Three-phase Unity-Power-Factor VIENNA Rectifier with Unified Constant-frequency Integration Control

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Abstract: A Unified Constant-frequency Integration (UCI) controller for a three-phase three-switch three-level rectifier (VIENNA) with unity-power-factor-correction is proposed. One advantage of the VIENNA rectifier is that the switch voltage stress is one half of the total output voltage so that MOSFETs can be used. The proposed control approach is based on one-cycle control and features great simplicity and reliability: all three phase will be power factor corrected using one integrator with reset along with several flips-flops, comparators and logic and linear components. It does not require multipliers to scale the current reference according to the output power level as used in many other control approaches. In addition, the input voltage sensor is eliminated. It employs constant switching frequency modulation that is desirable for industrial applications. The proposed controller can operate by sensing either the inductor currents or the switching currents. If the switching currents are sensed, the cost is further reduced because switching currents are easier to sense comparing with inductor currents. The proposed approach is supported by experimental results.

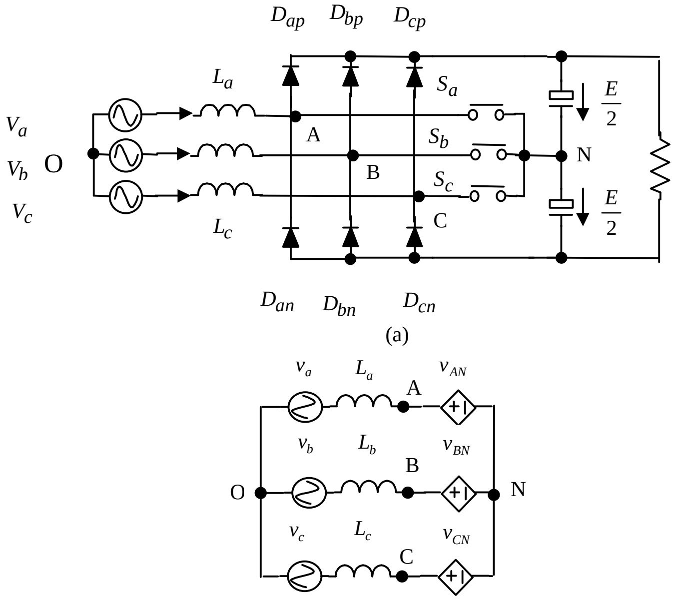
1 Introduction

Traditional diode rectifiers and thyristor rectifiers draw pulsed current from the ac main, causing significant current harmonics pollution. The international standards presented in IEC 1000-3-2 or EN61000-3-2 imposed harmonic restrictions to modern rectifiers, which stimulated a focused research effort on the topic of unity power factor rectifiers. Among the reported three-phase rectifier topologies, three-phase three-switch three-level rectifier (VENNA rectifier) [1]-[3] is an attractive choice because its switch voltage stress is one half of the total output voltage so that fast switches such as MOSFETs can be used. In this paper, a Unified Constant-frequency Integration (UCI) controller based on one-cycle control [4]-[7] is proposed for this rectifier. The proposed controller employs constant switching frequency modulation and is very simple that are very desirable for industrial applications.

Assuming that the rectifier is operated in Continuous-Conduction-Mode (CCM), a general equation that relates the input phase voltage and duty ratios of switches is derived from an average model. Based on one of the solutions and using One-Cycle control, a UCI controller is proposed for the VIENNA rectifier with the following features:

- Constant switching frequency.
- Simple and reliable. This controller is composed of one integrator with reset along with some flips-flops, comparators, and some logic and linear components.
- No need for multipliers that are required to scale the current reference according to the load level as used in many other control approaches.
- No 3-phase voltage sensors are required.
- The proposed control approach can be achieved by sensing either the inductor currents or the switching currents. If the switching currents are sensed, the cost is further reduced because switching current is easier to sense comparing with inductor currents.

2 Proposed Unified Constant-frequency Integration controller for the 3-phase VIENNA rectifier



(a)

(b)

Fig. 1. The 3-phase VIENNA rectifier (a) and its switching cycle average model (b).

The schematic and its switching cycle average model for the VIENNA rectifier are shown in Fig. 1. The average vector voltage at nodes A, B, C referring to the neutral point “O” equal the phase vector voltages minus the voltage across the inductors L_a, L_b, L_c, which is given by

$$\begin{cases} \dot{v}_{AO} = \dot{v}_a - jwL \cdot \dot{i}_{La} \\ \dot{v}_{BO} = \dot{v}_b - jwL \cdot \dot{i}_{Lb} \\ \dot{v}_{CO} = \dot{v}_c - jwL \cdot \dot{i}_{Lc} \end{cases} \text{------------(1)}$$

where L is the inductance of the input inductors and w is the line angular frequency if we assume that the inductance for all three-phase is same. The symbols $\vec{i}_{La}, \vec{i}_{Lb}, \vec{i}_{Lc}$ signify inductor current vectors. The inductance L is very small with regards to the line frequency variation, since the inductors are designed for switching frequency operation. For a 60Hz utility system, the voltages across the inductor $jwL \cdot \vec{i}_{La}$ is very small comparing with the phase voltage, thus can be neglected. Therefore, the equation (1) can be approximately simplified as

$$\begin{cases} \dot{v}_{AO} \approx \dot{v}_a \\ \dot{v}_{BO} \approx \dot{v}_b \\ \dot{v}_{CO} \approx \dot{v}_c \end{cases} \Rightarrow \begin{cases} v_{AO} \approx v_a = V_{gp} \cdot \sin(wt) \\ v_{BO} \approx v_b = V_{gp} \cdot \sin(wt + 120^\circ) \\ v_{CO} \approx v_c = V_{gp} \cdot \sin(wt + 240^\circ) \end{cases} \text{-----(2)}$$

where v_{AO}, v_{BO}, v_{CO} are cycle average of the voltage at nodes A,B,C referring to node O and V_{gp} are peak of the phase voltage. For a three-phase system, it holds that

$$v_a + v_b + v_c = 0 \text{--------(3)}$$

Equation (2) leads to

$$v_{AO} + v_{BO} + v_{CO} = 0 \text{---------(4)}$$

The voltages at nodes A, B, C referring to the neutral point O are given by

$$\begin{cases} v_{AO} = v_{AN} + v_{NO} \\ v_{BO} = v_{BN} + v_{NO} \\ v_{CO} = v_{CN} + v_{NO} \end{cases} \text{---(5)}$$

Combination of equation (4) and (5) yields

$$v_{NO} = -\tfrac{1}{3} \cdot (v_{AN} + v_{BN} + v_{CN}) \text{-------(6)}$$

Substituting equation (6) and (2) into (5) results in

$$\begin{cases} v_a \approx v_{AN} - \tfrac{1}{3} \cdot (v_{AN} + v_{BN} + v_{CN}) \\ v_b \approx v_{BN} - \tfrac{1}{3} \cdot (v_{AN} + v_{BN} + v_{CN}) \\ v_c \approx v_{CN} + v_{NO} = v_{CN} - \tfrac{1}{3} \cdot (v_{AN} + v_{BN} + v_{CN}) \end{cases}$$

Simplification yields

$$\begin{bmatrix} \frac{2}{3} & -\frac{1}{3} & -\frac{1}{3} \\ -\frac{1}{3} & \frac{2}{3} & -\frac{1}{3} \\ -\frac{1}{3} & -\frac{1}{3} & \frac{2}{3} \end{bmatrix} \cdot \begin{bmatrix} v_{AN} \\ v_{BN} \\ v_{CN} \end{bmatrix} = \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \text{-----------(7)}$$

For the VIENNA rectifier, if the converter operates in CCM, the average node voltages in each switching cycle are given by

------------(8)

where are duty ratios of switches respectively. Simplification yields

where depends on the polarity of inductor currents. For example,

-----------(9)

Substitution equation (8) into equation (7) yields

-----(10)

Equation (10) shows the inherent relationship between the duty ratios and the input phase voltage in CCM condition. For a three-phase rectifier with unity-power-factor, the control goal is given by

------------(11)

where is the emulated resistance that reflects the output power level. Substitution of the above equation into (10) and simplification yield

---(12)

where is the equivalent current sensing resistor and is the output of the feedback error compensator.

---------(13)

Since the matrix in equation (12) is singular, there is no unique solution. One simple solution can be found as

---------------(14)

where are constant. Parameters can be determined by substituting the above equation in equation (12) which results in the following: parameter can be any real number, while parameter satisfies the following

--------(15)

For a 3-phase system, it holds that .
Combination of the above two equations yields

Select . The equation (14) can be rewritten by

----------(16)

With the assistance of the following equations, the above equation can be simplified as shown in equation (17)

--(17)

This is the control key equation for the VIENNA rectifier. The absolute value of current can be realized by using three full-wave rectifier circuits. No voltage sensors are required. The implementation can be achieved by sensing either inductor currents or switching currents. Replacement of the with peak inductor current results in the control implementation equations:

------------(18)

(a)

(b)

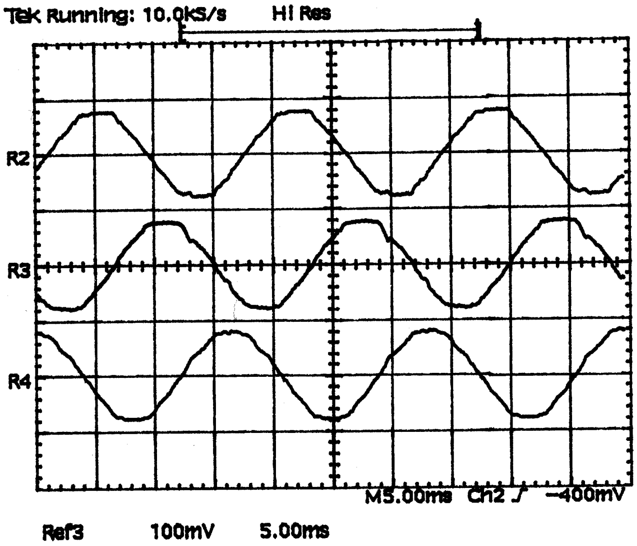
Fig. 2. Schematic of proposed 3-phase PFC controller for VIENNA rectifier by sensing peak inductor currents (a) and its operation waveforms (b).

Equation (18) can be realized by one integrator with reset as well as some logic and linear components. The proposed controller as well as its operation waveforms for peak inductor current sensing are shown in Fig. 2; where the integration time constant equals the switching period, i.e. .

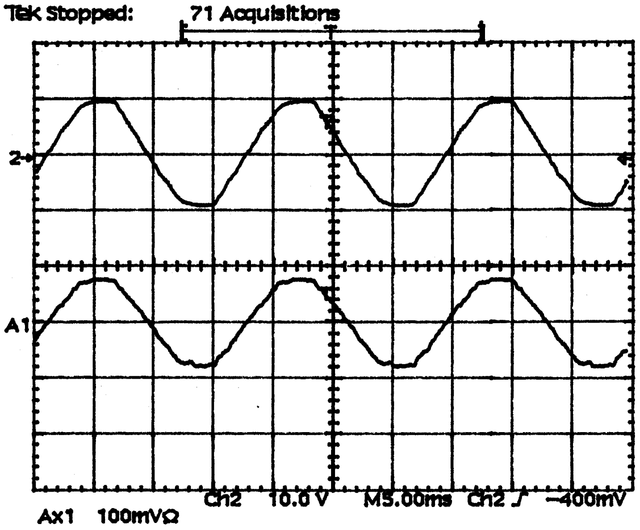
Fig. 3. Experimental 3-phase VIENNA rectifier.

3 Experimental verification

In order to verify the concept, a 1 kW prototype of a 3-phase VIENNA rectifier with proposed control approach using peak inductor current sensing was built. The VIENNA rectifier in the experiment is shown in Fig. 3. The experimental condition is as follows: 3-phase input filter inductance is 88uH; input filter capacitance is 1uF; main inductance is 1.4mH; diodes , etc are MUR8100; the three main switches are implemented with two MOSFETs in series back-to-back. The input voltage is 120Vrms. The output voltage is 485V. The output resistance is 233ohm and the output power is 1kwatts. The switching frequency is 100kHz. The experimental waveforms are shown in Fig. 4. Fig. 4 (a) shows three-phase inductor currents; Fig. 4 (b) shows the phase voltage and phase current . The measured THD is 6.5% while the input voltage has about 4% THD itself.



(a) Three-phase input currents. R1: , 5A/div. R2: , 5A/div. R3: , 5A/div. Horizontal: 5ms/div.



(b). Phase A voltage and current. Upper curve: input voltage, 10V/div; sensed through a 120V: 6V transformer Bottom curve: input Phase A current, 5A/div.

Fig. 4. Experimental waveforms for 3-phase VIENNA rectifier with proposed control approach.

4 Extension of the proposed control approach by sensing switching currents

The VIENNA rectifier with unity-power-factor can also be implemented by sensing switching current, which costs less comparing with inductor current sensing. One possible implementation of switching current sensing is illustrated in Fig. 5.

(a)

(b)

Fig. 5. Illustration of switching current sensing with current transformer for VIENNA rectifier. (a) One leg of VIENNA rectifier. (b) Switching current sensing.

When the inductor operates in CCM, the relationship between the inductor current and switching current is given by

----------(19)

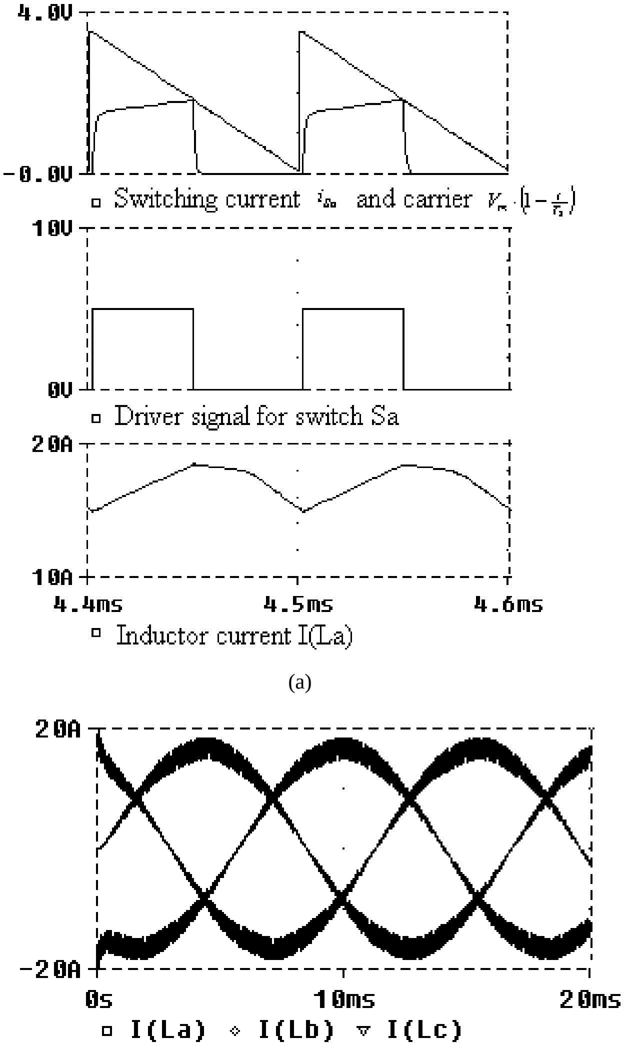
and ---(20)

Replace the inductor peak current with switching current in equation (18) yields

Fig. 6. Schematic of 3-PFC controller for VIENNA rectifier with peak switching current control.

----------(21)

Equation (21) shows that 3-PFC for VIENNA rectifier can be realized by sensing switching current. The schematic for the control block is shown in Fig. 6. Simulation results are shown in Fig. 7. The simulation conditions are as follows: the input phase voltage is 120Vrms; the output voltage is ; . The measured THD is 2%.



(a)

(b)

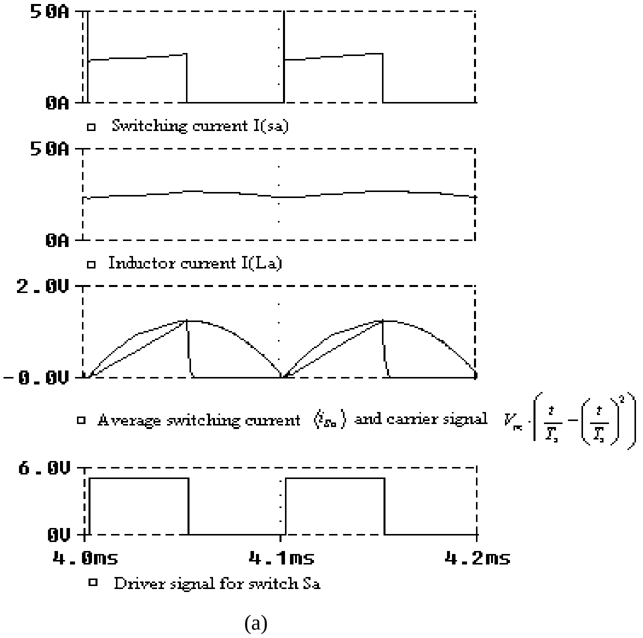
Fig. 7. Simulation results for 3-PFC for VIENNA rectifier with peak switching current sensing. (a) Operation waveforms of the controller. (b). Simulated inductor current waveforms.

The control based on peak switching current sensing is more sensitive to noise. Sensing average switching current is an alternative solution. Replace the average inductor current in equation (18) with average switching current in equation (20) yields

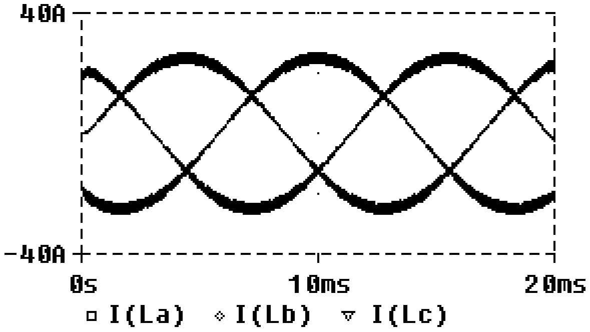
-------------(22)

The item can be realized with two integrators with reset. The schematic of control block for VIENNA rectifier with average switching current sensing is shown in Fig. 8 and simulation results are shown in Fig. 9.

Fig. 8. The schematic of control block for 3-PFC VIENNA rectifier with average switching current sensing.



(a)



(b)

Fig. 9. Simulated waveforms for 3-phase VIENNA rectifier with average switching current sensing. (a). Operation waveforms of control block. (b). Simulated three-phase inductor current wavefroms.

The simulation conditions are: the input voltage is 120Vrms, the output voltage is 600V; the switching frequency is 10KHz, the power is 6KW; and the measured THD is 0.3%.

5 Conclusion

In this paper, a three-phase three-switch three-level (VIENNA) rectifier with unity power factor is investigated. A general equation that relates the relationship between input phase voltage and switch duty ratios is derived. Based on one of the solutions and using One-Cycle Control, a new 3-phase PFC controller is proposed. The proposed controller is composed of one or two integrators with reset along with several comparators and flip/flops. No multipliers and input voltage sensors are required. The controller employs constant frequency modulation that is desirable for industrial applications. An experimental circuit of a 1kW VIENNA rectifier with peak current sensing was built to verify the concept. Near unity power factor was measured in all three phase. The proposed controller can be implemented by sensing either inductor currents or switching currents. The controller is very simple and reliable.

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