Three-Phase Unity-Power-Factor Star-Connected Switch (VIENNA) Rectifier With Unified Constant-Frequency Integration Control

Chongming Qiao, Student Member, IEEE, and Keyue Ma Smedley, Senior Member, IEEE

Abstract—A unified constant-frequency integration (UCI) controller for a three-phase star-connected switch three-level rectifier (VIENNA) with unity-power-factor-correction is proposed. One of advantages of this rectifier is that the switch voltage stress is one half of the total output voltage. The proposed control approach is based on one-cycle control and features great simplicity and reliability: all three phases will be power factor corrected using one or two integrators 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.

Index Terms—One cycle control, power factor correction.

I. INTRODUCTION

T RADITIONAL 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 star-connected switch three-level rectifier (VIENNA rectifier) [1]–[3] is an attractive choice because its switch voltage stress is one half of the total output voltage. 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 that is very simple and 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 star-connected switch (VIENNA) rectifier with the following features.

1) Constant switching frequency.
2) Simple and reliable. This controller is composed of one or two integrators with reset along with some flips-flops, comparators, and some logic and linear components.
3) No need for multipliers that are required to scale the current reference according to the load level as used in many other control approaches.
4) No three-phase input ac voltage sensors are required.
5) 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.

II. PROPOSED UNIFIED CONSTANT-FREQUENCY INTEGRATION CONTROLLER FOR THE THREE-PHASE STAR-CONNECTED SWITCH RECTIFIER

The schematic and its switching cycle average model for the VIENNA rectifier are shown in Fig. 1. The average vector...
Fig. 2. Schematic of proposed three-phase PFC controller for VIENNA rectifier by (a) sensing peak inductor currents and (b) its operation waveforms.

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

\[
\begin{align*}
\dot{v}_{AO} &= v_a - jwL \cdot i_{La} \\
\dot{v}_{BO} &= v_b - jwL \cdot i_{Lb} \\
\dot{v}_{CO} &= v_c - jwL \cdot i_{Lc}
\end{align*}
\]

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 \( i_{La}, i_{Lb}, i_{Lc} \) 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 60 Hz utility system, the voltages across the inductor \( jwL \cdot i_{La} \) is very small comparing with the phase voltage, thus can be neglected. Therefore, the (1) can be approximately simplified as

\[
\left\{
\begin{align*}
\dot{v}_{AO} &\approx \dot{v}_a \\
\dot{v}_{BO} &\approx \dot{v}_b \\
\dot{v}_{CO} &\approx \dot{v}_c
\end{align*}
\right. \quad (2)
\]

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

\[
v_a + v_b + v_c = 0
\]

(3) leads to

\[
v_{AO} + v_{BO} + v_{CO} = 0.
\]

(4)

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

\[
\left\{
\begin{align*}
v_{AO} &= v_{AN} + v_{NO} \\
v_{BO} &= v_{BN} + v_{NO} \\
v_{CO} &= v_{CN} + v_{NO}
\end{align*}
\right. \quad (5)
\]

Combination of (4) and (5) yields

\[
v_{NO} = \frac{-1}{3} \cdot (v_{AN} + v_{BN} + v_{CN}).
\]

(6)

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

\[
\left\{
\begin{align*}
v_a &\approx v_{AN} - \frac{1}{3} \cdot (v_{AN} + v_{BN} + v_{CN}) \\
v_b &\approx v_{BN} - \frac{1}{3} \cdot (v_{AN} + v_{BN} + v_{CN}) \\
v_c &\approx v_{CN} - \frac{1}{3} \cdot (v_{AN} + v_{BN} + v_{CN})
\end{align*}
\right.
\]

Simplification yields

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

For this rectifier, if the converter operates in CCM, the average node voltages in each switching cycle \( v_{AN}, v_{BN}, v_{CN} \) are given by

\[
\left\{
\begin{align*}
v_{AN} &= \left(1 - d_a\right) \cdot \frac{E}{2} \quad \text{when } i_a \geq 0 \\
v_{BN} &= \left(1 - d_b\right) \cdot \frac{E}{2} \quad \text{when } i_b < 0 \\
v_{CN} &= \left(1 - d_c\right) \cdot \frac{E}{2} \quad \text{when } i_c \geq 0
\end{align*}
\right.
\]

where \( d_a, d_b, d_c \) are duty ratios of switches \( S_a, S_b, S_c \), respectively. Simplification yields

\[
\left\{
\begin{align*}
v_{AN} &= (1 - d_a) \cdot \frac{E}{2} \cdot \text{sign}(i_a) \\
v_{BN} &= (1 - d_b) \cdot \frac{E}{2} \cdot \text{sign}(i_b) \\
v_{CN} &= (1 - d_c) \cdot \frac{E}{2} \cdot \text{sign}(i_c)
\end{align*}
\right. \quad (8)
Substitution (8) into (7) yields
\[
\begin{bmatrix}
\frac{2}{3} & -\frac{1}{3} & -\frac{1}{3} \\
-\frac{2}{3} & \frac{1}{3} & \frac{1}{3} \\
-\frac{1}{3} & -\frac{1}{3} & \frac{1}{3}
\end{bmatrix}
\cdot
\begin{bmatrix}
(1 - d_a) \cdot \text{sign}(i_a) \\
(1 - d_b) \cdot \text{sign}(i_b) \\
(1 - d_c) \cdot \text{sign}(i_c)
\end{bmatrix}
= \frac{2}{E}
\begin{bmatrix}
v_a \\
v_b \\
v_c
\end{bmatrix}
\]  
(10)

(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
\[
\begin{align*}
v_a &= R_e \cdot i_a \\
v_b &= R_e \cdot i_b \\
v_c &= R_e \cdot i_c
\end{align*}
\]  
(11)
where \( R_e \) is the emulated resistance that reflects the output power level. Substitution of the above equation into (10) and simplification yield
\[
\begin{bmatrix}
\frac{2}{3} & -\frac{1}{3} & -\frac{1}{3} \\
-\frac{2}{3} & \frac{1}{3} & \frac{1}{3} \\
-\frac{1}{3} & -\frac{1}{3} & \frac{1}{3}
\end{bmatrix}
\cdot
\begin{bmatrix}
(1 - d_a) \cdot \text{sign}(i_a) \\
(1 - d_b) \cdot \text{sign}(i_b) \\
(1 - d_c) \cdot \text{sign}(i_c)
\end{bmatrix}
= \frac{R_e}{V_m}
\begin{bmatrix}
i_a \\
i_b \\
i_c
\end{bmatrix}
\]  
(12)
where \( R_e \) is the equivalent current sensing resistor and \( V_m \) is the output of the feedback error compensator
\[
V_m = \frac{E \cdot R_e}{2 \cdot R_e}
\]  
(13)
Since the matrix in (12) is singular, there is no unique solution. One simple solution can be found as
\[
\begin{align*}
V_m \cdot (1 - d_a) \cdot \text{sign}(i_a) &= K_1 + K_2 \cdot i_a \\
V_m \cdot (1 - d_b) \cdot \text{sign}(i_b) &= K_1 + K_2 \cdot i_b \\
V_m \cdot (1 - d_c) \cdot \text{sign}(i_c) &= K_1 + K_2 \cdot i_c
\end{align*}
\]  
(14)
where \( K_1, K_2 \) are constant. Parameters \( K_1, K_2 \) can be determined by substituting the above equation into (12) which results in the following: parameter \( K_1 \) can be any real number, while parameter \( K_2 \) satisfies
\[
\begin{bmatrix}
\frac{2}{3} & -\frac{1}{3} & -\frac{1}{3} \\
-\frac{2}{3} & \frac{1}{3} & \frac{1}{3} \\
-\frac{1}{3} & -\frac{1}{3} & \frac{1}{3}
\end{bmatrix}
\cdot
\begin{bmatrix}
i_a \\
i_b \\
i_c
\end{bmatrix}
= R_s
\begin{bmatrix}
i_a \\
i_b \\
i_c
\end{bmatrix}
\]  
(15)
For a three-phase system, it holds that \( i_a + i_b + i_c = 0 \). Combination of the above two equations yields
\[
K_2 = R_s.
\]

Parameter \( K_1 \) can be any dc value. Parameter \( V_m \) is a voltage related to the output load and input voltages; it is from of the
output of voltage feedback regulator. Any dc voltage $K_1$ will not affect the control because it will be automatically compensated by the output voltage feedback loop. In fact, signal $K_1 + K_2 \cdot i_a$ can be viewed as the sensed current signal including dc offset. It will not affect the normal operation of proposed approach. For simplicity analysis, we choose $K_1 = 0$ and $K_2 = R_a$ are used. Equation (14) can be rewritten by

$$
\begin{align*}
V_m \cdot (1 - d_a) \cdot \text{sign}(i_a) &= R_a \cdot i_a \\
V_m \cdot (1 - d_b) \cdot \text{sign}(i_b) &= R_a \cdot i_b \\
V_m \cdot (1 - d_c) \cdot \text{sign}(i_c) &= R_a \cdot i_c
\end{align*}
$$

(16)

With the assistance of the following equations, the previous equation can be simplified as shown in

$$
\begin{align*}
| i_a | &= \frac{i_a}{\text{sign}(i_a)} \\
| i_b | &= \frac{i_b}{\text{sign}(i_b)} \\
| i_c | &= \frac{i_c}{\text{sign}(i_c)} \\
V_m \cdot (1 - d_a) &= R_a \cdot | i_a | \\
V_m \cdot (1 - d_b) &= R_a \cdot | i_b | \\
V_m \cdot (1 - d_c) &= R_a \cdot | i_c |
\end{align*}
$$

(17)

This is the control key equation for the rectifier. The absolute value of current $i_a, i_b, i_c$ 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 $i_a, i_b, i_c$ with peak inductor current results in the control implementation equations

$$
\begin{align*}
V_m \cdot (1 - d_a) &= R_a \cdot | i_{Lap} | \\
V_m \cdot (1 - d_b) &= R_a \cdot | i_{Lbp} | \\
V_m \cdot (1 - d_c) &= R_a \cdot | i_{Lcp} |
\end{align*}
$$

(18)

(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. $\tau = T_s$.

In the beginning of each switching cycle, the clock pulse sets the three flip-flops. The currents $R_a \cdot i_{Lap}, R_a \cdot i_{Lbp}, R_a \cdot i_{Lcp}$ pass an absolute value circuit and form an input to each of the three comparators. At other input of the three comparators is the value of $V_m$ minus the integrated value of $V_m$. Signal $v_m - v_m \cdot (1/T_s)$ is compared with $R_a \cdot | i_{Lap} |$ in the first comparator as shown in Fig. 2. When the two inputs of a comparator meet as shown in Fig. 2(b), the comparator changes its state, which resets the correspondent flip-flop. As a result, the correspondent switch is turned off. Therefore, the duty ratios $d_a, d_b$ and $d_c$ are determined for the correspondent switch in each switching cycle.

III. EXPERIMENTAL VERIFICATION

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

The star-connected switch (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. When the inductor operates in CCM, the relationship between the inductor current and switching current is given by

\[
\begin{align*}
\dot{i}_{L_p} &= \dot{i}_{SPk} \\
\dot{i}_{S_p} &= \dot{i}_{LPk} \\
\dot{i}_{S_p} &= \dot{i}_{LPk}
\end{align*}
\]

and

\[
\begin{align*}
\langle \dot{i}_{SL} \rangle &= d_a \cdot \langle \dot{i}_{L_L} \rangle \\
\langle \dot{i}_{SB} \rangle &= d_b \cdot \langle \dot{i}_{L_b} \rangle \\
\langle \dot{i}_{SC} \rangle &= d_c \cdot \langle \dot{i}_{L_c} \rangle
\end{align*}
\]

(19)

(20)

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

\[
\begin{align*}
V_m \cdot (1 - d_a) &= R_s \cdot \langle \dot{i}_{SL} \rangle \\
V_m \cdot (1 - d_b) &= R_s \cdot \langle \dot{i}_{SB} \rangle \\
V_m \cdot (1 - d_c) &= R_s \cdot \langle \dot{i}_{SC} \rangle
\end{align*}
\]

(21)

Equation (21) shows that three-PFC for the star-connected switch (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 120 Vrms; the output voltage is \( E = 600 \) V; \( L = 3 \) mH; \( f = 10 \) kHz; \( P = 4.2 \) kW. The measured THD is 2%.

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 (18) with average switching current in (20) yields

\[
\begin{align*}
V_m \cdot (1 - d_a) \cdot d_a &= R_s \cdot \langle \dot{i}_{SL} \rangle \\
V_m \cdot (1 - d_b) \cdot d_b &= R_s \cdot \langle \dot{i}_{SB} \rangle \\
V_m \cdot (1 - d_c) \cdot d_c &= R_s \cdot \langle \dot{i}_{SC} \rangle
\end{align*}
\]

(22)

The item \( V_{m1} \cdot (1 - d_a) \cdot d_a \) can be realized with two integrators with reset. The schematic of control block for the star-connected switch (VIENNA) rectifier with average switching current sensing is shown in Fig. 8 and simulation results are shown in Fig. 9.

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

In this paper, a three-phase star-connected 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 three-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 1 kW 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.

REFERENCES


Chongming Qiao (S’98) was born in Taiyuan, China, in 1969. He received the B.S. degree in electrical engineering from Xian Jiaotong University, China, in 1991, the M.S. degree in power electronics from Zhejiang University, China, in 1994, and the Ph.D. degree from the University of California, Irvine, in 2001.

In 1997, he joined the Power Electronics Group, University of California, Irvine. His research interests include single-phase and three-phase power factor correction, active power filter, and single-phase single-stage power factor correction. Currently, he holds one patent and has published many technique papers and one application notes.

Keyue Ma Smedley (SM’97) received the B.S. and M.S. degrees from Zhejiang University, Hangzhou, China, in 1982 and 1985, respectively, and the M.S. and Ph.D. degrees from the California Institute of Technology, Pasadena, in 1987 and 1991, respectively, all in electrical engineering.

She was an Engineer at the Superconducting Super Collider from 1990 to 1992 where she was responsible for the design and specification of ac–dc conversion systems for all accelerator rings. She joined the faculty of Electrical and Computer Engineering, University of California, Irvine, in 1992, where she has established a state-of-the-art Power Electronics Laboratory. Her research interest includes control, topologies, and integration of dc–dc converters, high fidelity class-D power amplifiers, active and passive soft switching techniques, single-phase and three-phase power factor corrected rectifiers, active power filters, and grid-connected inverters for alternative energy sources, etc.

Dr. Smedley is an At-Large AdCom member of the IEEE Power Electronics Society, an Associate Editor of IEEE TRANSACTIONS ON POWER ELECTRONICS, a Co-Chair of Industry/Education Committee of the Power Sources Manufacturer’s Association, and the Chair of IASTED and IEEE Power Electronics Society cosponsored International Conference on Power and Energy Systems 2003.