One-Cycle Control Based Vienna Rectifiers with Input Power Factor Regulation

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Abstract. In this paper, a crucial technique for incorporating reactive power compensation functionality into Vienna rectifiers is discussed and a modified one-cycle-control (MOCC) scheme is proposed for regulating three-phase Vienna rectifiers operating under leading, lagging or unity power factor with sinusoidal input current. The operating principle of the conventional OCC (COCC) strategy is reviewed simply at first, then the MOCC scheme with input current phase-shift control is discussed in detail. To mitigate input current distortion caused by the current phase-shift, a method by injecting some components to the current command signals is further presented. The implementation of the proposed MOCC scheme is as simple as that of the COCC scheme. In addition, all other advantages exhibited by the COCC scheme, such as no phase-locked loop, no frame transformation and constant switching frequency are also retained by MOCC scheme. The theoretical analysis of the proposed MOCC schemes is fully verified by simulations.

1. Introduction

With the increased use of power electronic converters, which generally exhibit a nonlinear load characteristic to the power grid, power quality problems are getting more and more concerned. Nonlinear loads connected to the power grid usually consume a large amount of reactive power and inject a great deal of harmonics to the line current. In consequence, bringing about serious power quality (PQ) problems, such as decreased stability of power system and increased cable power loss. Therefore, in order to reduce the effects caused by these PQ problems, many technologies have been studied industrially and academically. Among these technologies, power electronics based static VAR compensator (SVC), static synchronous compensator (STATCOM) and active power filters (APFs) have being utilized intensively to improve power quality through reactive power compensation (RPC) and harmonic current compensation (HCC). However, in recent years, with the increased utilization of distributed generation (DG) systems, many researchers believe that compared to the traditionally specifically designed SVCs, STATCOMs and APFs, integrating the RPC and HCC functionality into the existing bidirectional power converters, which are widely used as the interface of the DG systems, may be the more cost-effective solution for power quality management [1-3]. The obvious advantage of this solution for power quality improvement is that the distributed local compensation of reactive power will eliminate the additional power losses due to long distance transmission of reactive power with only a little additional hardware costs.
One cycle control, which was proposed by K. M. Smedley in 1991 and realized in buck PWM converters initially, has become the most widely used control strategy for single phase and three phase converters. It exhibits a series of commonly recognized advantages, such as PLL-less, no grid voltage sensors, no frame transformation, constant switching frequency and fast dynamic response [4]. The OCC strategy is also called the resistance emulation control. When OCC is used in boost type PWM rectifiers, it will force the input current in phase with the grid voltage in sinusoidal waveform automatically. Although in most applications, because of negligence to the input inductor voltage drop, the input current of the converter always lags the grid voltage by a small angle, resulting in non-unity displacement power factor. Several papers have discussed this problem and proposed some compensation methods to make the converter keep unity power factor really with varied load [5-6].

In this paper, a modified one-cycle-control scheme is proposed to achieving phase-shift control to the input current of the three-phase Vienna rectifiers under leading, lagging or unity power factor. The compensation method to mitigate the input current distortion caused by the input current phase-shift is also presented. Note that the MOCC scheme with input current phase-shift functionality applies to all rectifiers that use conventional OCC control strategy and the proposed control method for mitigating input current distortion can be applied to all other three-phase star-connected unidirectional rectifiers as well. Basic principles of conventional OCC.

2. Basic principles of conventional OCC

Although the basic working principle of COCC-based three-phase Vienna converters were presented in several papers previously, for sake of completeness, it is still briefly described at first.

![Image](image.png)

**Fig 1.** (a) A three-phase VIENNA rectifier and (b) its average model of switching period

The schematic and its average model of switching period for the three-phase Vienna rectifier are shown in Fig. 1(a) and 1(b), respectively. In Fig. 1(a), $U_o$ is the output voltage in DC side. In the average model shown in Fig.1(b), the average voltages at nodes A, B, C with respect to the neutral point “O” equal to the phase voltages minus the voltages across the inductors $L_a, L_b, L_c$ (assuming $L_a = L_b = L_c = L$). The COCC key equations for three-phase Vienna rectifier is shown below

$$
\begin{align*}
V_m (1 - d_a) &= R_s \cdot i_A \\
V_m (1 - d_b) &= R_s \cdot i_B \\
V_m (1 - d_c) &= R_s \cdot i_C 
\end{align*}
$$

where $i_A, i_B, i_C$ are inductor currents and $\omega$ is line angular frequency. In COCC strategy, when switching frequency is much higher than line frequency, the voltages across the inductors are usually seen as small enough to be neglected where $R_s$ is the equivalent resistance of current sensor and $V_m = U_o R_s / 2 R_s$, $d_a, d_b$ and $d_c$ are duty ratio of switches $S_A, S_B$ and $S_C$, respectively.
3. Current phase-shift control based on MOCC scheme and distortion mitigation strategy

From above description it can be seen that the essence of COCC scheme for three-phase Vienna rectifier is by resistive load emulation to achieve unity power factor operation. Although because of the negligence to the inductance voltage drop, the actual displacement angle always lags a little bit. Fig.2 (a) shows the per phase equivalent circuit.

In following discussion, a modification to COCC scheme will be provided to make the input power factor of Vienna rectifier become adjustable, to achieve this control goal, the per phase emulated load is changed from a pure resistor $R_e$ to a complex impedance $Z$ made up of a resistor $R_e$, a inductor $X_{el}$ and a capacitor $X_{ec}$ in series connection as shown in Fig.2(b). The complex impedance of the emulated load $Z$ is given by

$$Z = R_e + j \left( X_{el} - X_{ec} \right)$$

$$X_{el} = \omega L_e$$

$$X_{ec} = \frac{1}{\omega C_e}$$

Equations (3) is the proposed MOCC based key control equations for three-phase Vienna rectifier, compared to COCC based key control equations given by (1), there are two items instead of one on the right side of equations (3), the first item represents the active power required by the load, while the second one determines the reactive power can be supplied by Vienna rectifier, which will be used to regulate the phase-shift angle of the input current. If the second item is equal to zero, equation (3) will be the same as equation (1).
Fig 3. MOCC based control block diagram with current phase-shift control strategy

Fig 3. Shows the block diagram of the proposed MOCC based control system, a phase shifter block is added which shifts the phase angle of the sensed input current signals $R_s i_x (x = A, B, C)$ by 90° and then multiplies the gain $k$ determined by the second item of right side of (3) to generate the shifting current signals $R_s i_{xsh} (x = A, B, C)$. Note that achieving 90° phase shift is quite an easy work for a digital circuit. Adding the shifting current signals $R_s i_{xsh} (x = A, B, C)$ back to the sense input current signals $R_s i_x (x = A, B, C)$ gives the compensation current signals $R_s i_{conx} (x = A, B, C)$, the absolute value of compensation current signals are subsequently compared to triangular waveforms to generate PWM signals to force the Vienna rectifier to operate under the required input power factor.

If $X_{el} = X_{el} = 0$in the equation (3), then (3) will be simplified as

$$
\begin{align*}
V_m (1 - d_a) & = \left[ R_s - \left( j \omega L R / R_c \right) \right] \cdot i_A \\
V_m (1 - d_b) & = \left[ R_s - \left( j \omega L R / R_c \right) \right] \cdot i_B \\
V_m (1 - d_c) & = \left[ R_s - \left( j \omega L R / R_c \right) \right] \cdot i_C
\end{align*}
$$

The control system based on (4) will make the Vienna rectifier operate actually under unity power factor, the lagging displacement angle under COCC will be compensated to zero. So equation (6) can be seen as a more general expression for OCC key control equation.

In above discussion, an analysis to the input current distortion in a single-phase Vienna rectifier is carried out. In the three-phase Vienna rectifier, the mechanism causing input current distortion is similar to that of the single-phase Vienna rectifier, but if compare the equivalent circuit of single-phase Vienna rectifier based on average model as shown in Fig 4(a) with the per phase equivalent circuit of three-phase Vienna rectifier as shown in Fig 4(b), it can be easily observed that an additional controllable voltage $u_{NO}$ appear in the later circuit. $u_{NO}$ is the average voltage of the cycle between node O and node N, which is determined by the average node voltages $u_{AN}$, $u_{BN}$ and $u_{CN}$. In the following, a study will
be given to show the possibility of mitigating or even eliminating the input currents distortion of the three-phase Vienna rectifier by controlling voltage $u_{NO}$ based on the MOCC strategy.

**Fig 4.** (a) Equivalent circuit diagram of single-phase Vienna rectifier and (b) Equivalent circuit diagram of three-phase Vienna rectifier

**Fig 5.** Equivalent circuit of three-phase Vienna rectifier when $u_{AN} = 0$

Phase A input current distortion will be taken as an example to carry out the following analysis, here assuming three-phase Vienna rectifier is operating under leading power factor. Note that in normal conditions, the node voltages $u_{xN}$ ($x = A, B, C$) are employed to control the three input currents operating under required power factor. However, as seen from the above discussion, the node voltage $u_{AN}$ in phase A cannot have the polarity opposite to that of the input current $i_A$, so when the polarity of the input current $i_A$ and the reference node voltage $u_{AN}$ are opposite, an uncontrollable region appears, in this region, $u_{AN}$ will keep in zero as shown in Fig 5, which makes it can no longer be used to control the actual input current $i_A$ to follow the current reference $i_A^*$. In this case, Equation about average node voltages $u_{AN}$, $u_{BN}$ and $u_{CN}$ are changed to

$$
\begin{align*}
  u_{AN} &= 0 \\
  u_{BN} &= (1 - d_a) \cdot \text{sign}(i_B) \cdot U_O / 2 \\
  u_{CN} &= (1 - d_a) \cdot \text{sign}(i_C) \cdot U_O / 2
\end{align*}
$$

Re-derive the OCC can be derived as

$$
\begin{align*}
  V_a (1 - d_a) &= |R_{i_{conA}}| - \frac{R_{i_{conA}}}{\text{sign}(R_{i_{conA}})} \\
  V_a (1 - d_c) &= |R_{i_{conC}}| - \frac{R_{i_{conC}}}{\text{sign}(R_{i_{conC}})}
\end{align*}
$$

5
Equation (6) gives the MOCC based control key equation with function of mitigating the input current distortion, which indicates that as long as the MOCC based control law in phase B and phase C satisfies the strategy given by (6), in the uncontrollable region, the input current in phase A will keep to follow the sinusoidal reference current exactly with no distortion. The MOCC based control law in the uncontrollable region of phase B and phase C are similar to that in phase A.

4. Simulation results

In order to verify the effectiveness of the proposed MOCC scheme, simulations are carried out in the MATLAB/Simulink environment. The key parameters chosen for the simulation models are provided in Table II.

The simulation results based on COCC scheme for the three phase Vienna rectifier are depicted in Fig. 8, in which the phase A source voltage and input current waveforms is listed on the top, while the rectified sensed input current signal $I_{A}$ is listed at the bottom. Note that here the absolute value of $I_{A}$ is used directly to compare with the triangular wave to generate the required PWM pulses. Because of neglect to the input inductor voltage drop, the actual input current lags the phase a source voltage by a small angle.

MOCC scheme based simulation results with no distortion control strategy applied are depicted in Fig 7 (a) and (b), Fig 7 (a) and (b) show the simulation waveforms under leading power factor and lagging power factor respectively. Note that, this modification makes the phase angle of input current become adjustable. It can be seen that in the three Figs, the phase angle of the input current is fully controlled by the corresponding compensation current signal $I_{comA}$. It can also be seen that some distortion caused by the phase shift appears periodically in the input current.

| Table 1 Simulation Parameters |
|-------------------------------|-----------------|
| Parameter                     | VALUE           |
| Input line-line voltage        | 380V            |
| Input inductance               | 2.6mH           |
| Switching frequency            | 20kHz           |
| Load resistance                | 30Ω             |
| Source voltage frequency       | 50Hz            |
| DC-link capacitors             | 5000μF          |
| DC-link voltage                | 700V            |
Fig 7. MOCC based phase a source voltage and input current waveforms as well as the rectified compensation current signals $R_s l_{comx}(x = A, B, C)$ with no distortion control strategy applied.

MOCC scheme-based simulation results with application of distortion control strategy are depicted in Fig. 8(a) and (b). Fig 7 (a) and (c) show the phase A source voltage and input current waveforms as well as the rectified final command current signal $R_s l_{comA}$ under leading power factor with displacement angle $\theta = 18^\circ$ and lagging power factor with displacement angle $\theta = -33^\circ$ respectively. Note that, here the rectified final command current signal is used to compared with the triangular wave to generate the required PWM pulses. It can be seen that because of the application of current distortion mitigation control strategy, the input currents in all the three modes are in near-sinusoidal wave. It can be noted that in the final command current signal shown in Fig 10, some narrow pulses are superimposed to rectified sinusoidal waveform, which indicates that the distortion current signal is injected periodically to the compensation current signal in each uncontrollable region. The simulation results fully verified the effectiveness of the proposed method for mitigating the possible input current distortion caused by current phase-shift in the unidirectional three phase Vienna rectifier.
Fig 8. MOCC based phase a source voltage and input current waveforms and the rectified final command current signal $R_s i_{cmdA}$ with application of distortion control strategy.

5. Conclusion
In this paper, a crucial technique for incorporating reactive power compensation functionality into three phase Vienna rectifiers is discussed and a modified OCC scheme is proposed. The modified OCC scheme based on the input complex impedance emulation instead of resistive load emulation like conventional OCC scheme usually does, makes the input currents of the three phase Vienna rectifier could be controlled to operate in leading, lagging, or unity power factors through adding a 90° phase shifted current signals to the sensed current signals. In order to compensate the input current distortion caused by current phase shift, the method for mitigating the current distortion is also presented, in which distortion current signals are injected to the compensation current signals periodically in each uncontrollable region. The validity of the theoretical study to the proposed MOCC scheme is fully supported by simulations results.

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