Comparative Study of Two Level and Three Level PWM-Rectifier with Voltage Oriented Control

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Abstract. This article presents performance evaluation and comparison between Voltage Oriented Control (VOC) methods for PWM-rectifiers, two levels and three levels, in order to demonstrate the great advantages of using a three-level Neutral Point Clamped (NPC). The control of the DC bus voltage is carried out using the PI controller. The effectiveness of this approach is illustrated by simulation results using MATLAB/Simulink.

Keywords: Neutral point clamped (NPC) · PWM-rectifier
Total harmonic distortion (THD) · Voltage oriented control (VOC)

1 Introduction

Nowadays, the use of PWM-converters in the field of renewable energy such as solar and wind energy is in progress [1–8]. The tendency to use the AC/DC converter know a considerable increase seen to the advantages that it offers: (1) Ensure that the direct current of the THD alternating current is less than 5% of the total fluctuation to reduce the adverse effects on the grid; (2) Guarantee the power factor close to it and consider the rectifier as a “pure resistive load” in terms of grid and (3) Improve the dynamic characteristic of the DC bus voltage regulation, and reduce the dynamic response time, etc. [9–12].

In [13], the various current control techniques applied to the MLI rectifier are classified into two classes, linear current controller (PI-Stationary, PI-rotating reference, etc.) and non-linear current controller (fuzzy logic control, neural networks, hysteresis current control, etc.). The high-performance control strategies of PWM rectifiers are mainly Voltage oriented control (VOC) [11, 12, 14] and direct power control (DPC) [15, 16], which are similar to vector control (VC) and control direct

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current torque (DTC) [17] for ac machines. The VOC control technique is based on transforms in two coordinate systems. The first is the fixed coordinate system ($\alpha - \beta$), and the second is the rotating coordinate system ($d - q$). The measured values of three phases are converted into an equivalent system of two phases ($\alpha - \beta$) and are then transformed to the rotating coordinate system. By means of this type of transformation, the control variables are continuous signals, an inverse transformation ($d - q$)/($\alpha - \beta$) is performed on the output of the control system which gives the reference signals of the rectifier in the fixed coordinates.

On the other hand, multi-level inverters have become a very interesting solution for high-power applications [18, 19]. The three-stage neutral point clamped (NPC) inverter is one of the most widely used multi-level inverters in high-power AC drives. By comparing the standard level of two inverter levels, the three-level inverter has its superiority in terms of lower semiconductor stresses, lower voltage distortion, less harmonic content and lower switching frequency [20]. Three-level inverters are of great interest in the field of high voltages and high powers because they introduce less distortion and low losses with relatively low switching frequency [21].

This article presents a brief description and comparison of VOC methods to control the PWM rectifier at two and three levels and demonstrate the brilliant advantages of using three levels NPC type converters. The dc-bus controller output is provided by the conventional PI controller.

This paper is organized as follows: Sect. 2 presents the modelling of PWM Rectifier two level. Section 3 modelling of PWM Rectifier two level Sect. 4 gives an overview about the VOC algorithm used in this study. The simulation results and discussion are described in Sect. 5. Finally, conclusion is presented in Sect. 6.

2 The Principle and Modeling of the Two Level PWM-Rectifier

The structure of the three-phase PWM-rectifier with two voltage levels is illustrated in Fig. 1. The PWM-rectifier is connected to the three phases of the source via the smoothing L and the internal resistance R. The inductance acts as a line filter to smooth the line currents with minimal ripples.

Isolated gate bipolar transistors (IGBTs) are used as rectifier supply switches because IGBTs have high power characteristics, simple door control requirements and are suitable for high frequency switching applications.

The resistive load is assumed to be pure R_d and in parallel with DC capacitor C.

The logic states impose the input voltages of the PWM-rectifier with two levels voltage are given as follows

$$\begin{cases} u_{ea} = S_a.V_{dc} \\ u_{eb} = S_b.V_{dc} \\ u_{ec} = S_c.V_{dc} \end{cases} \tag{1}$$

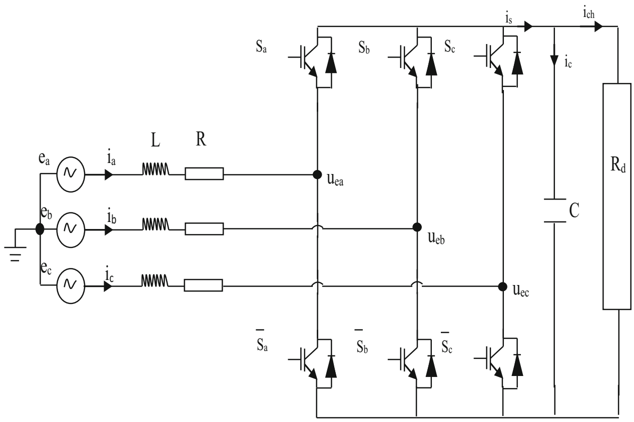

Fig. 1. PWM rectifier two level voltage

S_a, S_b, S_c are the switching states of the PWM-rectifier, the input voltages of the PWM-converter are equal to:

$$\begin{bmatrix} u_{ea} \\ u_{eb} \\ u_{ec} \end{bmatrix} = V_{dc} \begin{pmatrix} \frac{2}{3} & \frac{-1}{3} & \frac{-1}{3} \\ \frac{-1}{3} & \frac{2}{3} & \frac{-1}{3} \\ \frac{-1}{3} & \frac{-1}{3} & \frac{2}{3} \end{pmatrix} \begin{pmatrix} S_a \\ S_b \\ S_c \end{pmatrix} \tag{2}$$

The alternative side equation can be modelled as follows:

$$\begin{cases} u_{ea} = e_a - Ri_a - L\dfrac{di_a}{dt} \\ u_{eb} = e_b - Ri_b - L\dfrac{di_b}{dt} \\ u_{ec} = e_c - Ri_c - L\dfrac{di_c}{dt} \end{cases} \tag{3}$$

The direct current as a function of the switching states can be given by the following equation

$$i_s = S_a i_a + S_b i_b + S_c i_c \tag{4}$$

3 The Principle and Modeling of the Three Level PWM-Rectifier

In the neutral point rectifier illustrated in Fig. 2, the converter is built around twelve switching cells (based on IGBT) and six clamping diodes; each phase can produce three distinct levels by connecting the output to the positive (Vdc/2), negative (−Vdc/2) or zero (0) potential. In a system three, there are $3^3 = 27$ output voltage vectors linked to 19 possible voltage vectors at the output of the converter (see Fig. 3).

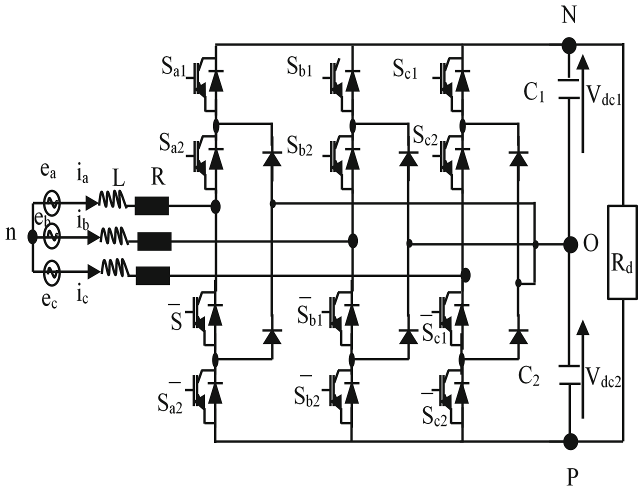

Fig. 2. PWM rectifier three level voltage

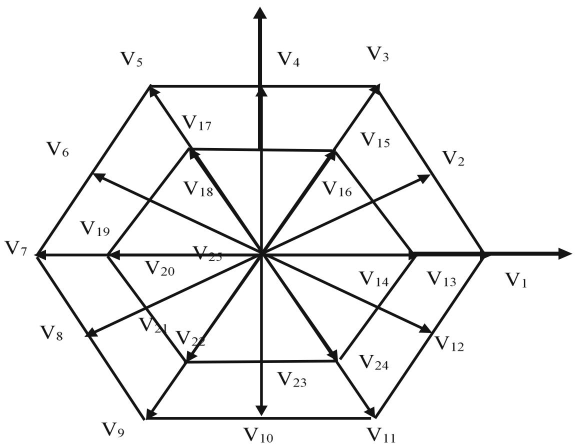

Fig. 3. Space vector diagram of three-level inverter.

According to the definition of the switching functions, the equations of the converter can be developed in the three-phase stationary coordinate system abc.

In addition to the line currents, the dynamics of the capacitors is taken into account and is selected as the state variable. However, the phase voltage of the gate and the load current are considered disturbances.

$$\begin{cases} L\frac{di_a}{dt} = e_a - Ri_a - S_{a1}.V_{dc1} + S_{a2}.V_{dc2} - u_{on} \\ L\frac{di_b}{dt} = e_b - Ri_b - S_{b1}.V_{dc1} + S_{b2}.V_{dc2} - u_{on} \\ L\frac{di_c}{dt} = e_c - Ri_c - S_{c1}.V_{dc1} + S_{c2}.V_{dc2} - u_{on} \end{cases} \tag{5}$$

$$\begin{cases} C_1\frac{dv_{dc1}}{dt} = S_{a1}.i_a + S_{b1}.i_b + S_{c1}.i_c \\ C_2\frac{dv_{dc2}}{dt} = S_{a2}.i_a - S_{b2}.i_b - S_{c1}.i_c \end{cases} \tag{6}$$

Considering that the Electrical Network is three-phase balanced one can write

$$\begin{cases} e_a + e_b + e_c = 0 \\ i_a + i_b + i_c = 0 \end{cases} \tag{7}$$

the voltage u_{on} is given by the following expression:

$$u_{on} = -\frac{1}{3}(S_{a1} + S_{b1} + S_{c1}).V_{dc1} + \frac{1}{3}(S_{a2} + S_{b2} + S_{c2}).V_{dc2} \tag{8}$$

4 Voltage Oriented Control Strategy

This control technique is based on transforms in two coordinate systems. The first is the fixed coordinate system ($\alpha - \beta$), and the second is the rotating coordinate system (d − q). The measured values of three phases are converted into an equivalent system of two phases ($\alpha - \beta$) and are then transformed to the rotating coordinate system. By means of this type of transformation, the control variables are continuous signals, an inverse transformation (d − q)/($\alpha - \beta$) is carried out on the output of the control system which gives the reference signals of the rectifier in fixed coordinates. In the rotating coordinate system (d − q) the current vector $\vec{i}$ has two perpendicular components $\vec{i} = \begin{bmatrix} i_d & i_q \end{bmatrix}$. Thus, the active and reactive powers can be controlled indirectly by the intermediate internal loops of the currents. The condition for a unit power factor is obtained when the current vector $\vec{i}$ is aligned with the voltage vector $\vec{e}$ by choosing the orientation of the voltage towards the axis d, a simplified dynamic model is obtained.

The VOC had two control loops, the internal current loop and the external voltage loop.

4.1 The Internal Current Loop

The voltage equations in the synchronous frame (d − q) are

$$\begin{aligned} e_d &= Ri_d + L\frac{di_d}{dt} + v_d + wLi_q \\ e_q &= Ri_q + L\frac{di_q}{dt} + v_q - wLi_d \end{aligned} \tag{9}$$

Decoupling between the axes d and q is carried out by the variable h_p and h_q:

$$h_d = e_d - v_d - wLi_q = Ri_d + L\frac{di_d}{dt}$$
$$h_q = e_q - v_q + wLi_d = Ri_q + L\frac{di_q}{dt} \quad (10)$$

The system of uncoupled state presented by:

$$\begin{bmatrix} \frac{di_d}{dt} \\ \frac{di_q}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{R}{L} & 0 \\ 0 & -\frac{R}{L} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} \frac{1}{L} & 0 \\ 0 & \frac{1}{L} \end{bmatrix} \begin{bmatrix} h_d \\ h_q \end{bmatrix} \quad (11)$$

4.2 The External Voltage Loop

The controller in the external control loop of the PWM rectifier is used to regulate the DC voltage side and to generate the amplitude of the reference line current which will be multiplied by the DC voltage to obtain the reference of the instantaneous active power to have the current I_{dref} reference. In this work the regulator used is the conventional PI illustrated in Fig. 4, and to have a unit power factor it is necessary that i_{qref} equal to zero.

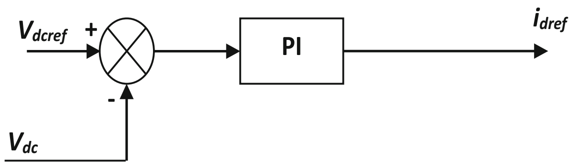

Fig. 4. DC voltage regulation

The transfer function of the studied system is given by:

$$v_{dc}^2 = P_{ref}.\frac{2}{C.s} \quad (12)$$

The transfer function of the PI controller can be expressed by:

$$K_p + \frac{K_i}{s} = \frac{1 + \tau s}{s.T_i} \quad (13)$$

The transfer function of the closed loop system is given by:

$$F(s) = \frac{\omega_0^2.(1 + \tau s)}{s^2 + 2\varepsilon_0\omega_0 s + \omega_0^2} \quad (14)$$

With:

$$\omega_0 = \sqrt{\frac{2}{CT_i}} \text{ and } \varepsilon_0 = \frac{\tau}{\sqrt{2CT_i}}.$$

After calculation; we find

$$K_p = \frac{\tau}{T_i} \text{ and } K_i = \frac{1}{T_i}.$$

5 Simulation Results

In order to validate the effectiveness of the control strategy developed in this paper for the control of the PWM-rectifier either at two levels or at three levels a numerical simulation was carried out under MATLAB/SIMULINK. The system parameters are summarized in Table 1.

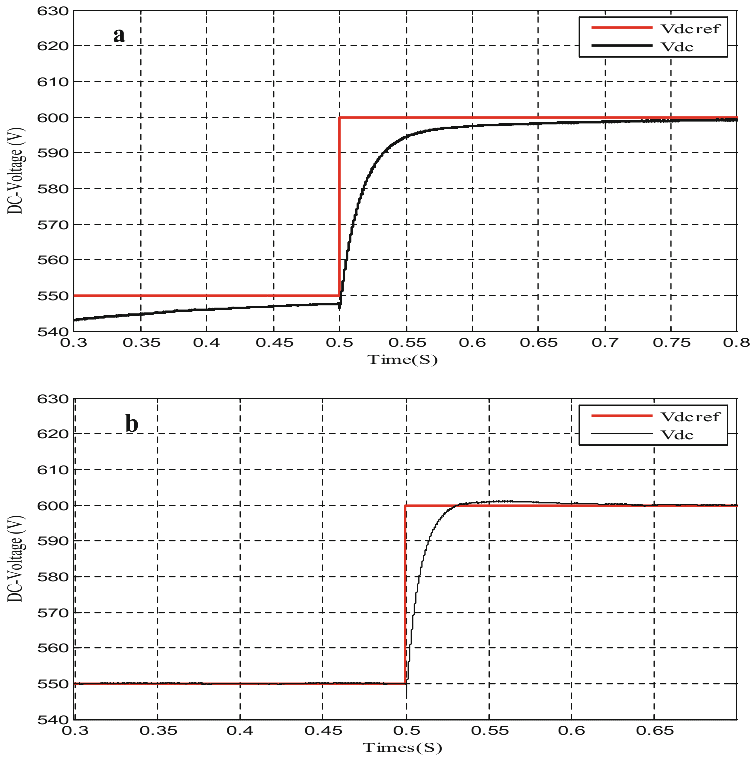

Fig. 5. DC voltage response Vdc with VOC: (**a**) two-level rectifier and (**b**) three-level rectifier

The DC voltage control system for both PWM-converter control by Voltage Oriented Control is tested following a DC-voltage variation occurred at t = 0.5 s from 550 V to 600 V.

Figure 5a and b shows the DC voltage for the two and three levels of PWM rectifiers. The DC voltage measurement follows its new reference when applying a V_{dcref} to the time (t = 0.5 S). It's noted that the response of the DC voltage is faster for a three-level than two-level PWM rectifier.

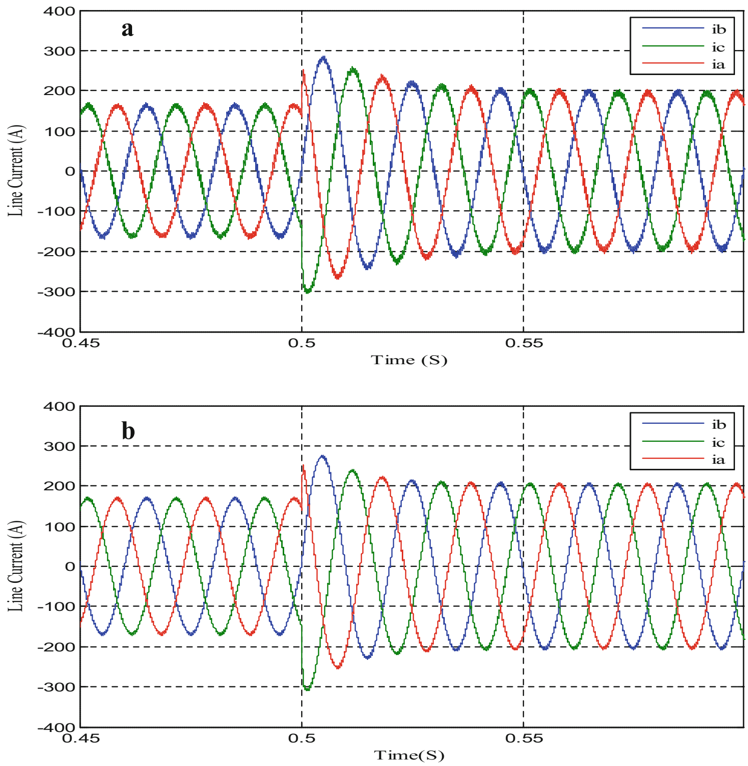

Fig. 6. Line currents with VOC: (**a**) two-level rectifier and (**b**) three-level rectifier.

Figure 6a and b shows that the line currents of the two PWM-rectifier structures are substantially sinusoidal. When changing the DC voltage reference, the current maintains its new value with acceptable response time and a good signal quality of the current for the three-level structure.

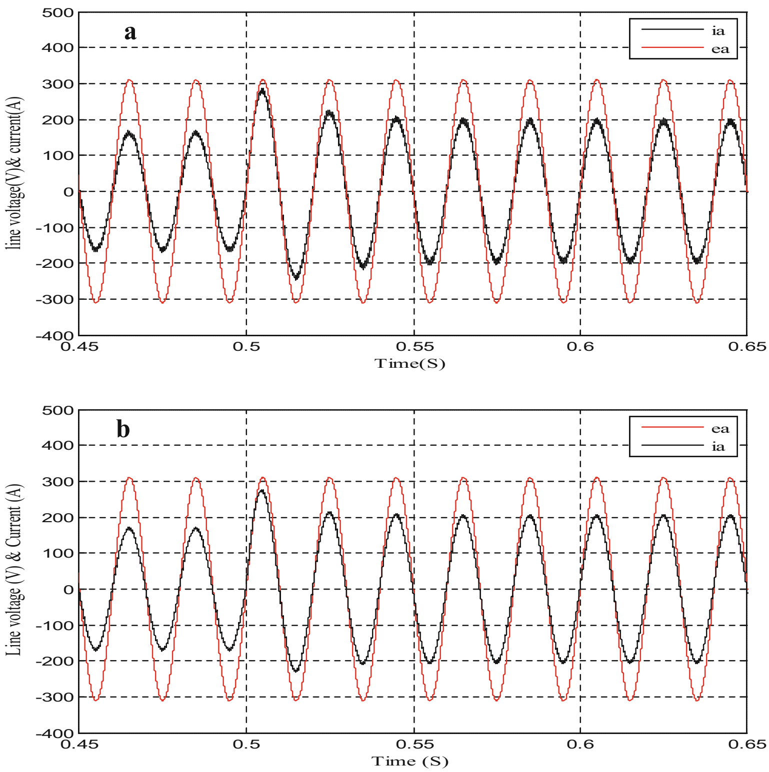

Fig. 7. Voltage is in phase with current ia with VOC: (**a**) two-level rectifier and (**b**) three-level rectifier.

Current and line voltage are shown (Fig. 7a) for a two-level VOC and (Fig. 7b). For a three-level VOC rectifier. As shown in these figures, the line current is in phase with the voltage of the same phase, which confirms operation under a unit power factor and has zero reactive power.

To compare the two level and the three level structure of PWM rectifier with VOC strategy the harmonic spectrums of the current are given in (Fig. 8a) and (Fig. 4b). It is shown that the three level structure (THD = 1.16%) is better than the two level structure (THD = 3.06%).

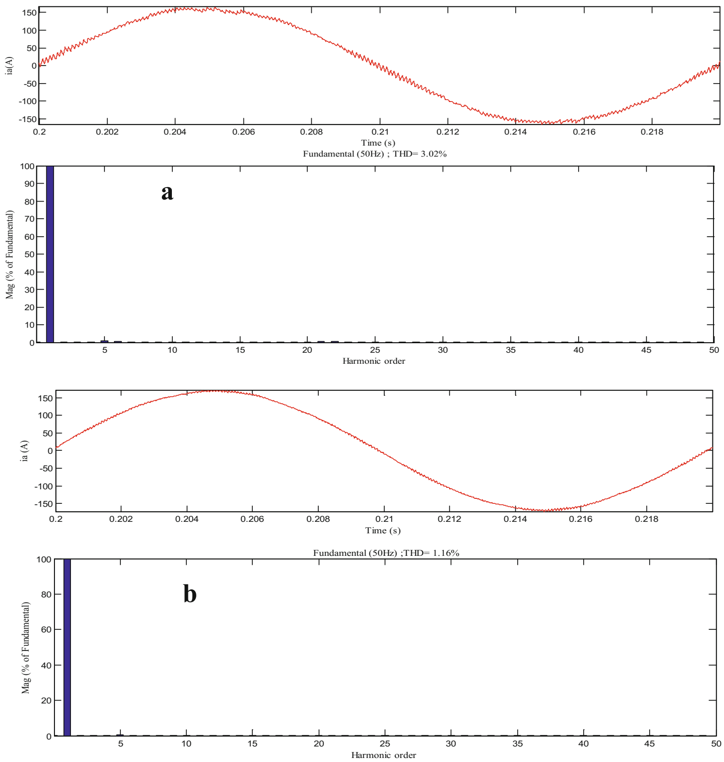

Fig. 8. Harmonic spectrum of the line current with VOC: (**a**) two-level rectifier (THD = 3.06%) and (**b**) three-level (THD = 1.16%) rectifier.

Table 1. System parameters

R	Line resistance
L	Line inductance
C	DC-capacitor
R_d	Load resistance
e_{abc}	Peak amplitude of line voltage
f	Source voltage frequency
f_c	Switching frequency
V_{dcref}	DC-Voltage reference
R	Line resistance
L	Line inductance

6 Conclusion

In this work, the VOC control strategy for a two-level and three-level PWM rectifier is presented. To predict the behavior of the PWM-three-phase rectifier VOC under different load and feed conditions, the dynamic model is implemented in SIMULINK/MATLAB.

The main objective of the control system is to maintain the DC bus voltage at a desired value and to achieve the operation of a unit power factor. The VOC using three-level PWM-rectifiers has good performance and ripple reductions, compared to the VOC using PWM-two-level rectifier.

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