Control of a Three-Phase PWM Rectifier Using Estimated AC-Side and DC-Side Voltages

Toshiya Ohnuki, *Member, IEEE,* Osamu Miyashita, *Member, IEEE,* Philippe Lataire, and Gaston Maggetto

***Abstract*—A new control method of a pulsewidth modulation (PWM) rectifier without measuring ac- and dc-side voltages is proposed. As information about these voltages is necessary for the controller, all required voltage values are estimated from the measured line currents and the calculated values of the input reactor voltage during switching of the rectifier circuit. The input reactor voltage can be obtained by using a differentiator that produces the derivative of the line current or by detecting the voltage induced in a secondary winding wound on the input reactor. The secondary winding creates the electric isolation between the main circuit and the controller. The proposed method is verified by experiment. This paper describes the estimation method, gives the configuration of the controller, and discusses steady-state and transient performances of the rectifier.**

***Index Terms*—AC-voltage sensorless control, dc-voltage sensorless control, high power factor, PWM rectifier.**

I. Introduction

PULSEWIDTH modulation (PWM) control techniques for rectifiers have widely been used to improve the mains current waveform and the input power factor. The sinusoidal-waveform control of the input ac current of the rectifiers is of importance and increasingly focused on the prevention of accidents and failure in the power system apparatuses.

Recently, methods for reducing the number of sensors have been discussed to simplify the system configuration of such rectifiers and their control circuits. For example, it was reported that a voltage sensor on the mains side could be omitted by using the information of the other sensor outputs and calculation [1]. A method using only voltage measurement for control was presented [2]. For single-phase rectifiers, a high-power-factor controller with only a current sensor can be implemented; the mains voltage and the dc voltage are estimated from the measured mains current [3]. These sensorless methods can make technical and economical contributions to system simplification, isolation between the power circuit and controller, and cost effectiveness.

In this paper, a new PWM rectifier controller that excludes measurement of the mains voltage and dc-side voltage is proposed. This controller, which also has the advantages mentioned above, is based on the modification of the voltage sensorless technique for the single-phase PWM rectifiers [3] and the proposed technique for inherent problems of three-phase systems. The mains voltage and dc-voltage values, both being necessary for instantaneous current control [4], [5], are estimated from the measured currents and their derivatives with respect to time.

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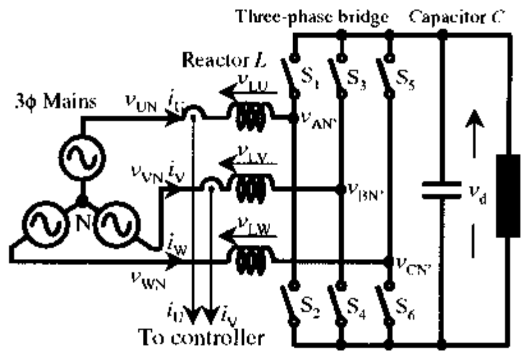

Fig. 1. Three-phase PWM rectifier.

The mains voltage can be estimated from the input-reactor voltage when the mains side of the bridge is short circuited; the reactor voltage is easily obtained by multiplication of the reactor inductance and the derivative of the measured line current or by using a secondary winding wound on the input reactor. The dc-side voltage can be estimated by calculating the difference between the estimated mains voltage and the reactor voltage when the mains side and dc side of the bridge are electrically connected. Consequently, if a differentiator is employed in the controller to calculate the derivative of the line current, the rectifier works without any voltage sensors. Using the secondary winding instead of the differentiator delivers voltage information that is required for control with an isolated condition between the main circuit and the controller.

This paper describes the voltage estimation method and its implementation and performance characteristics of the three-phase rectifier. The effectiveness of the rectifier is confirmed by experiment.

II. Estimation of the Mains and DC Voltages

A. Mains-Side Phase-Voltage Estimation

Fig. 1 shows a configuration of a three-phase PWM rectifier. The bridge consists of three legs, and its ac side is connected to the three-phase mains through the input reactors denoted by L. The load is connected to the output capacitor in parallel. In this rectifier circuit, the gate signals of the switching devices

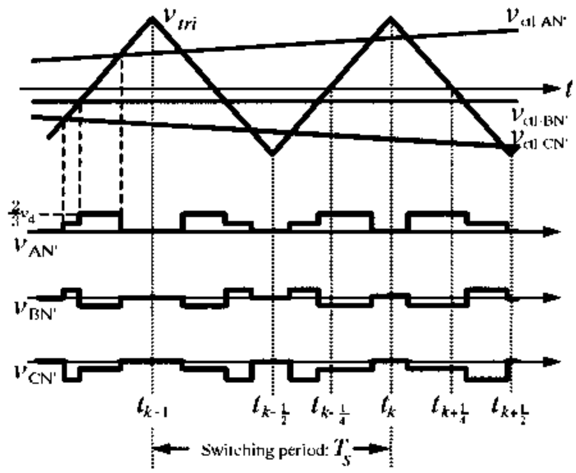

Fig. 2. Relationship between phase-voltage reference and triangular carrier.

S_1–S_6 are generated by a PWM process, or comparison of the phase-voltage references (with respect to a virtual neutral) $v_{\text{ctl-AN}'}$, $v_{\text{ctl-BN}'}$, and $v_{\text{ctl-CN}'}$ and a triangle carrier v_{tri} as shown in Fig. 2.

If two of the three line currents—i_U and i_V for example—are detected, the reactor voltages v_{LU}, v_{LV}, and v_{LW} are given by

$$v_{LU} = L\,\frac{di_U}{dt} = Lpi_U \tag{1}$$

$$v_{LV} = Lpi_V \tag{2}$$

$$v_{LW} = -v_{LU} - v_{LV} \tag{3}$$

where d/dt is denoted by p and resistances of the reactor windings are neglected. Consider an instant of time when the triangular carrier reaches its minimum or maximum, i.e., $t = t_{k-1/2}$ or $t = t_k$. Since all the bridge-input voltages $v_{\text{AN}'}, v_{\text{BN}'}$, and $v_{\text{CN}'}$ take a zero value, in other words, the voltage vector is zero at this instant, an equivalent circuit of one phase can be illustrated as in Fig. 3(a). Therefore, the estimated mains phase voltages v^*_{UN}, v^*_{VN}, and v^*_{WN} at $t = t_{k-1/2}$ or $t = t_k$ are given

$$v^*_{\text{UN}} = v_{LU}|_{t=t_{k-1/2} \text{ or } t_k} = Lpi_U|_{t=t_{k-1/2} \text{ or } t_k} \tag{4}$$

$$v^*_{\text{VN}} = v_{LV}|_{t=t_{k-1/2} \text{ or } t_k} = Lpi_V|_{t=t_{k-1/2} \text{ or } t_k} \tag{5}$$

$$v^*_{\text{WN}} = -v^*_{\text{UN}} - v^*_{\text{VN}}. \tag{6}$$

Thus, the reactor voltage is easily obtained by multiplication of the reactor inductance and the derivative of the measured line current. In practice, these voltages are sampled and held for the control to be proposed in this paper. If a secondary winding is wound on the input reactor, the winding provides a voltage proportional to the derivative of the line current flowing in the reactor (primary winding).

B. DC-Side Voltage Estimation

The phase voltage references $v_{\text{ctl-AN}'}$, $v_{\text{ctl-BN}'}$ and $v_{\text{ctl-CN}'}$, vary in positive or negative regions. The bridge input voltages, $v_{\text{AN}'}, v_{\text{BN}'}$, and $v_{\text{CN}'}$ at zero-cross point of the carrier are $2v_d/3, -v_d/3$, and $-v_d/3$, respectively, in just the time duration shown in Fig. 2. In this case, equivalent circuits

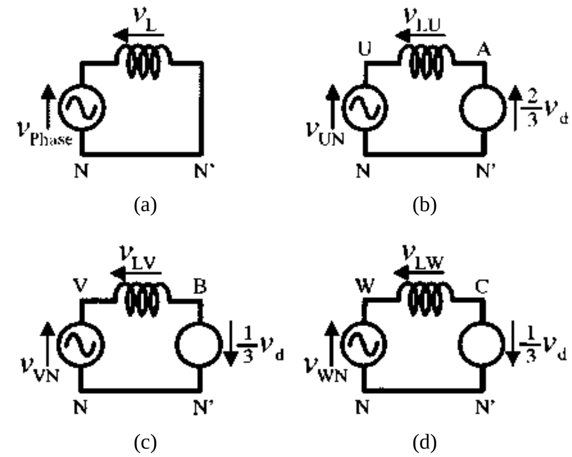

Fig. 3. Equivalent circuits for ac side.

TABLE I
VOLTAGE EQUATIONS OF THE AC SIDE AT ZERO-CROSS POINTS OF THE CARRIER

	$v_{UN} - v_{LU}$	$v_{VN} - v_{LV}$	$v_{WN} - v_{LW}$
$v_{\text{ctl-AN}'} > 0$ $v_{\text{ctl-BN}'} < 0$ $v_{\text{ctl-CN}'} < 0$	$\frac{2}{3}v_d$	$-\frac{1}{3}v_d$	$-\frac{1}{3}v_d$
$v_{\text{ctl-AN}'} < 0$ $v_{\text{ctl-BN}'} > 0$ $v_{\text{ctl-CN}'} < 0$	$-\frac{1}{3}v_d$	$\frac{2}{3}v_d$	$-\frac{1}{3}v_d$
$v_{\text{ctl-AN}'} < 0$ $v_{\text{ctl-BN}'} < 0$ $v_{\text{ctl-CN}'} > 0$	$-\frac{1}{3}v_d$	$-\frac{1}{3}v_d$	$\frac{2}{3}v_d$
$v_{\text{ctl-AN}'} < 0$ $v_{\text{ctl-BN}'} > 0$ $v_{\text{ctl-CN}'} > 0$	$-\frac{2}{3}v_d$	$\frac{1}{3}v_d$	$\frac{1}{3}v_d$
$v_{\text{ctl-AN}'} > 0$ $v_{\text{ctl-BN}'} < 0$ $v_{\text{ctl-CN}'} > 0$	$\frac{1}{3}v_d$	$-\frac{2}{3}v_d$	$\frac{1}{3}v_d$
$v_{\text{ctl-AN}'} > 0$ $v_{\text{ctl-BN}'} > 0$ $v_{\text{ctl-CN}'} < 0$	$\frac{1}{3}v_d$	$\frac{1}{3}v_d$	$-\frac{2}{3}v_d$

are depicted in Fig. 3(b)–(d), and their voltage equations are expressed by

$$\tfrac{2}{3}\,v_d = v_{\text{UN}} - v_{\text{LU}} \tag{7}$$

$$-\tfrac{1}{3}\,v_d = v_{\text{VN}} - v_{\text{LV}} \tag{8}$$

$$-\tfrac{1}{3}\,v_d = v_{\text{WN}} - v_{\text{LW}}. \tag{9}$$

Table I indicates the other cases of voltage equations on the ac side. According to (7)–(9) and Table I, the estimated dc-side voltage v_d* may be written

$$v^*_d = \tfrac{3}{4}\,\{|v_{\text{UN}} - v_{\text{LU}}| + |v_{\text{VN}} - v_{\text{LV}}| + |v_{\text{WN}} - v_{\text{LW}}|\}|_{t=t_{k-1/4} \text{ or } t_{k+1/4}}. \tag{10}$$

Assuming that the mains phase voltages at $t = t_{k-1/2}$ and at $t = t_k$ are equal to those at $t = t_{k-1/4}$ and at $t = t_{k+1/4}$,

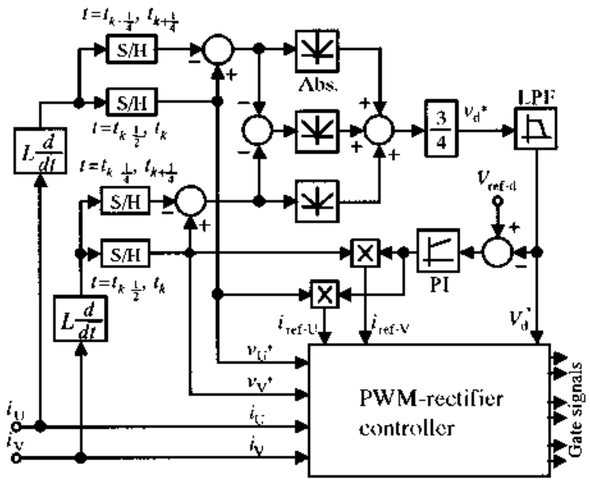

Fig. 4. Block diagram of controller.

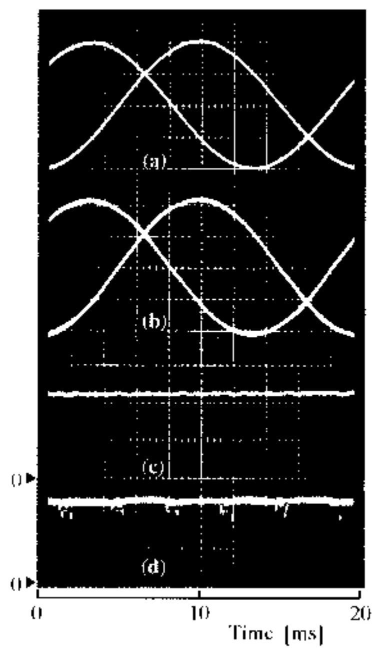

Fig. 5. Mains and dc voltage waveforms. (a) Measured mains phase voltages (80 V/div). (b) Estimated mains phase voltages (80 V/div). (c) Measured dc-side voltage (160 V/div). (d) Estimated dc-side voltage (160 V/div).

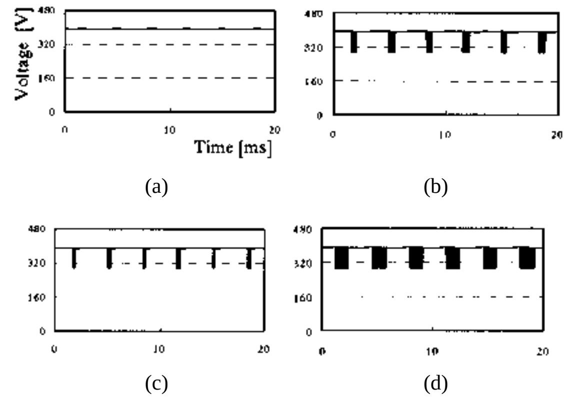

Fig. 6. Simulated waveforms of estimated dc-side voltage in various S/H acquisition times t_a. (a) $t_a = 0$, (b) $t_a = 2$ μs, (c) $t_a = 1$ μs, and (d) $t_a = 5$ μs.

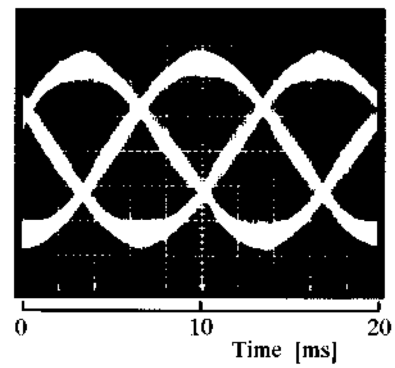

Fig. 7. Line current waveforms (5 A/div).

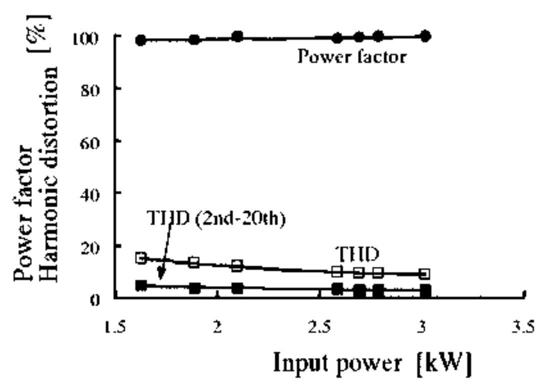

Fig. 8. Steady-state characteristics.

respectively, the mains phase voltages in (10) can be replaced with the estimated mains phase voltages given by (4)–(6). Therefore, the estimated dc-side voltage may be expressed as

$$\begin{aligned} v_d^*(t_{k-1/4}) = \frac{3L}{4}\ [&|pi_U(t_{k-1/2}) - pi_U(t_{k-1/4})| \\ &+ |pi_V(t_{k-1/2}) - pi_V(t_{k-1/4})| \\ &+ |pi_U(t_{k-1/4}) + pi_V(t_{k-1/4}) \\ &- pi_U(t_{k-1/2}) - pi_V(t_{k-1/2})|] \end{aligned} \tag{11}$$

$$\begin{aligned} v_d^*(t_{k+1/4}) = \frac{3L}{4}\ [&|pi_U(t_k) - pi_U(t_{k+1/4})| \\ &+ |pi_V(t_k) - pi_V(t_{k+1/4})| \\ &+ |pi_U(t_{k+1/4}) + pi_V(t_{k+1/4}) - pi_U(t_k) \\ &- pi_V(t_k)|]. \end{aligned} \tag{12}$$

Thus, the estimated dc-side voltage v_d^* may be expressed by using only the line currents.

C. Estimation of Initial Voltages

The mains voltages and dc-side voltage are unknown at start up. Applying a first switching operation sequence at the start up allows an estimation of the initial voltage values. This switching sequence being used to know the initial voltages, its duration should be chosen short enough in order to avoid an overcurrent.

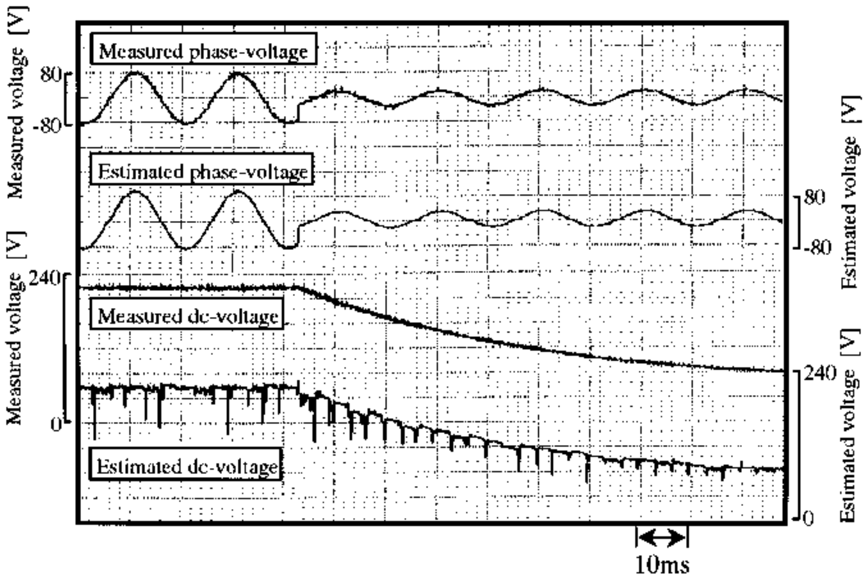

Fig. 9. Transient responses of the estimated voltages.

III. Experiments

A. System Configuration

Fig. 4 shows a block diagram of the proposed controller. Theoretically, this controller measures only two input line currents. In the experimental setup, the controller measures two input line currents and two secondary-winding voltages; differentiators are not used and secondary windings are wound on the input reactors. Utilizing the secondary windings instead of differentiators has the merit that the reactor voltages are directly and easily measured and that the noise sensitivity of the controller becomes lower. In this case, although the sensing of secondary-winding voltages is needed, an isolated condition between the main circuit and its controller is still kept.

In Fig. 4, S/H is a sample-and-hold circuit; the data acquisition time is 2 μs. The gate signals to be applied to the switching devices can be generated by a pulsewidth prediction controller [4], [5]. In addition, other control schemes are also applicable if the measured and estimated values above are enough for controlling the rectifier. DC-side voltage v_d is governed at the dc-voltage reference $(V_{\text{ref-d}})$ by a proportional–integral (PI) controller that gives the amplitude of the line-current references.

The constants of the experimental rectifier setup of Fig. 1 are as follows: the mains voltage (line-to-line) $= 200$ V, the mains frequency $= 50$ Hz, $L = 1.88$ mH, $C = 1000$ μF, $R = 51$ Ω, $V_{\text{ref-d}} = 380$ V, and switching frequency $= 8$ kHz (carrier period $T_s = 125$ μs). A three-phase insulated gate bipolar transistor (IGBT) bridge is employed.

B. Steady-State Characteristics

Fig. 5 shows the measured voltages and estimated voltages when the input ac power is about 3 kW. The estimated values are utilized to control the rectifier. The measured phase voltages v_{UN} and v_{VN} are observed by using a balanced Y-connected resistor. The estimated phase voltages are very close in waveshape to the measured voltages. The estimation of the dc-side voltage is partly degraded. The failure of estimation occurs at a sampling point when one of the phase voltage references $v_{\text{ctl-AN}'}$, $v_{\text{ctl-BN}'}$, and $v_{\text{ctl-CN}'}$ is close to zero, i.e., when the switching devices are turned on or off during the acquisition time of the S/H circuits.

To confirm the effect of the S/H acquisition time, the simulations of dc-side voltage estimation are shown in Fig. 6. In this simulation, the S/H circuit outputs the average of the input at the beginning and at the end of the sampling operation. Fig. 6(a) is the estimated dc-side voltage with ideal S/H operation, i.e., the acquisition time is zero. In this case, a satisfactory estimation can be obtained over the whole time. In Fig. 6(b) and (d), as the acquisition time becomes longer, the duration of the failure is increasingly noticeable.

To solve this problem, sampling at the sampling point should be suspended or a low-pass filter should be employed. In the experimental system, the low-pass filter is used.

In the dc-side voltage estimation, since the mains phase voltage is assumed to be equal to its previous value at a quarter switching period before, the accuracy of the estimation is affected by the switching interval. According to the simulation results, the maximum estimation error in the steady-state condition is 0.3% at $f_s = 8$ kHz. The error increases if the switching frequency decreases; the error reaches 1.4% at $f_s = 2$ kHz and 2.8% at $f_s = 1$ kHz. This error is, however, acceptable for controlling the rectifier as long as the switching frequency is kept at a few kilohertz or higher. The impedance of the mains also affects the accuracy because the estimation becomes faulty due to the mains voltage dips caused by the switching operation. This problem will be practically solved by installing the ac-side filter capacitors that are usually employed to eliminate the switching ripples of the line currents.

Fig. 7 shows the experimental waveforms of the line currents. The line currents flow sinusoidally and are approximately in phase with the phase voltages. The total harmonic distortion (THD) is 8.9%, and the THD including only lower harmonics (2nd–20th) is 2.8%. The total power factor is about 99%.

Fig. 8 depicts the steady-state characteristics of the rectifier. The rectifier achieves high power factor and low THD operation regardless of the output power.

C. Estimated Voltages in Transient

Fig. 9 shows a comparison of the measured voltages and the estimated voltages when the mains voltage is abruptly changed. The rectifier is controlled so that it equivalently acts as a constant balanced resistor at the ac input terminals of the rectifier. The estimated phase voltage agrees well with the measurements. On the dc side, the estimated value reproduces well the actual voltage except at the sampling points, as mentioned above.

IV. Conclusion

A new PWM rectifier controller has been discussed. This controller estimates the mains voltage and dc-side voltage by using the input reactor voltages. The input reactor voltages can be obtained from differentiation of the line currents or from direct measurement at the sensing windings of the reactors. In the first method, PWM rectifier operation is achieved without any voltage sensors. The second method gives ac- and dc-side voltage information while measuring only sensing-winding voltages and realizes an isolated condition between the main circuit and its controller; the practicality of this method has been shown by experiment.

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