABLE I
PARAMETERS OF THE SINGLE-PHASE MMC UNDER STUDY

Define $H(e^{j\omega t}) = Q(e^{j\omega t}) - K_r S(e^{j\omega t}) e^{jk\omega t} P(e^{j\omega t})$. Equation (12) means that the end of vector $H(e^{j\omega t})$ should never exceed the unity circle. Smaller magnitude of $H(e^{j\omega t})$ indicates larger stability margin, faster error convergence, and better steady-state harmonic suppression [23]. Fig. 11(a) shows the locus of vector $H(ej\omega t)(\omega \in [0, \pi/Ts])$ with $Kr = 1$. The entire locus remains well within the unity circle. A similar Nyquist plot based on parameters of [15] is given in Fig. 11(b) for comparison. The initial section of the locus is found to be dangerously close to the stability boundary. This is because the low-frequency gains of *P′*(*s*) are significantly below 0 dB in the parallel control structure. If the control structure is changed to the proposed plug-in style shown in Fig. 6 or Fig. 7 while all the control parameters are kept unchanged (except for the repetitive gain being reduced *Kp* times to account for the different loop gains of these two structures), the Nyquist plot will become the one shown in Fig. 11(c). The stability margin is improved, and magnitudes of $H(ej\omega t)$ at 50 and 100 Hz are reduced, indicating better command-following and disturbance rejection at these frequencies.

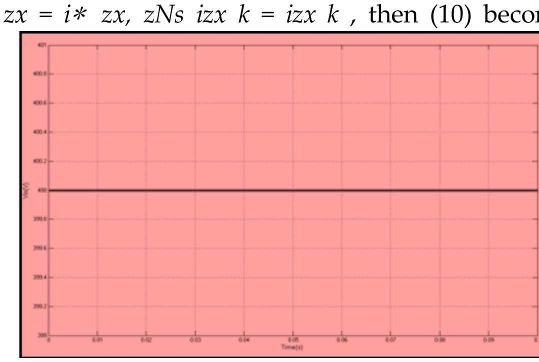
The performance of the parallel structure can definitely be improved with more sophisticated repetitive controller design [17], [19]. But this seems an unnecessary effort since a better control structure could have prevented most of the difficulties in the first place.

3.2 Harmonic Rejection Ability

The open-loop gains of original plant $|G(e^{j\omega t}|$ PI control system $|PI(ej\omega t)G(ej\omega t)|$, and repetitive control system $|Grp(ej\omega t)P(ej\omega t)|$ are compared in Fig. 12.

Fig. 12 indicates that the repetitive controller provides much higher gains at fundamental frequency and its multiples than the PI controller. Therefore, the repetitive controller can achieve much better command following and harmonic suppressing capability.

If $Q(z) = 1$, and the disturbance as well as reference are purely repetitive, i.e., $zNs\ i*$ $zx = i*\ zx$, $zNs\ izx\ k = izx\ k$, then (10) becomes



Equation (14) reveals that after each control cycle (i.e., fundamental period), the magnitude of the error reduces to $|H(ejk\omega 1\ t)|$ times its previous value. For the chief harmonic component $izx\ 2$,

$|H(ej2\omega 1\ t)| = -13.8$ dB, indicating that the second-order harmonic in the circulating current can be suppressed within 3 ~4 fundamental periods by the repetitive controller.

Due to the dynamics of the MMC (mainly the SM capacitors' voltages) in practical operation, the "purely repetitive" assumption does not hold exactly; therefore, the actual error convergence will be slower

4 SIMULATION RESULTS

A simulation model of a single-phase MMC

FIG.9 INPUT VOLTAGE

inverter is established in MATLAB/Simulink to verify the proposed control scheme. The parameters are already given in Table I.

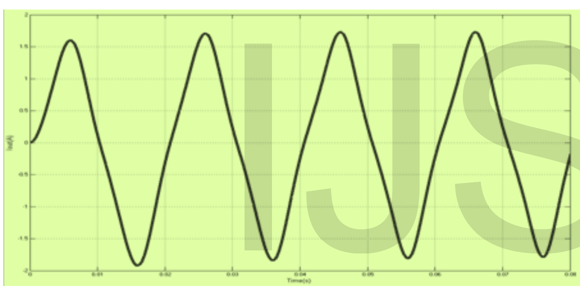


FIG 10 OUTPUT CURRENT

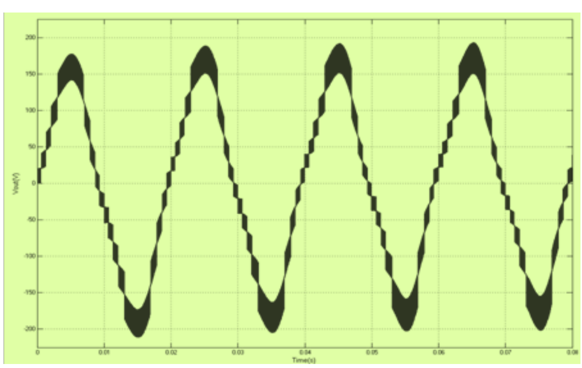


FIG 11 OUTPUT VOLTAGE

5 Conclusion

The second-order as well as other higher order harmonics in circulating current brings extra power losses and may affect stable operation of the MMC. This paper proposed a "PI + Repetitive" control scheme to suppress these harmonics in the circulating current. It greatly improves the harmonic suppression of the conventional PI controller. It is applicable to both single-phase and three-phase systems, and is able to eliminate multiple harmonics with a single controller. Compared with another "PI + Repetitive" control scheme in which the two controllers are paralleled, the control structure proposed in this paper results in a more friendly plant for the repetitive controller, and poses no design limit on the PI controller

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