A MAXIMUM POWER POINT TRACKING TECHNIQUE BASED ON RIPPLE CORRELATION CONTROL COMMON-MODE VOLTAGE AND DIFFERENTIAL-MODE HARMONICS IN THREE-PHASE INVERTERS.

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Abstract—A hybrid filter is presented to reduce the CM voltage (CMV) and the differential-mode (DM) harmonics in a three-phase inverter with carrier peak position modulation (CPPM) using RCC control is proposed in this paper. Total harmonic distortion in power electronic system deteriorates the performance of the converters and inverters, many researchers working on power electronic systems to reduce the fault and THD that causes various problems in the power electronic system. In the motor systems driven by sinusoidal pulse width modulation (SPWM) three-phase inverters, the peaks of common-mode (CM) voltage are so high that it will cause many negative effects. Because the use of CPPM strategy in the inverter can ensure that the output CMV will be only two levels in any condition, the simple active CM filter (composed of a half-bridge circuit) in the hybrid filter can effectively suppress the output CMV and CM current. The passive filter in the hybrid filter consists of an added single tuned filter and the original DM low-pass filter. The method which makes use of such ripple and correlates this with switching function to control the operating point of PV array is called ripple correlation control (RCC). In this paper, a modified RCC method has been proposed to implement the MPPT technique with reduced component count which makes the implementation easier compared to existing techniques presented in this paper. By using simulation results the validity of CMV and DM harmonics suppression by the hybrid filter in the three-phase inverter is verified and in the optional schemes the control active CM filter is proved as best one.

I. INTRODUCTION

Power electronics has become essential for electrical conversion. In the present technology static converters are used in almost every electrical system in different fields like industry, renewable energy, embedded system, transport or domestic applications. SWITCHED-MODE power supplies are more and more widely used in industrial equipments. But this switched mode will bring many negative effects. In the motor regulation systems driven by pulse width modulation (PWM) inverters, the peaks of output common-mode (CM) voltage are very high due to the instantaneous imbalance of three phase voltages. The CM voltage (CMV) will produce a huge pulsating CM current (CMC) through the distributed capacitance of the system. The CMC could interfere with the adjacent devices along the ground wire and even will result in the wrong operation of the devices. In addition, the CMV will cause the high shaft voltage through the parasitic capacitors between the stator and the rotor.

To reduce the output CMV in the three-phase inverter. For the inverter with the space vector modulation (SVM) strategy, the CMV is reduced by using nonzero vectors to synthesize zero vectors some optimized control strategies are used. For the inverter with the discontinuous PWM (DPWM) strategy, the CMV is reduced by avoiding the generation of zero vectors. In this method, three triangular carriers with various polarities are used to modulate three reference voltages. Under different carrier polarity combinations there are different DPWM methods such as active zero state PWM (AZSPWM), remote state PWM (RSPWM), near state PWM (NSPWM), and so on. For the sinusoidal PWM (SPWM) control inverter, the CMV can be reduced by using the carrier phase shift (CPS) strategy. Thus, the zero state is avoided and the CMV is reduced.

CM filters can be divided into passive and active ones. Most passive filters are realized with two
common ways: a CM choke or CM transformer cascading into the main circuit; a resistor-capacitor (RC) or resistor inductor-capacitor (RLC) attenuation network paralleling into the main circuit. In the conventional SPWM or SVM three-phase inverter, the CMV is a four-level pulse. So the active filter is implemented by using a multi-level inverter and the four-level voltage is yielded to counteract the CMV. The structure of this multi-level active filter is too complex to be used in the low cost cases, while RCC is a general method for optimization method, its application to the solar MPPT problem is well established. Tracking the maximum power point is extremely important for solar applications.

II. CMV IN THREE-PHASE INVERTER

The active power filter composed of switching circuits is not affected by the limit of voltage class. In the conventional SPWM or SVM three-phase inverter, the CMV is a four-level pulse. So the active filter is implemented by using a multi-level inverter and the four-level voltage is yielded to counteract the CMV. In the three-phase inverter as shown in Fig. 1, the output CMV $v_{cm}$ can be expressed as

$$v_{cm} = (v_a + v_b + v_c)/3 \quad (1)$$

Where $v_a$, $v_b$, and $v_c$ are the output voltages of three legs respectively.

![Fig. 2. Modulation of three-phase reference voltages with different carriers (top), three-phase output pulses (middle) and output CMVs (bottom) in the three-phase inverter under the SPWM strategy.](image)

When $v_a$, $v_b$, and $v_c$ are of high (or low) level, which is called the zero state, the peaks of the output CMV are maximal (about $\pm V_{dc}/2$).

The zero state is the major cause of the huge CMV. If the peaks of three carriers are mutually staggered $T_c/3$ ($T_c$ is the carrier cycle) in the inverter, the probability for the occurrence of the zero state will be the lowest. This is the key idea of the CPS strategy. As shown in Fig. 2(b), the occurrence frequency and the duration time of $\pm V_{dc}/2$ in CMV are reduced greatly.

![Fig. 3. Modulation of three-phase reference voltages with different carriers (top), three-phase output pulses (middle) and output CMVs (bottom) in the CPS strategy.](image)

Research results have shown that significant control objectives, such as cost function optimization, can be addressed with a ripple correlation technique. Ripple correlation control (RCC) has opened a whole
suite of new possibilities for converter action and for control loops. However, ripple which is inherent to the switching actions and represents a consistent perturbation signal has been found to be a source of information and a basis for control.

In order to avoid the zero state in all cases, the variant oblique triangular carrier is used to modulate the reference sinusoidal carrier instead of the usual symmetric triangular carrier in the inverter with the CPPM strategy.

Fig. 4. Modulation of three-phase reference voltages with different carriers (top), three-phase output pulses (middle) and output CMVs (bottom) in the CPPM strategy.

Fig. 2(c) shows that the peaks of the output CMV with CPPM are reduced to ±Vdc/6. The problem of the switching dead-time has been considered in the calculation of carrier peak positions. Thus, using the CPPM strategy can ensure that the output CMV of the inverter will appear only two-level voltage(±Vcd/6) in any case.

### III. HARMONICS OF DMV

For the asymmetrical regular-sampled SPWM, the output voltage of Phasor(r=a, b, c) in the three-phase inverter can be expressed. nth order Bessel function; f0 is the output power-frequency; mis the carrier index; nis the baseband index; q=m+n/f0; θrcand θr0 are the initial phases of the carrier and the reference sinusoid respectively. θrcand θr0of the inverter under the conventional SPWM strategy or under the CPS strategy are listed in Table I.

\[
v_r(t) = \frac{2V_{dc}}{\pi} \sum_{m=0}^{\infty} \sum_{n=-\infty}^{\infty} \frac{1}{q} j_{n}(qM_a) \sin \left( \frac{(m+n)\pi}{2} \right) \cos \left( m(2\pi f_c t + \theta_{rc}) + n((2\pi f_c t + \theta_{r0}) \right) \]

(2)

The DMV vab between Leg A and Leg B of the three-phase inverter under the conventional SPWM strategy can be deduced. Its result is revealed in (3).

\[
v_{ab, SPWM}(t) = -\frac{4V_{dc}}{\pi} \sum_{m=0}^{\infty} \sum_{n=-\infty}^{\infty} \frac{1}{q} j_{n}(qM_a) \sin \left( \frac{(m+n)\pi}{2} \right) \sin \left( 2\pi (mf_c + nf_0)t - n\pi/3 \right)
\]

(3)

### TABLE I

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Leg A</th>
<th>Leg B</th>
<th>Leg C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional SPWM</td>
<td>θrc</td>
<td>θr0</td>
<td>θrc</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>0</td>
<td>-2π/3</td>
</tr>
<tr>
<td>CPS</td>
<td>0</td>
<td>0</td>
<td>-2π/3</td>
</tr>
</tbody>
</table>

In the similar manner, the DMV under the CPS strategy can be got by (4)

\[
v_{ab, CPS}(t) = -\frac{4V_{dc}}{\pi} \sum_{m=0}^{\infty} \sum_{n=-\infty}^{\infty} \frac{1}{q} j_{n}(qM_a) \sin \left( \frac{(m+n)\pi}{2} \right) \sin \left( \frac{(m+n)\pi}{3} \right) \sin \left( 2\pi (mf_c + nf_0)t - (m+n)\pi/3 \right)
\]

(4)

Under different strategies, the DMVs of the three-phase inverter with no-load (i.e. load impedance is infinite) are simulated. The simulated parameters are listed in Table II. The switching dead-time is not considered in the simulations. The output DMV behind the filter in the three-phase inverter

\[
v_{AB}(f) = v_{ab}(f) / \left( 1 - 4\pi^2 L_f C_f f^2 \right)
\]

RCC

Ripple has typically not been considered as a source of information, and numerous techniques have been configured to minimize ripple and discontinuities of switching by smoothing out the switch actions and averaging through filters. Switching actions produce ripple, which cannot be
avoided without a power loss penalty. In many power converters and their controls, ripple is at best a substitute for a switching control (as in hysteresis control) and at worst a nuisance and a source of noise and interference.

![Block diagram showing implementation of the proposed MPPT algorithm](image)

Ripple correlation control (RCC) has opened a whole suite of new possibilities for converter action and for control loops. However, ripple which is inherent to the switching actions and represents a consistent perturbation signal has been found to be a source of information and a basis for control. RCC represents a minor addition to the converter control to achieve tracking of the panel maximum power with minimum extra cost.

**TABLE I**

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<tr>
<th>Symbol</th>
<th>Value</th>
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<tr>
<td>$V_{dc}$</td>
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<td>Capacitor of low-pass filter</td>
</tr>
<tr>
<td>$f_0$</td>
<td>50 Hz</td>
<td>Output power-frequency</td>
</tr>
</tbody>
</table>

![Simulated FFT results of output DMV in the inverter under the (a) conventional SPWM strategy, (b) CPS strategy, and (c) CPPM strategy at fc=3.6kHz.](image)

Based on which goes through most of the existing MPPT techniques, RCC better suits our application, not only because of its ability to track the true MPP of the PV array, but also because of its simple analog implementation and incorporation in the MIBB. The measured current-voltage (I-V) and power-voltage (P-V) curves of the PV array used for the experiment. These curves were obtained at full irradiance. Since the incremental cost of solar energy is very low, it makes sense to use the maximum power out of the PV array and use the smallest fraction of the secondary source only to meet the load requirement. The shapes are typical of PV arrays at any irradiance level. The P-V curve shows that there is a unique global MPP at PMPP.
IV. HYBRID FILTER

In this paper, the primary task of the designed filter is to suppress the output CMV in the three-phase inverter. Using the CPPM strategy can ensure that the output CMV will be only two-level voltage in any case (see Section II). Thus, to suppress the CMV, a simple switching circuit can be designed as an active CM filter to produce the two-level voltage, which is the reversal of the original CMV. Meanwhile, a special design of DM filter aims at the suppression of the DMV harmonics in the carrier frequency band, because the DMV harmonics will make the THD exceed the standards (see Section III). The organic combination of the active CMV filters and the passive DMV filter forms the hybrid filter in this paper.

A. Active CM Filter

In the design procedure of the active CM filter, the switching circuit structure must be determined in accordance with the characteristic of the CPPM strategy firstly. Secondly, the coupling mode of the filter output must be designed. Lastly, the acquisition mode of the CMV signal must be selected. Because the output CMV in the inverter with CPPM is a two-level voltage, a single-phase inverter structure can be designed to generate a reverse two-level voltage to the CMV. There are full-bridge structure and half-bridge structure in single inverters. In view of the cost, the simple half-bridge structure is the best choice. As shown in Fig. 8, the output voltage $v_{rcm}$ of the half-bridge is $\pm kV_{dc}/2$.

The counteractive voltage of the CMV can be generated. The class of the dc-side voltage in the active CM filter can be changed by the proportional coefficient $k$. This is useful for the flexibility in choosing switching devices. There are two ways by which the active CM filter is coupled into the main circuit of the three-phase inverter. In the first way, the three-phase CM transformer with wideband is cascaded in the main circuit of inverter and the compensation of the CMV is in the form of voltage. The essence of this method is to change the potential of the neutral point and to make it close to zero in theory. According to Fig. 8, the CMV of the inverter’s output is

$$v_{cm} = \frac{v_{a} + v_{b} + v_{c}}{3} \left( Z_{r} + Z_{p} + 3Z_{rcm} \right)$$

Where $Z_{rcm}$ is the output equivalent impedance of the active circuits in the filter network, and $Z_{s}$ and $Z_{p}$ are, respectively, the series impedance and the parallel impedance of the inverter’s output. According to (6), if $v_{rcm}$ is controlled as follows:

$$v_{rcm} = \frac{-Z_{rcm} \left( v_{a} + v_{b} + v_{c} \right)}{Z_{s} + Z_{p}}$$

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$$v_{rcm} = \frac{-Z_{rcm} \left( v_{a} + v_{b} + v_{c} \right)}{Z_{s} + Z_{p}}$$
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v_{cm} will be zero in theory. Because \( v_{cm} = \pm kV_{dc}/2 \), \( v_a + v_b + v_c = \pm V_{dc}/2 \), and they are opposite to each other, the design results can be obtained as follows:

\[
v_{rcm} = -k(v_a + v_b + v_c) \quad (8)
\]

\[
Z_{rcm} = k(Z_a + Z_p) \quad (9)
\]

According to (8), the control signal \( S_{rcm} \) of an active filter’s switch should have the reverse polarity to the signal \( v_a + v_b + v_c \). Two schemes can be used to obtain the control signal \( S_{rcm} \). The first is the “detection-control” scheme. To solve the latter problem, the devices with short switching dead-time can be adopted. Considering the need of short switching dead-time devices and the fact that the switch frequency of the active counteractive circuit is the triple of the carrier frequency in the three-phase inverter, it will be a good plan to select power metallic oxide semiconductor field effect transistors (P-MOSFETs) and anti-parallel fast recovery diodes as the switches in the active circuit.

\[
S_{rcm} = S_{La} \oplus S_{Lb} \oplus S_{Lc} \quad (10)
\]

Where \( S_{La} \), \( S_{Lb} \), and \( S_{Lc} \) are the control logic signals of the top switches of Leg A, Leg B, and Leg C, respectively. There are two types of three-phase single tuned filters (see Fig. 6). In view of the connection with the active CM filter, the Y-type filter is better than the \( \Delta \)-type one.

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<td>Capacitor of low-pass filter</td>
</tr>
<tr>
<td>( L_b )</td>
<td>90 ( \mu )H</td>
<td>Inductor of single tuned filter</td>
</tr>
<tr>
<td>( C_b )</td>
<td>22 ( \mu )F</td>
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</tr>
<tr>
<td>( R_b )</td>
<td>0.09 ( \Omega )</td>
<td>Resistor of single tuned filter</td>
</tr>
<tr>
<td>( R_f )</td>
<td>1 M( \Omega )</td>
<td>Resistor for detecting CMV</td>
</tr>
<tr>
<td>( R_{s} )</td>
<td>230 ( \Omega )</td>
<td>Current-limiting resistor</td>
</tr>
<tr>
<td>( R_c )</td>
<td>4.7 k( \Omega )</td>
<td>Pull-up resistor</td>
</tr>
<tr>
<td>( L_{s1} )</td>
<td>300 ( \mu )H</td>
<td>Inductor of active filter</td>
</tr>
<tr>
<td>( L_{s2} )</td>
<td>30 ( \mu )H</td>
<td>Inductor of active filter</td>
</tr>
<tr>
<td>( C_s )</td>
<td>75 ( \mu )F</td>
<td>Capacitor of active filter</td>
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<tr>
<td>( C_{s2} )</td>
<td>66 ( \mu )F</td>
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<tr>
<td>( R_c )</td>
<td>0.03 ( \Omega )</td>
<td>Resistor of active filter</td>
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<tr>
<td>( f_0 )</td>
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</tr>
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<td>( f_c )</td>
<td>3.6 kHz</td>
<td>Carrier frequency</td>
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<tr>
<td>( t_{dead} )</td>
<td>5 ( \mu )s</td>
<td>Switching dead-time of IGBT</td>
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<tr>
<td>( t_{dead} )</td>
<td>1 ( \mu )s</td>
<td>Switching dead-time of P-MOSFET</td>
</tr>
</tbody>
</table>

Fig. 10. Three-phase single tuned filter. (a) \( \Delta \)-type and (b) Y-type. be shortened.

The second way to obtain \( S_{rcm} \) is the “calculation-control” scheme. Under this scheme, the signal \( S_{rcm} \) is calculated in the processor as the following:

The single tuned filter can greatly suppress the harmonics near the carrier frequency. The passive DM filter is composed of the inductors \( L_f \) in the original low-pass filter and the impedances \( Z_p \). In theory, the THD of the output DMV can also be reduced by simply increasing the \( C_{fo} \) of the original low-pass filter. But the previous studies [34], [35] show that a single tuned filter with a parallel capacitor has higher cost performance than a single capacitor in the harmonic suppression.

### C. Hybrid Filter

It will form an organic whole to connect the above designed active CM filter with the passive DM filter through the neutral point \( n \). That is the hybrid filter in the design plan.

![Fig. 11. Three-phase inverter with the hybrid filter](image-url)
From Fig. 9, it can be seen that the midpoint of the inverter dc input is equipotential with the ground in essence because of the Line Impedance Stabilization Network (LISN). Then the voltage at any point is equal to the potential difference from the point to the midpoint of the dc input. Because the output CMVs of the inverter with the CPPM strategy are $\pm V_{dc}/6$, the dc input voltage levels of the active CM filter must also be $\pm V_{dc}/6$ when $k=1/3$. So the dc voltage of the active filter can be taken from the divided voltage of the inverter dc voltage through the middle capacitor which is one of the series capacitors on the inverter dc-side. The potentials of the middle capacitor’s two ends are just $\pm V_{dc}/6$.

More sophisticated applications use a switching power converter to interface between the solar panel and the load. When a switching power converter is present, RCC represents a minor addition to the converter control to achieve tracking of the panel maximum power with minimum extra cost.

TABLE V

<table>
<thead>
<tr>
<th>Condition</th>
<th>Without a hybrid filter</th>
<th>With a hybrid filter</th>
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<tbody>
<tr>
<td>THD</td>
<td>3.42%</td>
<td>1.40%</td>
</tr>
</tbody>
</table>

V. SIMULATION RESULTS

![Simulated FFT results of output DMV in the inverter under the (a) conventional SPWM strategy, (b) CPS strategy, and (c) CPPM strategy At fc=2.5e-3.](image)

![Simulated FFT results of output DMV in the inverter under the (a) conventional SPWM strategy, (b) CPS strategy, and (c) CPPM strategy At fc=3.6e-3.](image)
Fig 14. Simulated FFT results of output DMV in the inverter under the (a) conventional SPWM strategy, (b) CPS strategy, and (c) CPPM strategy.

At \( f_c = 5 \times 10^{-3} \)

Fig 15. Simulated FFT results of output DMV in the inverter under the (a) conventional SPWM strategy, (b) CPS strategy, and (c) CPPM strategy.

At \( f_c = 100 \times 10^{-3} \)
Fig 16. Experimental results of the CMV $v_{cm}$ (top) and its FFT (bottom) in the three-phase inverter without a hybrid filter (a) under the conventional SPWM strategy, (b) under the CPPM strategy, and (c) with the detection-control hybrid filter (d) with the calculation-control hybrid filter under the CPPM strategy.

Fig 17. Experimental results of the shaft voltage $v_{shaft}$ (top) and its FFT (bottom) in the three-phase inverter (a) under the conventional SPWM strategy without a hybrid filter, and under the CPPM strategy (b) with the detection-control hybrid filter or (c) with the calculation-control hybrid filter.
VI. CONCLUSION

In this paper the hybrid filter, which is designed to suppress the CMV and DM harmonics of the three-phase inverter, is proved to have the following characteristics. The method which makes use of such ripple and correlates this with switching function to control the operating point of PV array is called ripple correlation control (RCC). In this paper, a modified RCC method has been proposed to implement the MPPT technique with reduced component count which makes the implementation easier compared to existing techniques presented in literature. 1) Simple in structure: The simple structure means lower cost. 2) Easy in installation: As the added active DMV filter and single tuned filter in the hybrid filter are paralleled into the output lines of the inverter, they can be installed conveniently and are very suitable for the revamping of the established system. 3) Flexible in application. 4) Optimized in effect: As for the CMV suppression effect, the inverter with the hybrid filter is much better than that without the hybrid filter and the hybrid filter under the
calculation-control scheme is superior to that under the detection-control scheme. 5) Compatible in THD standard: The phase-shifting of the carrier in the CPPM strategy enhances the output DM harmonics of the inverter in the carrier frequency band. Compared to existing methods which uses only sign of the error signal generated by the MPPT block, this method uses both magnitude and sign of the error signal which makes the system respond faster. The effectiveness of the proposed method has been verified by using simulation results.

REFERENCES


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