# 멀티레벨 PWM 인버터/정류기의 모델링

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# Modeling of Multilevel PWM Inverter/Rectifier

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## Abstract

*This paper deals with a novel method of modeling and analyzing multilevel pulse width modulation(PWM) inverter/rectifier, which leads to extraction of equivalent circuit in fundamental frequency domain. By the technique, we can draw out the corresponding linear time invariant circuit even thuogh the actual circuit is switched. A statc VAR compensator using five-level inverter is modeled and simulated for the verification of the modeling.*

## I. Introduction

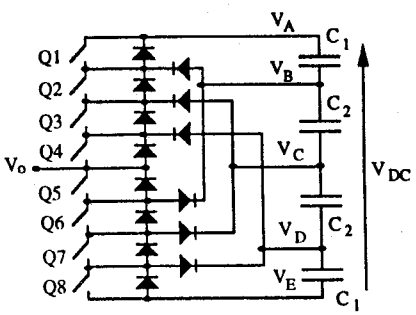
Harmonic reduction in controlling the output waveform of a voltage source inverter(VSI) with variable voltage variable frequency(VVVF) capability is basic importance. To do so, either increasing switching frequency or employing multilevel structure has been needed along with various modulation techniques.[1-2]

Recently, multilevel approach draws an attention not only under the aspect of harmonic reduction but also under the aspect of full utilization of switching devices in very high power applications especially with high input voltage. The actual structure of the the five-level PWM inverter is shown in Fig. 1(a) and the associated basic switching table is followed in Fig. 1(b). Note that the voltage stress of each active switches is clamped to only one capacitor voltage and thus the semiconductor power devices could be fully utilized. As a result, multilevel inverter is basically suited for high power/high voltage applications.[1]

This paper deals with a high power/high voltage three phase static VAR compensator(SVC) system[1-4] with the multilevel VSI, especially five-level inverter. Especially focusing on the open loop analysis of the SVC system,[5] multilevel PWM inverter/rectifier is modeled in fundamental frequency domain. Using the modeled circuit of the SVC, both static and dynamic behaviours can be completely described.

## II. Modeling of the Multilevel Rectifier/Inverter

Fig. 2. shows the schematic of the SVC system consisting of series connected DC side capacitors and the five-level PWM inverter which is connected to the ac mains through linked reactors.[5] A pole of the five-level inverter can be regarded as a multiplexer which may be switched to any DC side potentials according to the multilevel PWM strategy employed. Utilizing these DC voltages, the objective of the five-level PWM adopted is to produce the output voltage waveform as sinusoidal as possible despite switching operation.[6] The source voltages with angular speed ω are assumed ideal and balanced ones and are given as follows:




(a)

| $V_o$ | $V_A$ | $V_B$ | $V_C$ | $V_D$ | $V_E$ |
|---|---|---|---|---|---|
| Q1 | 1 | 0 | 0 | 0 | 0 |
| Q2 | 1 | 1 | 0 | 0 | 0 |
| Q3 | 1 | 1 | 1 | 0 | 0 |
| Q4 | 1 | 1 | 1 | 1 | 0 |
| Q5 | 0 | 1 | 1 | 1 | 1 |
| Q6 | 0 | 0 | 1 | 1 | 1 |
| Q7 | 0 | 0 | 0 | 1 | 1 |
| Q8 | 0 | 0 | 0 | 0 | 1 |

(b)

1 = ON, 0 = OFF

Fig. 1. (a) A pole of the five-level inverter, (b) Basic switching table for the five-level inverter.

$$v_{sa} = V_{sa}\sin(\theta)$$

$$v_{sb} = V_{sb}\sin\left(\theta - \frac{2\pi}{3}\right)$$

$$v_{sc} = V_{sc}\sin\left(\theta + \frac{2\pi}{3}\right) \quad (1)$$

Fig. 2. illustrates the five-level PWM assuming balanced switching. Then, the respective existence functions $d_1^a$ through $d_5^a$ can be expressed as follows:

$$d_1^a = D_1 + m_1\sin(\theta + \phi_m) \quad (2)$$

$$d_2^a = D_2 + m_2\sin(\theta + \phi_m)$$

$$d_3^a = D_0 + m_0\sin(\theta + \phi_m)$$

$$d_4^a = D_2 - m_2\sin(\theta + \phi_m)$$

$$d_5^a = D_1 - m_1\sin(\theta + \phi_m)$$

Eq. (2) represents only the DC and fundamental components of the corresponding existence function and thus will be free from a specific five-level PWM strategy. The superscript in Eq. (2) denotes a-phase quantity and $\phi_m$ is a phase angle of the inverter with respect to the AC source voltage. Thus,

$$d_n^b(\theta) = d_n^a\left(\theta - \frac{2\pi}{3}\right) \quad (3)$$

$$d_n^c(\theta) = d_n^a\left(\theta + \frac{2\pi}{3}\right)$$

with $n = 1, \cdots, 5$. Therefore, the fundamental component of the output phase voltage can be found to be

$$v_{ia} = d_1^a v_1 + d_2^a v_2 + d_3^a(0) + d_4^a(-v_2) + d_5^a(-v_1)$$

$$= (2m_1 v_1 + 2m_2 v_2)\cdot\sin(\theta + \phi_m) \quad (4)$$

Similarly,

$$v_{ib} = (2m_1 v_1 + 2m_2 v_2)\cdot\sin\left(\theta + \phi_m - \frac{2\pi}{3}\right) \quad (5)$$

$$v_{ic} = (2m_1 v_1 + 2m_2 v_2)\cdot\sin\left(\theta + \phi_m - \frac{2\pi}{3}\right) \quad (6)$$

Note that a five-level PWM can be decomposed into two three-level PWM's as shown in Fig. 3(c) so that a five-level PWM has not two control variables, modulation index controlling the amplitude and phase angle, but three, that is, $m_1$, $m_2$ and $\phi_m$. Then, two three-level inverters seems to be series connected in that their single-pole-triple-throw switches are exclusively grounded. Thus, each three-level modulation indexes are defined as

$$M_1 = 2m_1 \quad (7)$$

$$M_2 = 2m_2$$

On the other hand, the DC side currents flowing into each nodes connecting the capacitors depend on the AC side

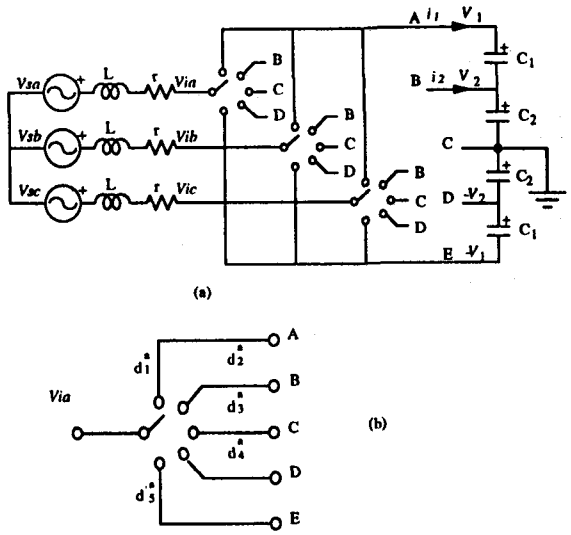



Fig. 2. (a) The schematic of five-level inverter/rectifier, (b) A switch model as a multiplexer.

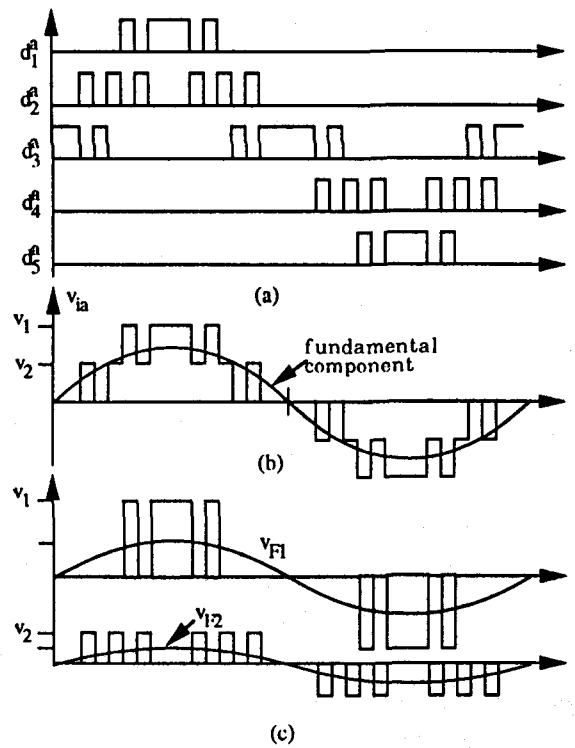



Fig. 3. (a) Existence functions, (b) the resultant output phase voltage, (c) decomposition of five-level PWM into two three-level PWMs.

line currents and the corresponding existence functions as follows:

$$i_1 = d_1^{abc} \cdot i_{abc} \tag{8}$$

$$= m_1 \cdot \mathrm{SIN}(\theta + \phi_m) \cdot i_{abc}$$

where

$$d_1^{abc} = [d_1^a \quad d_1^b \quad d_1^c]$$

$$i_{abc} = [i_a \quad i_b \quad i_c]^T$$

$$\mathrm{SIN}(\theta + \phi_m) = \tag{9}$$

$$\left[\sin(\theta+\phi_m) \quad \sin\left(\theta+\phi_m-\frac{2\pi}{3}\right) \quad \sin\left(\theta+\phi_m+\frac{2\pi}{3}\right)\right]$$

Driving Eq. (8), no assumption is made for the AC line currents. Similarly,

$$i_2 = d_2^{abc} \cdot i_{abc} \tag{10}$$

$$= m_2 \cdot \mathrm{SIN}(\theta + \phi_m) \cdot i_{abc}$$

with $d_2^{abc} = [d_2^a \quad d_2^b \quad d_2^c]$

Taking the balanced switching operation into account,

$$i_4 = -i_2, \qquad i_5 = -i_1 \tag{11}$$

Thus, $i_3$ becomes zero for the fundamental component.

Using Eqs. (4), (5), (6), (8) and (10), we can draw out the fundamental equivalent circuit extracted from the original switching circuit as shown in Fig. 4. The resultant fundamental circuit model is no longer time varying and becomes linear as long as the control variables of the inverter do not change. Moreover, it is found that the five-level inverter can be modeled as a set of voltage controlled voltage sources and current controlled current sources on the fundamental frequency domain.

## III. Simulated Results

To confirm the validity of the fundamental circuit modeling of the SVC system with a five-level inverter, the system was simulated using commercial simulation packages such as PC-SIMNON for the switched circuit and PSPICE for the modeled circuit. Fig. 5 shows a possible switching pattern for the five-level inverter whereby 5,7,11,13th harmonics is selectively vanished with the approate angles. In the simulation, the circuit parameters and controlling conditions are as follows:

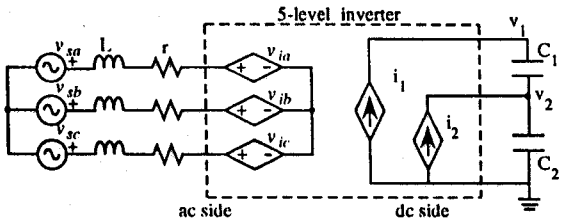



Fig. 4. Extracted fundamental circuit model for the SVC system.

$V_s$=100V, $f$=60Hz, $r$=1Ω, $L$=5mH, $C_1$=500μF, $C_2$ = 1500 μF, modulation index $M_I$=0.8.

With numerical computation, all the α's can be obtained as follows: $\alpha_1$ = 0.1084, $\alpha_2$ = 0.3857, $\alpha_3$ = 0.5445, $\alpha_4$ = 0.7954, $\alpha_5$ = 0.9995, $\alpha_6$ = 1.4207.

In open loop test, attention is especially made on the DC side voltage balancing and thus, given $\phi_m$, whether the DC side capacitor voltages are equivalued or not. Fig. 6 shows the variation of $v_1$ and $v_2$ starting from zero initial conditions with $\phi_m$=5°, and thus the open-loop controlled inverter seems to inject the capacitive reactive power into the ac mains. From Fig. 5, it can be seen that, at each time, $v_1 \equiv 2v_2$ and a DC side voltage of the system is stable, i.e. it dose converge to some value. Also, from Fig. 6 it is found that the modeling of the system is valid.

## IV. Conclusion

The multilevel inverter has many advantages over the other inverter as a high power source such that full utilization of the switching devices, lower switching frequency at each semiconductor switches and multilevel output.

In this paper, the SVC system using the multilevel PWM inverter is modeled in the fundamental frequency domain. The modeled circuit is no longer time varying and becomes linear as long as control variable of the inverter is not changed. As a result, the fundamental circuit modeling the original switched circuit will make it possible to determine oprating point, predict dynamic behaviors of the system and to design controller which is more stable and better.

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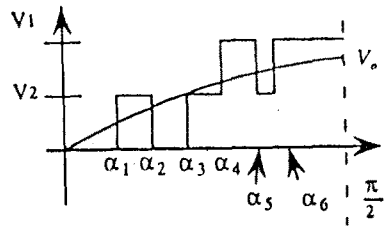
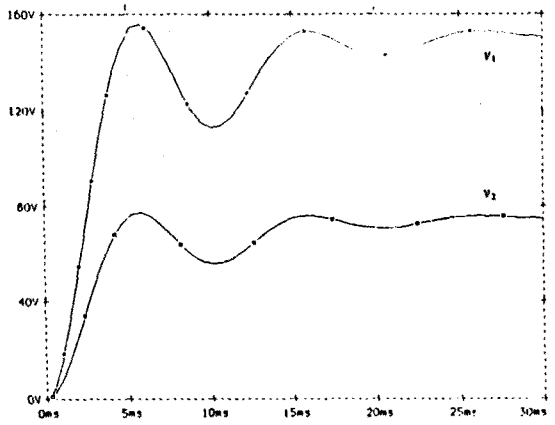
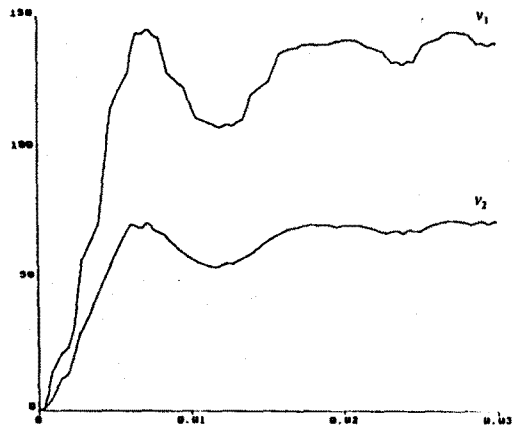



Fig. 5. A possible switching pattern for the inverter. A quater wave symmetry in the waveform is assumed.




(a)




(b)

Fig. 6. Variations of DC side voltages $v_1$ and $v_2$ ($\phi_m$=5°), (a) simulation with the fundamental circuit, (b) simulation with the switched circuit.