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Single Shunt Current Sensing Technique in Three-level PWM Inverter

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Abstract-- **This paper describes how to reconstruct the three phase current using the only single shunt in a three-level Neutral-Point-Clamped (NPC) PWM inverter. The area where phase currents are measurable is analyzed and the reconstruction method is proposed in three-level PWM inverter. According to the characteristics of the immeasurable areas in voltage plane, the voltage injection method, which relocates the original voltage reference in the immeasurable area to that in a measurable area in the voltage plane, has been devised. For this relocation, the compensating voltage is added and subtracted to the voltage reference in a switching period. And a control algorithm to inject the compensating voltage is also proposed. The proposed reconstruction of the phase currents in the single shunt sensing inverter has been tested by the computer simulation at various reference voltages, being in or passing in the immeasurable area. The results show the satisfactory measurement of the phase currents in overall operating conditions.**

Index Terms— **Current sensor reduction, Shunt current sensing technique, multi-level PWM inverter.**

I. Introduction

An AC electric power conversion based on PWM inverter or converter is very popular in these days [1]-[2]. The AC energy conversion technology is widely used from a small size home appliance to huge industry applications. AC power conversions have been used not only in motor drives, which account for the largest part of the electric energy consumptions, but also in many electric energy conversions itself like AC to DC, DC to AC or AC to AC. According to the deep penetration of the distributed power generation systems with different frequency and voltage and their connection to gird, especially, AC power conversion is getting more popular.

Multilevel inverter topologies have been researched in the past three decades because of their inherent characteristics as high voltage blocking capability, small voltage harmonics, and higher equivalent switching frequency compared to the two-level inverter. Until now, many multilevel inverter topologies have been proposed and implemented in many industrial fields such as Neutral-Point-Clamped (NPC) Pulse-Width-Modulation (PWM) inverter [3]-[4] capacitor clamped PWM inverter, cascaded H-bridge inverter and so on [5].

As increasing popularity of three-level NPC inverter, the cost of production has become the important issue. Because the structure of multilevel NPC inverter can be explained as a extension of the conventional two-level PWM inverter, the cost reduction strategies in the conventional two-level PWM inverter design can also be adopted in three-level NPC inverter. Among these strategies in two-level PWM inverter, current sensorless or sensor-reduction method is one of them [6]-[15]. Fig. 1 shows current sensing methods in the conventional two-level PWM inverter. In general, phase currents are measured at the each phase outputs as in Fig. 1(a). To reduce or remove the current sensors for the measurement of output or input AC phase current, the only single DC-link current sensor incorporating the reconstruction technique of each phase current can be used in Fig. 1(b) [6]. To reconstruct three phase currents simultaneously from the only DC-link current information, the power switch turn-on and turn-off sequence are used [7]. To measure the specific phase current, turn-on time of bottom switch of the inverter should be long enough to measure corresponding DC link current. While, the phase current appeared at DC link in one PWM period varies according to the output voltage. Practically, the effective voltage vector should be with a minimum amount of time to ensure the reliable current measurement from the DC-link. That means that the phase current cannot be measured in specific output voltage conditions. In two-level PWM inverter, there are three situations in the un-reconstruction condition: low modulation index, voltage vector with only one effective voltage vector, and over-modulation [9]. To reconstruct three phase currents in whole operating conditions, many methods have been proposed as in switching duty ratio modification [7], [9], [11], PWM pattern modification [8], switching turn-on time extension [13], voltage injection [15] and so on.

In addition, there are two important factors in single current sensing technology on the PWM inverter. The first is a fault detection ability of the inverter, and the other is a correct sampling of the phase currents. To assure the full fault detection ability, the single current sensing topology was modified in [9]. And, to get more exact phase current value, the predictive estimation technique was been applied in [10], [11], [12], [14], [16].

In this paper, this single shunt sensing technique is applied to the three-level NPC inverter. To reconstruct three phase current with only single DC-link current sensor, the PWM switch turn-on/off sequence is analyzed and the current immeasurable area is defined in the voltage plane of three-level PWM inverter. To reconstruct three phase currents in these current immeasurable area, voltage injection method is proposed.

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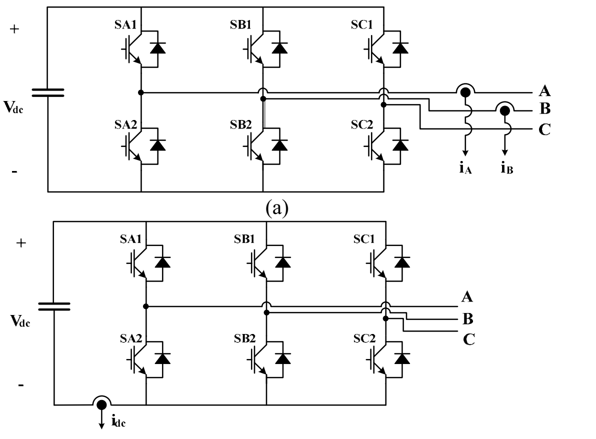
Simulation results show the feasibility of the proposed method for reconstruction of three phase currents in extended operating voltage condition.



(a)

(b)

Fig. 1. Current sensing method of conventional two-level PWM inverter. (a) Phase current sensing two-level PWM inverter (b) Single DC-link current sensing two-level PWM inverter.

II. Three-level PWM Inverter Topology and PWM Sequence

A general circuit configuration of three-level Neutral-Point-Clamped (NPC) PWM Inverter is shown in Fig. 2. According to the switching state, output terminal of inverter, namely, *A*, *B* and *C* are connected to the DC-link voltages, V_{dcN}, V_{dc0} and V_{dcP}. To connect the *A* phase of output to V_{dcP}, for example, switch *SA1* and *SA2* should be turned-on and *SA3*, *SA4* should be turned off. In the case of connection the *A* phase and V_{dcN}, *SA3* and *SA4* should be turned-on and the others should be turned off. In the case of V_{dc0}, *SA2* and *SA3* should be turned on and the others should be opposite. According to these switch turn-on combinations, the output voltage vector can be depicted in the voltage plane as shown in Fig. 3.

Output voltage vectors consist of 27 switching states, which are 19 effective voltage vectors including three zero voltage vectors. Switch state can be designated with three numbers, where each number means the switch state of *A*, *B* and *C* phase switch leg, respectively. The value of the number signifies the level of voltage: *2* means that the output phase voltage is connected to the V_{dcP} in Fig. 2, *1*, for phase voltage to be connected the V_{dc0}, and *0*, for phase voltage to be connected the V_{dcN}. These effective voltage vectors can be divided into three groups: zero voltage vectors, inner voltage hexagon vectors and outer voltage hexagon vectors. Switching states for zero voltage vector, V_0 are *(0,0,0)*, *(1,1,1)* and *(2,2,2)*. In these zero voltage vectors, all of three output phase voltages are zero. Inner voltage hexagon consists of six voltage vectors, from V_{13}, to V_{18} in Fig. 3, which come from twelve switching states. In these voltage vectors a half of DC-link voltage is applied to the load. This half of DC-link voltage can be generated by higher half V_{dc} between V_{dcP} and V_{dc0} or by lower half V_{dc} between V_{dc0} and V_{dcN}. All of these twelve switching states have at least one phase which has V_{dc0} as the output. Outer voltage hexagon consists of twelve voltage vectors. These voltage vectors in the outer voltage hexagon impress V_{dc} into the load. Therefore, there is no V_{dc0} voltage in phase output voltages with those outer voltage vectors.

A most popular PWM method in three-phase NPC inverter is double carrier comparison method shown in Fig. 4. Two carrier waves divide DC-link voltage into halves. And the output phase voltage references are compared to the two carrier waves. When the output voltage reference is larger than the upper carrier wave, then the switch state of that output phase is V_{dcP}. When the output voltage reference is smaller than the lower carrier wave, the switch state of that output phase is V_{dcN}. If output voltage reference is larger than the lower carrier wave and smaller than the upper carrier wave, then the switch state of that output phase is V_{dc0}. With this simple comparison, the output voltage reference can be easily generated by adjacent three voltage vectors. In Fig. 4, two cases of output voltage reference of NPC inverter are shown together with the phase switching states. Fig. 4(a) shows the switching state where the output voltage reference is in the inner voltage hexagon. Output voltage reference is synthesized by V_{14}, V_0 and V_{13}. And Fig. 4(b) expresses the switch states when the output phase voltage reference is out of the inner voltage hexagon. The output voltage reference is synthesized by three effective voltage vectors, V_{14}, V_7 and V_2.

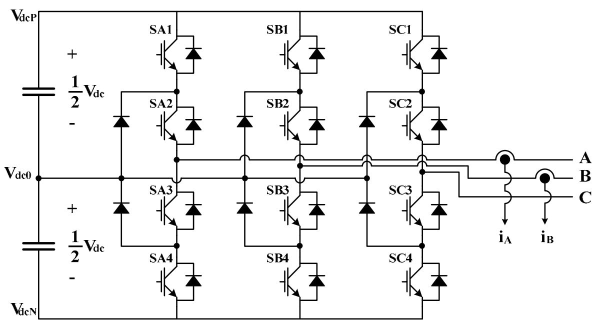


Fig. 2. Three-level neutral-point-clamped PWM inverter.

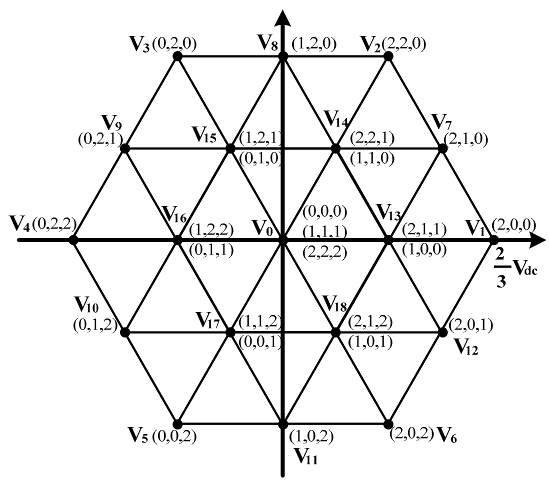
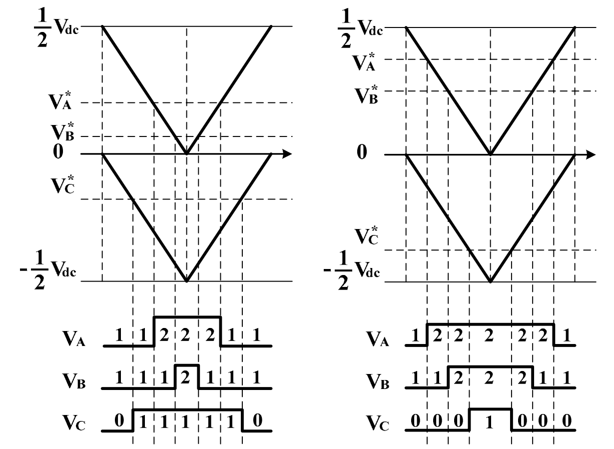


Fig. 3. Output voltage vector diagram of three-level NPC PWM inverter according to the switch turn-on combination.



(a) (b)

Fig. 4 PWM pattern in three-level NPC inverter. (a) Switching sequence when voltage reference is in the inner voltage hexagon. Voltage sequence is $V_{14} \rightarrow V_0 \rightarrow V_{13} \rightarrow V_{14} \rightarrow V_{14} \rightarrow V_{13} \rightarrow V_0 \rightarrow V_{14}$. (b) Switching sequence when voltage reference is out of the inner voltage hexagon. Voltage sequence is $V_{14} \rightarrow V_7 \rightarrow V_2 \rightarrow V_{14} \rightarrow V_{14} \rightarrow V_2 \rightarrow V_7 \rightarrow V_{14}$.

TABLE I
SWITCH STATE AND RELATED NEUTRAL POINT CURRENT OF DC-LINK IN THREE-LEVEL NPC INVERTER

	Voltage Vector	Switching State	Sensing Current	Voltage Vector	Switching State	Sensing Current
Outer Voltage Hexagon	V_1	(2,0,0)	X	V_7	(2,1,0)	I_B
	V_2	(2,2,0)	X	V_8	(1,2,0)	I_A
	V_3	(0,2,0)	X	V_9	(0,2,1)	I_C
	V_4	(0,2,2)	X	V_{10}	(0,1,2)	I_B
	V_5	(0,0,2)	X	V_{11}	(1,0,2)	I_A
	V_6	(2,0,2)	X	V_{12}	(2,0,1)	I_C
Inner Voltage Hexagon	V_{13}	(1,0,0)	I_A	V_{16}	(0,1,1)	$-I_A$
		(2,1,1)	$-I_A$		(1,2,2)	I_A
	V_{14}	(1,1,0)	$-I_C$	V_{17}	(0,0,1)	I_C
		(2,2,1)	I_C		(1,1,2)	$-I_C$
	V_{15}	(0,1,0)	I_B	V_{18}	(1,0,1)	$-I_B$
		(1,2,1)	$-I_B$		(2,1,2)	I_B
Zero Voltage	V_0	(0,0,0)	X			
		(1,1,1)	X			
		(2,2,2)	X			

III. SINGLE SHUNT SENSING TECHNIQUE IN THREE-LEVEL NPC PWM INVERTER

The single shunt sensing technique, which had been developed for two-level PWM inverter, is applied to the three-level NPC PWM inverter. Fig. 5 shows the configuration of three-level NPC inverter using single shunt resistor to measure the DC-link neutral current. The measurement with shunt resistor can be replaced with Hall-effect based current sensor. Instead of two or three output phase current sensors, one current sensor is employed between DC-link neutral point and output phase. From this neutral point current, therefore, the output phase currents should be reconstructed according to the effective voltage vector in one PWM period. A relationship between the actual voltage vector and the measured phase current from the DC-link is summarized in Table I. Among twelve four switching states, one phase current can be measured in eighteen switching states.

In general PWM method of three-level NPC, all voltage reference can be generated by three adjacent effective voltage vectors. Fig. 6(a) shows the current measurable voltage vector and current measurable phase. Every triangle which consists of adjacent effective voltage vector has two different phase current measurable voltage vectors. That means that PWM switching sequence generated by double carrier comparison method, have an opportunity to measure at least two different phase currents. Fig. 6(b), (c) describes how the two phase currents can be measured in the case of different output voltage. The minimum current measurable time should be maintained in the current measurable voltage vector [9], [15]. In Fig. 6(b),(c), the effective on-time of current measurable voltage vector should be larger than the minimum current measurable time, T_m. The minimum current measurable time, T_m is time delay between time point where the current measurable voltage vector is active and the time point where current is sampled. To properly measure the current from the single shunt in neutral point, T_m is decided by the timing of the hardware of the inverter such as dead-time of inverter (T_d), the diode reverse recovery time (T_{rr}) and A/D converter sample and hold time (T_{AD}). The minimum current measurable time T_m can be described as in (1). The minimum current measurable time can be converted to the voltage magnitude, V_m as (2). V_m can be expressed in d-/q-axis reference frame. The nearest current measurable point to the origin can be described as ($V_{dsensing}$, $V_{qsensing}$). These $V_{dsensing}$ and $V_{qsensing}$ value can be derived as (3). To measure the two phase currents in one PWM period, the current measurable voltage vectors should be larger than V_m. The voltage reference area where the voltage vector is unable to satisfy this condition, are illustrated as shaded region in Fig. 7(a). Because of deficiency of current measuring time, it is impossible to control current in this current immeasurable area shown in Fig. 7(a).

$$T_m = T_d + T_{rr} + T_{AD}. \tag{1}$$

$$V_m = \frac{T_m}{T_{samp}} \frac{2}{3} V_{dc} \tag{2}$$

$$V_{\text{dsensing}} = V_m + \frac{1}{2} V_m = \frac{T_m}{T_{samp}} V_{dc}$$
$$V_{\text{qsensing}} = \frac{\sqrt{3}}{2} V_m = \frac{1}{\sqrt{3}} \frac{T_m}{T_{samp}} V_{dc} . \tag{3}$$

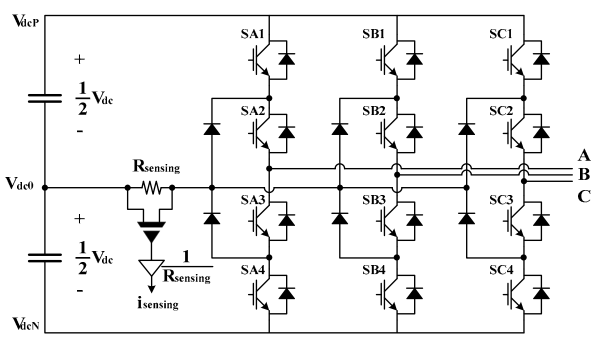


Fig. 5. Three-level neutral-point-clamped PWM inverter employed single shunt current sensing resistor

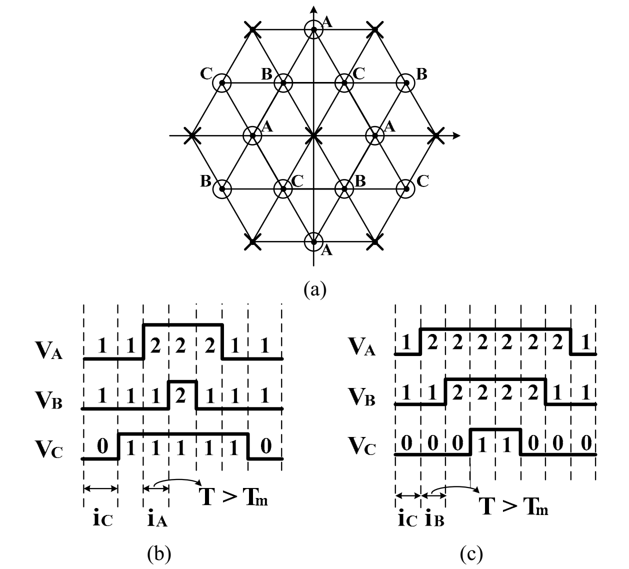


Fig. 6. Current measurable voltage vector. The effective on-time of the current measureable voltage vector should be larger than minimum current measurable time, T_m. (a) Current measureable voltage vector and measurable current phase (b) Output voltage reference is in the inner voltage hexagon. (c) Output voltage reference is out of the inner voltage hexagon.

IV. Minimized Immeasurable Area by Voltage Injection

Also, the issue of the current immeasurable area with single shunt current sensing technique has been in the conventional two-level PWM inverter. To overcome this problem, voltage injection method had been proposed. In the same way, the issue in three-level NPC inverter can be solved. When the output voltage reference is in the current immeasurable area, the reference voltage vector, V^* can be modified as V_m^*, measureable voltage, which located in the current measureable area. The difference between reference voltage vector, V^* and modified voltage vector, V_m^* is defined as compensation voltage, V_{comp} in (4). After that, the compensation voltage, V_{comp} is subtracted from the original voltage reference, V^* to keep the average output voltage as the original voltage reference, V^*. This V_c^* in (5) is called as compensated voltage.

$$V_m^* = V^* + V_{comp.} \tag{4}$$

$$V_c^* = V^* - V_{comp.} \tag{5}$$

Applying the compensation voltage, V_{comp}, the current reconstruction area can widen. However, this compensation voltage causes the dispensable ripple in phase currents. To minimize the current ripple, the compensation voltage, V_{comp} should be minimized. To determine the compensation voltage, V_{comp} clearly, the current immeasurable area is divided into four parts according to the compensation voltage determination criteria, as shown in Fig. 7(b). These four parts have their own voltage compensation criteria. Fig. 7(c)-(f) depicts the voltage injection method in each current immeasurable area, A, B, C and D.

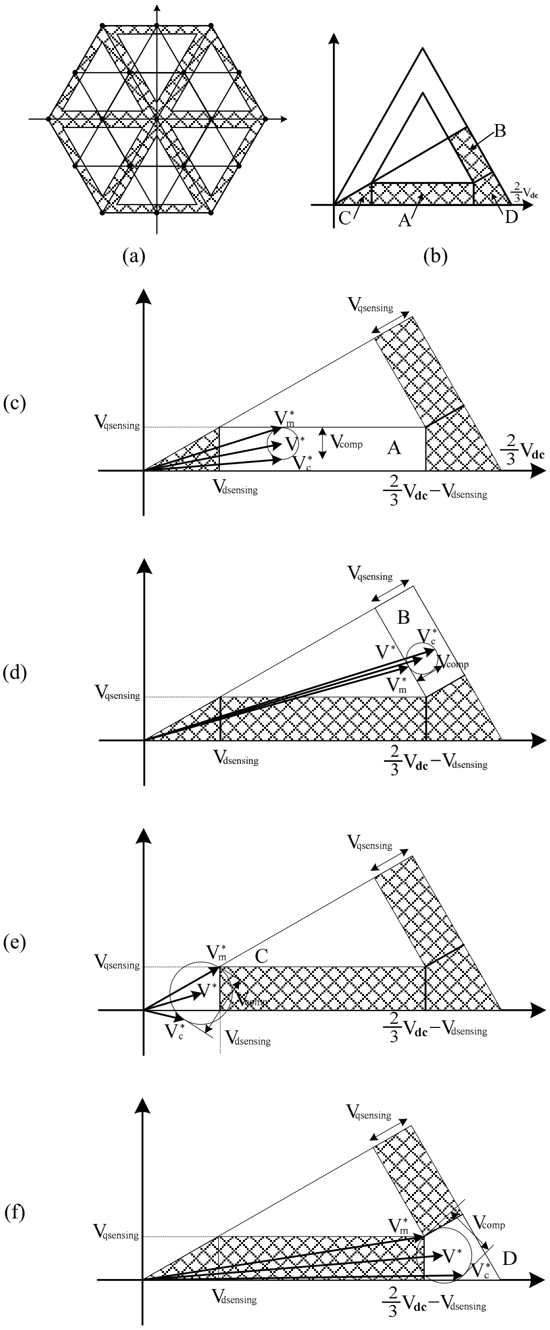


Fig. 7 Current immeasurable area in the voltage plane and voltage injection area. (a) Current immeasurable area. (b) Basic voltage area on the right triangle. According to the voltage injection type, this area is divided into four parts: A, B, C and D (c) Voltage injection method in area A. (d) Voltage injection method in area B. (e) Voltage injection method in area C. (f) Voltage injection method in area D.

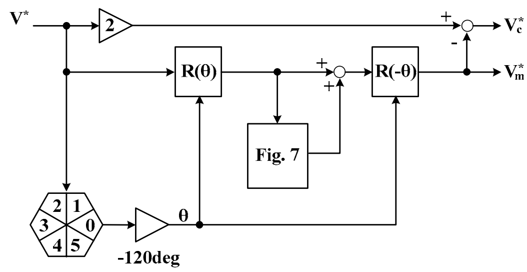


Fig. 8. Block diagram of voltage injection method for current measurement.

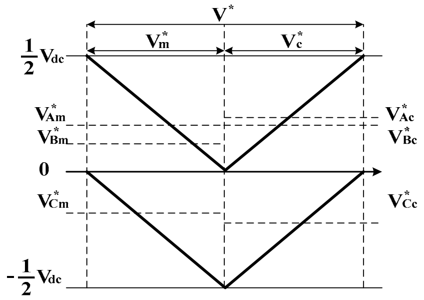


Fig. 9. Voltage injection for current reconstruction.

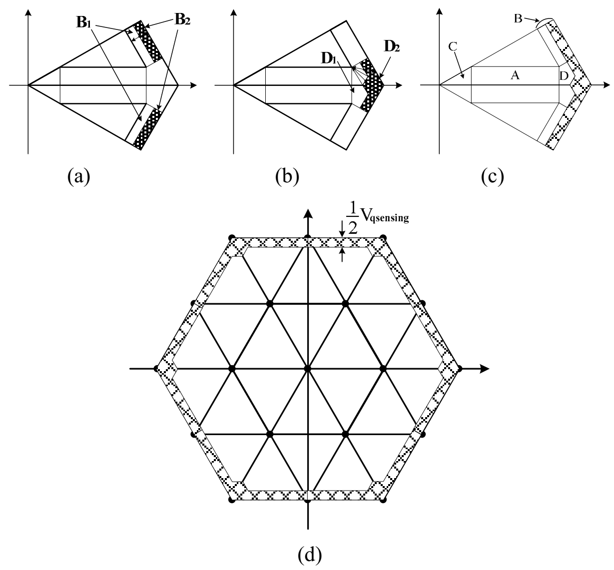


Fig. 10. Three phase current immeasurable area even though applying voltage injection method. (a) Three phase current immeasurable area in area B. (b) Three phase current immeasurable area in area D. (c) Current immeasurable area with proposed signal injection method.

Before calculating the compensation voltage, the voltage reference is transformed to the basic voltage right triangle in Fig. 7(b). To do that, the sector of voltage reference in Fig. 8 should be detected and reference frame is shifted. Then the transformed voltage reference lay on the basic right triangle in Fig. 7(b). When the voltage reference is in the area A, the output voltage should be shifted to the small right triangle area, which is current measurable area. To compensate the difference between the current measurable voltage, V_m*, and the voltage reference, V*, the compensation voltage, V_{comp} should be added and subtracted to the original voltage reference, V*. This process is illustrated in Fig. 7(c) well. In other current measurable area, the similar voltage injection method can be implemented as in Fig. 7(d),(e),(f), respectively. The current measurable voltage reference, V_m*, and the compensated voltage reference, V_c*, can be calculated as Fig. 8. In this proposed method, current measurable voltage reference and the compensated voltage reference are output voltage reference of half PWM period in Fig. 9.

Even though applying the proposed method, there are current immeasurable areas in B and D. Half of area B, B1 can be shifted to the current measurable area and the compensated voltage reference can be generated. However, other half of B, B2 is not able to be compensated because the compensation voltage is out of outer voltage hexagon in Fig. 10(a). In the similar way, area D2 in Fig. 10(b) cannot be compensated. These B2 and D2 area is immeasurable area. The whole current measurement limit is illustrated in Fig. 10(c).

V. Simulation Results

To verify the feasibility of the previous analysis of single shunt current sensing technique and voltage injection method in three-level NPC inverter, a current sensing scheme with a three-level NPC inverter connected to R-L load was simulated using Matlab®. In the simulation condition, PWM carrier frequency is 5kHz, current sampling frequency is 5kHz, DC-link voltage is 900V, load resistance is 100Ω, load inductance is 100uH and minimum current measurable time, T_m is set as 6usec.

Fig. 11 shows the current reconstruction results. When the voltage reference is 15V, the voltage vector is in the immeasurable area C in Fig. 7(e). In this area, the DC-link current from single shunt can not reflect the output phase current at all as shown in Fig. 11(a). However, as shown in Fig. 11(b), with injected voltage, currents from the shunt reflects the output phase current information. Because of the injected voltage signal, current with modified PWM has a little more harmonics than that with the conventional PWM. Fig. 11(c) and 11(d) show current sensing results in the condition of voltage reference 300V and 10Hz. When the voltage reference magnitude is 300V and frequency is 10Hz, the voltage vector is passing the current immeasurable area A in Fig. 7(b) six times in every one voltage reference period. Without the proposed method, single shunt sensing current in lower figure of Fig. 11(c) have immeasurable region. With proposed method, however, real three-phase currents can be reconstructed by the single shunt. When the output voltage is 520V and 10Hz, the DC-link current sensing results was illustrated in Fig. 11(e) and 11(f). In this case, voltage vector passes the area B and D. In these areas, the output phase currents are not able to be reconstructed. However, by compensated voltage, the voltage reference moved to the current measurable area and current can be reconstructed in whole operating region. Table II indicates the harmonics of output phase current. Because of injected voltage, the current harmonics in the proposed method is a little poor compared to that of conventional current sensing system. However, the amount of harmonic increasing is negligible.

TABLE II
HARMONICS IN THE PHASE CURRENT AND LINE TO LINE VOLTAGE WITHOUT VOLTAGE INJECTION AND WITH VOLTAGE INJECTION

Voltage Reference		Current THD[%]	
Magnitude[V]	Frequency[Hz]	General	Voltage Injection
15	10	9.11	20.37
300	10	0.96	1.04
520	10	0.73	2.7
Six-step	10	10.38	11.52

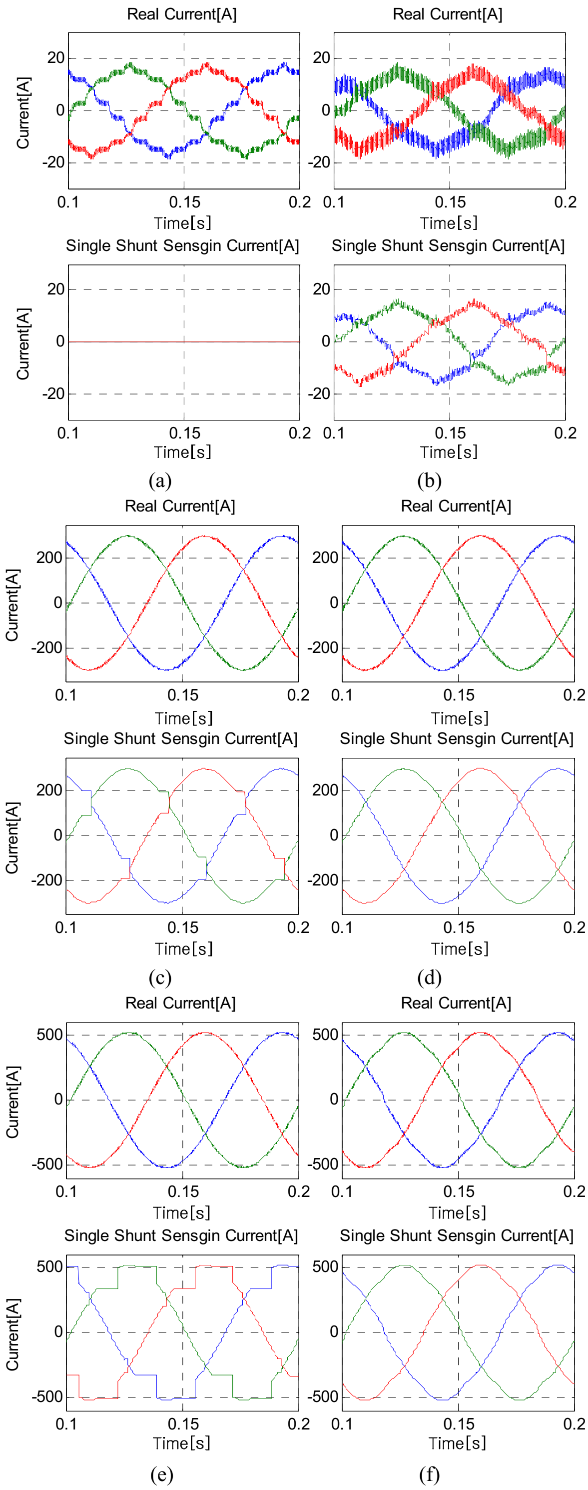


Fig. 11 Current measurement results. Real current, single shunt sensing current, real voltage reference and modified compensated voltage. (a) Current sensing results without the proposed signal injection method. Upper figure shows real three-phase currents and the lower figure indicates reconstructed three phase currents by single shunt with 15V and 10Hz voltage reference. (b) Current sensing results with the proposed signal injection method with 15V and 10Hz voltage reference. (c) Current sensing results without the proposed signal injection method with 300V and 10Hz voltage reference. (d) Current sensing results with the proposed signal injection method with 300V and 10Hz voltage reference. (e) Current sensing results without the proposed signal injection method with 520V and 10Hz voltage reference. (f) Current sensing results with the proposed signal injection method with 520V and 10Hz voltage reference.

VI. Conclusion

The single shunt current sensing technique with three-level PWM inverter has been discussed. The issue in the current reconstruction with the single shunt has been addressed with the concept of the inherent immeasurable areas of voltage vector plane. According to the characteristics of each immeasurable area, the voltage injection method, which relocates the original voltage reference vector in the immeasurable area to the current measurable area in the voltage plane in a switching period, has been devised to reconstruct the three phase currents. For relocation, the compensating voltage is added and subtracted to the voltage reference in a switching period. And a control algorithm to inject the compensating voltage automatically is also proposed. With the computer simulation results, the effectiveness of the proposed voltage injection method has been demonstrated.

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