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Modeling and Execution the Control Strategy for the Three-level Rectifier Based on Voltage Oriented Control

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ABSTRACT

In the recent years, three-level rectifier becomes an attractive rectifier replaced the two-level rectifiers. This rectifier provides many advantages, such as sinusoidal input current which contains low harmonics, unity power factor, bi-directional power flow, low voltage and switching loss for each switch. This paper presents a modelling and execution of the three-level rectifier for improvement of power quality under different loading based on voltage oriented control. The mathematical model and the control design were presented in this paper for the current inner loop and voltage outer loop, respectively. In order to evaluate the operation of the three-level rectifier under different conditions, the model was simulated by using MATLAB/Simulink. The experiment has been used to confirm the operation of the rectifier and its controller. The simulation and experimental results show that the excellent performance under steady-state and dynamic load variations was achieved; the unity power factor and pure sinusoidal in the grid side has also been accomplished.

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1. INTRODUCTION

Three-level, three-phase rectifier is one of the very useful power electronic converter topologies, which changes power from AC to DC. The three phase rectifier with Pulse Width Modulation (PWM) has attracted more concern due to its well-known advantages of power factor improvement, low harmonic distortion bi-directional power flow, and the ability to adjust the DC-bus voltage. It has overcome the issue of the conventional two level rectifier with a great future and additional academic concern. The three phase PWM rectifier will replace diode rectifiers not only in low voltage but also in medium and high voltage applications[1-4]. The PWM rectifier can be divided into two types of categories, conventional two-level the PWM rectifier and multilevel PWM rectifier. The multilevel PWM rectifier or three-level rectifiers have clear advantages compared to the conventional rectifier in the medium voltage level and high power applications. The three-level rectifier has more switches than the conventional two-level rectifier so the losses and voltage stress on each switch are comparably smaller. Therefore, this topology has a higher switching frequency and voltage limitation.

A multilevel converter was presented in 1981 to reduce the output voltage harmonics for the voltage source inverter by Nabae et al. [5]. The multilevel converter has more attractive features than a two-level converter, such as: harmonic elimination provided by the multilevel input voltage and has high-voltage levels without increasing the voltage rating of semiconductor devices. Besides all these attractive features, the multi converter eliminates: imbalance problems and packaging inconvenience due to the number of semiconductor devices. Some approaches have been reported to solve the imbalance problem in the literature[6-8]. To prevent the packaging problem the number of levels has been limited to three levels. Besides that, different works have dealt with the control aspects and the modelling of these converters. Actually, based on the equivalent circuit developed by [9-11], the authors have derived the converter model in a *d-q* reference frame as in [12-14] to apply a direct power feedback method or to realize dc as well as ac analysis.

This research study proposed the novel voltage oriented control to improve the system's robustness and dynamic response of the dc- bus voltage when the sudden change happens if the load side, to keep the output voltage constant when the dynamic change happens in the input or on the load side and to improve the power quality.

2. MODELING OF THE THREE LEVEL RECTIFIER

The circuit configuration of the three-phase, three-level rectifier shown in Figure 1. In order to setup the mathematical model, we can assume the source voltage is a symmetricalfor the three phase, and the IGBT switch is an ideal and it is lossless.

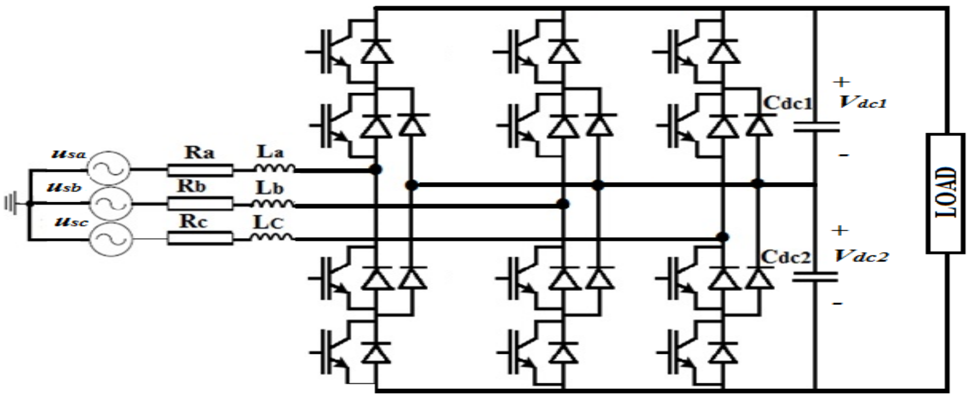


Figure 1. Three-level PWM rectifier.

The three phase line voltage:

$$u_{sa} = v_{sm}\cos(\omega t) \tag{1}$$

$$u_{sb} = v_{sm}\cos(\omega t - \frac{2\pi}{3}) \tag{2}$$

$$u_{sc} = v_{sm}\cos(\omega t + \frac{2\pi}{3}) \tag{3}$$

u_{sa}, u_{sb}, u_{sc} are the three-phase input AC voltages, v_{sm} is the peak value of the phase to the neutral voltage and ω is the grid angle frequency. According to the Kirchhoff's voltage and current laws of circuit theory, the PWM mathematical model of the three-level PWM rectifier is:

$$u_{sa} = L.\frac{di_a}{dt} + Ri_a + s_{a1}v_{dc1} - s_{a2}v_{dc2} + u_{no} \tag{4}$$

$$u_{sb} = L.\frac{di_b}{dt} + Ri_b + s_{b1}v_{dc1} - s_{b2}v_{dc2} + u_{no} \tag{5}$$

$$u_{sc} = L.\frac{di_c}{dt} + Ri_c + s_{c1}v_{dc1} - s_{c2}v_{dc2} + u_{no} \tag{6}$$

$$c_d.\frac{dv_{dc1}}{dt} = s_{a1}i_a + s_{b1}i_b + s_{c2}i_c - i_L \tag{7}$$

$$c_d.\frac{dv_{dc2}}{dt} = -s_{a2}i_a - s_{b2}i_b - s_{c2}i_c - i_L \tag{8}$$

Where L and R are the input inductance and resistance respectively, V_{dc1} and V_{dc1} are the capacitances dc voltage and S_a, S_b, S_c are the switching control function of a three level converter. Add Equations (4), (5) and (6) together you get:

$$u_{no} = -\frac{1}{3}(s_{sa1} + s_{sb1} + s_{sc1})v_{dc1} + \frac{1}{3}(s_{sa2} + s_{sb2} + s_{sc2})v_{dc} \tag{9}$$

For modeling and designing of the controller, it is very useful and suitable to convert the three-phase variables into a rotating d-q frame. The convert matrix below is used.

$$P = \frac{2}{3}\begin{bmatrix} \cos(\omega t) & \cos(\omega t - 2\pi/3) & \cos(\omega t + 2\pi/3) \\ -\sin(\omega t) & -\sin(\omega t - 2\pi/3) & -\sin(\omega t + 2\pi/3) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \tag{10}$$

The mathematical model of the three-level PWM rectifier in the two-phase synchronous rotation d-q coordinate is:

$$L.\frac{di_{ds}}{dt} = -Ri_{ds} + \omega Li_{sq} - s_{d1}v_{dc1} - s_{a2}v_{dc2} + u_{sd} \tag{11}$$

$$L.\frac{di_{qs}}{dt} = -Ri_{qs} + \omega Li_{sd} - s_{q1}v_{dc1} - s_{q2}v_{dc2} + u_{sq} \tag{12}$$

And the dc capacitor voltages are:

$$c_d.\frac{dv_{dc1}}{dt} = \frac{3}{2}(s_{d1}i_d + s_{q1}i_q) - i_L \tag{13}$$

$$c_d.\frac{dv_{dc2}}{dt} = -\frac{3}{2}(s_{d2}i_d + s_{q2}i_q) - i_L \tag{14}$$

3. PWM RECTRFIER CONTROL STRARGY

The main purposes associated with the rectifier control are to keeping the output voltage at the desired reference value, improve the input power factor, and reducing the THD on the grid side [15]-[16]. The rectifier control was design based on Equations (11)-(14). Those equations show that the current’s i_{ds} and i_{qs} are coupled with other components. Without decoupling, the stress in the PI controller is tremendous and the system dynamic response is far from the engineers' satisfaction. The voltage is supposed to be constant, the most effective way to control the three-level PWM rectifier output voltage and unity power factor are to control the current’s i_{ds} and i_{qs}. The control block diagram for the three-level PWM rectifer shown in Figure 2.

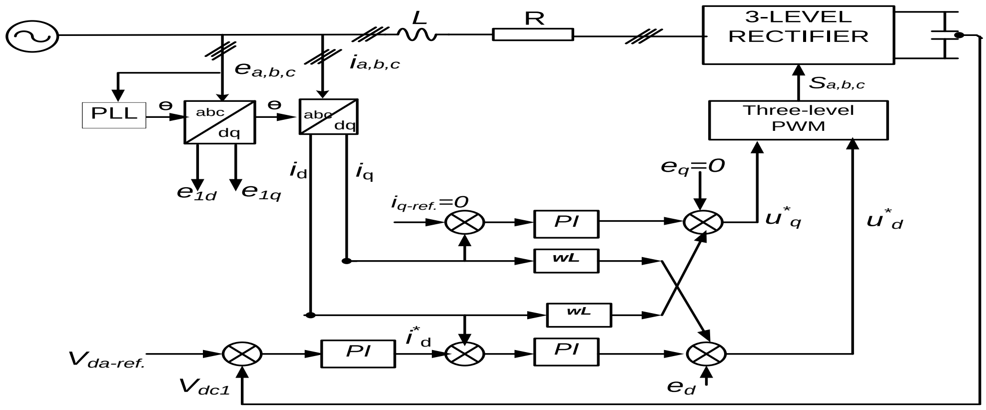


Figure 2. Three-level rectifier controller.

The output DC voltage is compared to the reference voltage in order to implement the control for the outer voltage-loop and then the difference passes through the PI control to generate the reference value of the inner current control i_d when the i_q reference is set to zero; this is to realize the power factor to one. The three phase input currents in the current inner loop are converted into *d-q* axis current components. The components are compared with the reference values of both *d-q* axis currents and the differences, then the modulated wave signal is created by the PI controller.

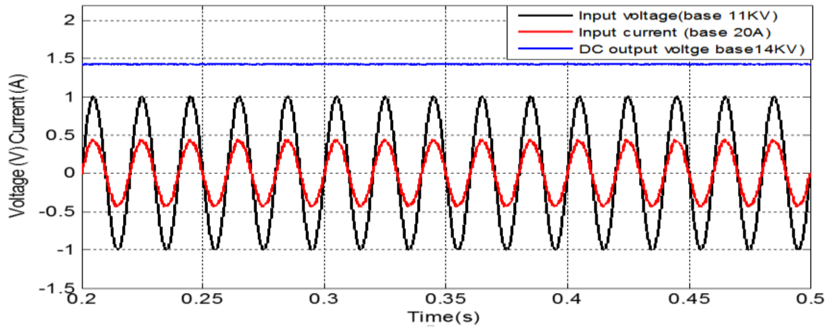
4. RESULTS AND DISCUSSION

In this section, MATLAB/Simulink was used to simulate the three-level PWM converter based on the control strategy as well as mathematical model. The parameters of the simulation are present in Table 1.

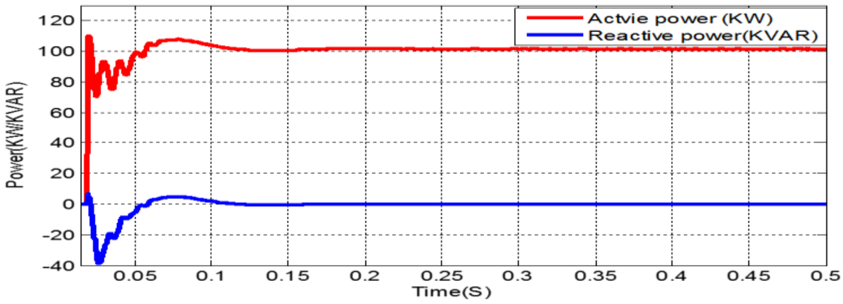
Table .1 Simulation parameters

Parameter	Value
Line to line Input voltage	11 kV
Input resistance, R_{sa}	0.7 Ω
Input inductance, L_{sa}	250 mH
DC link HV side capacitor C_1, C_2	20 μF
The input frequency	50 Hz
Switching frequency	3 KHz
Modulation index	0.85
Output DC voltage	20 KV
Load	100 KW

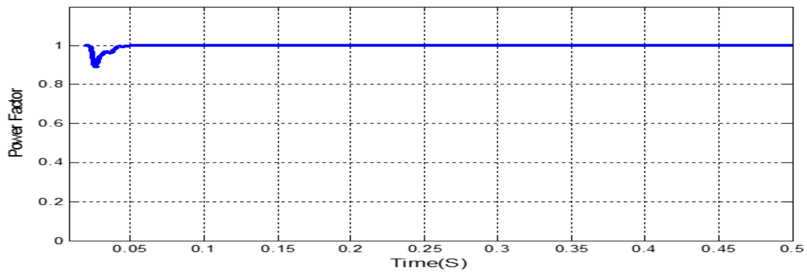
The simulation and experimental test have been conducted under different conditions, such as steady state and dynamic load variation to evaluate the operating performance of a three-level rectifier. Figure 3 presents the simulation result under the steady state. The output DC voltage reached to the 20KV as it adjust in the reference voltage and the input phase voltage, as well as the current waveforms are purely sinusoidal are in phase as shown in Figure (a), hence, the unity power factor was achieved as presented in Figure 3(c). The active and reactive power was presented in Figure 3(b). The Total Harmonic Distortion for the input current was equal to 1.32%. THD levels were smaller than the specified limit that mentioned in the IEEE 519-1992 standard as shown in Figure 3(d).



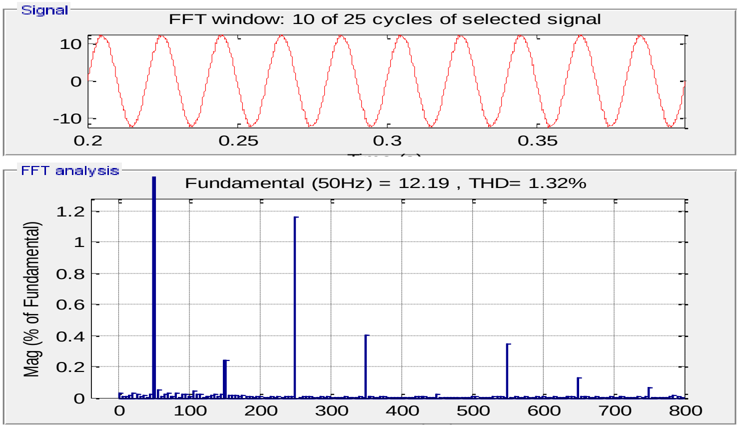
(a)



(b)



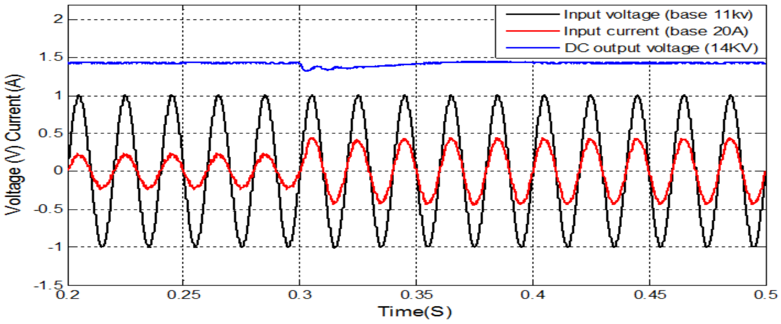
(c)



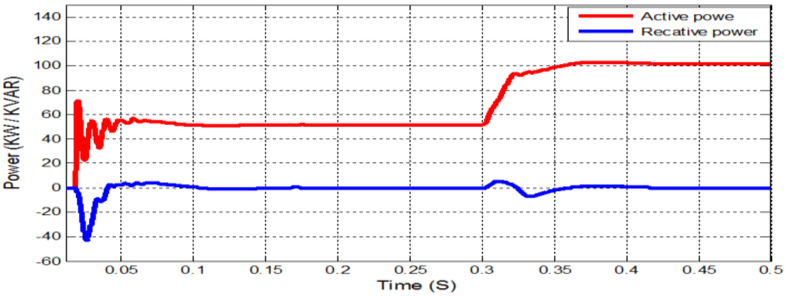
(d)

Figure 3. (a) Input voltage, input current and output dc voltage, (b) Active and reactive power, (c) Input power factor and (d) THD on the grid side

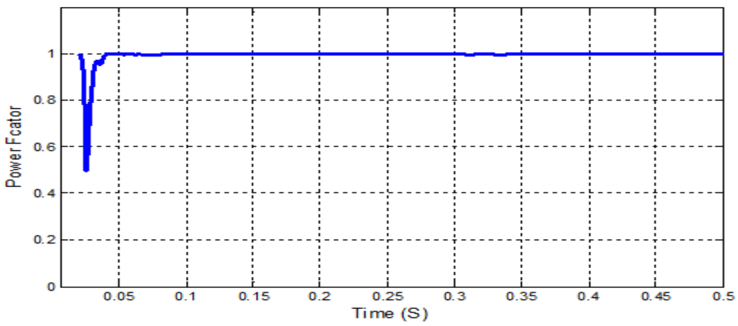
Figure 4 shows the DC voltage regulation response when the dynamic load variation happened from 50 kW to 100 kW at t=300ms. The output dc voltage went back to the reference value within 0.02s as seen in Figure 4(a) and the unity power factor and THD on the grid side was maintained as shown in Figure 4(b).



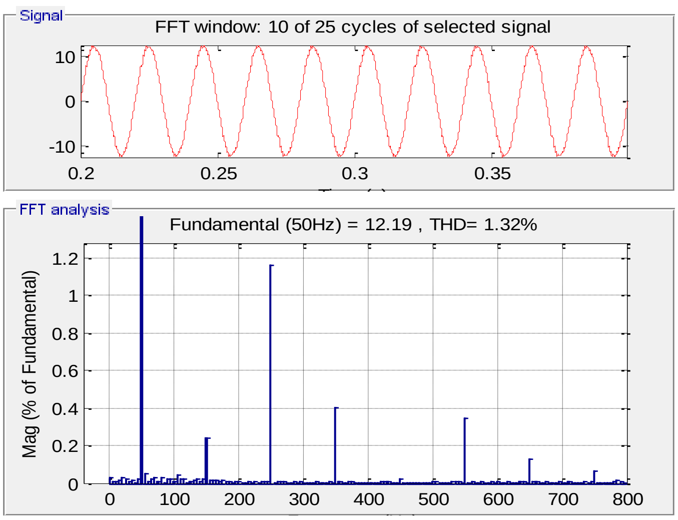
(a)



(b)



(c)



(d)

Figure 4. (a) Input voltage, input current and output dc voltage, (b) Active and reactive power, (c) Input power factor and (d) THD on the grid side.

5. EXPERIMENTAL RESULTS

The lower-scale prototype design for the three-level PWM rectifier was built to test and confirm the actual hardware operation. And, the experimental design has been shown in Figure 5. Three ATG 75TL60T3G IGBT power modules were selected to build the three-level PWM rectifier circuit. And, the digital control was implemented by using digital signal processing (DSP), TMS320F28335. The parameters of the experimental are present in Table 2.

Table .1 Simulation parameters

Parameter	Value
Line to line Input voltage	50 V
Input resistance, R_{sa}	0.2 Ω
Input inductance, L_{sa}	2 mH
DC link HV side capacitor C_1, C_2	8000 μF
The input frequency	50 Hz
Switching frequency	3 KHz
Modulation index	0.85
Output DC voltage	100 V

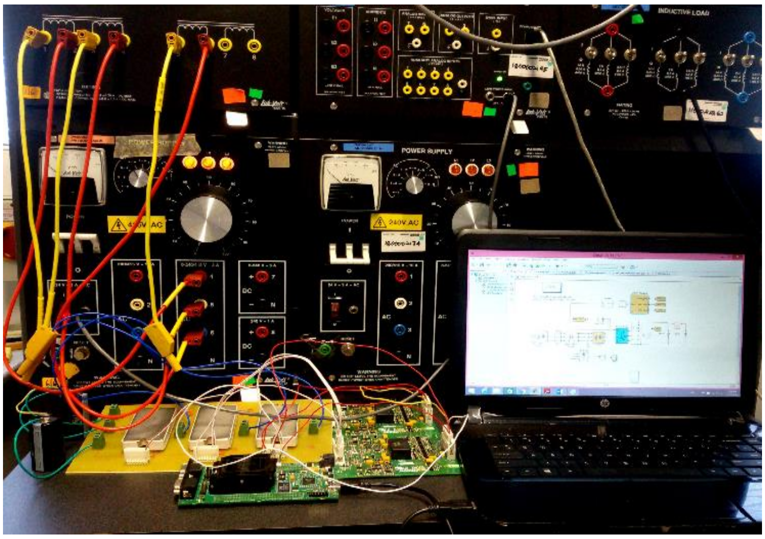
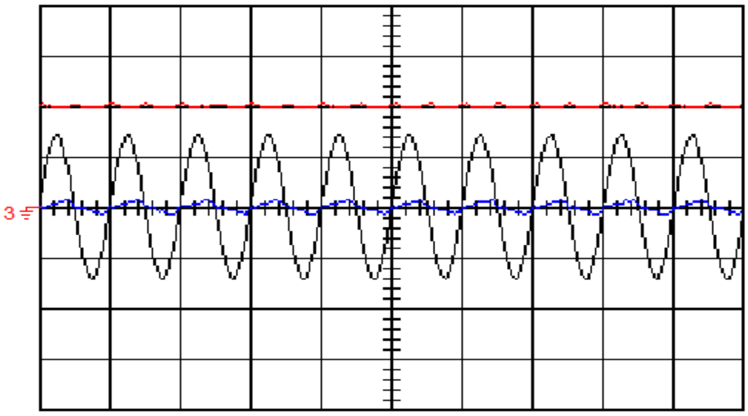


Figure 5. The laboratory prototype of a 3-level rectifier.

Figure 6 presents the waveforms of the input voltage and current in phase (a) and the DC output voltage for the prototype design of the three-level PWM rectifier, the voltage and current waveforms were sinusoidal and in phase. The THD was measured on the input side was 3.78% and the power factor was 0.886. The experimental results are shown to be consistent with the simulation result.



Channel	Input	RMS	AVG	f(Hz)	Scale
1	E2 (V)	49.75	0.03	49.84	50 V/div.
2	I1 (A)	0.02	0.00	49.93	0.2 A/div.
3	E1 (V)	100.14	100.14	99.67	50 V/div.

Figure 6. Input voltage input current and output dc voltage

6. CONCLUSION

The three level-three phase PWM rectifier will be applied more and more widely in high power situations. In this work, the voltage oriented control has been adopted to get better dynamic response performance based on the presented mathematical model. The simulation results indicate that the excellent power quality was achieved, such as unity power factor, the sinusoidal input current with 1.32% THD and better voltage regulation under steady state and dynamic load variations. Finally, the experimental results are provided to validate the simulation and the effectiveness of the adopted controller.

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