Voltage Injection Method for Boundary Expansion of Output Voltages in Three Shunt Sensing PWM Inverters

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***Abstract*-- This paper describes boundary conditions for phase current reconstruction of a three current-shunt inverter and suggests a voltage injection method to expand the measurable areas. The boundary conditions are derived on voltage vector plane for symmetric space vector PWM. For the expansion of the areas, different voltages are injected depending on the position of the voltage vector with double sampling. When voltage vector is located in the insensible area, additional voltage is injected to place the voltage vector in the measurable area during next half of switching period and compensation voltage is added in the other half period. Voltages with minimum magnitudes are chosen to minimize the current ripples. Simulation results are presented to support the effectiveness of boundary condition derivation and proposed voltage injection method.**

***Index Terms*-- Current reconstruction, PWM inverters, Three shunt sensing, shunt resistor.**

I. Introduction

Three phase PWM inverters are widely used in industry applications for AC motor drive systems ([1]~[3]). Especially in motor drives where instantaneous torque control is achievable with vector control by dividing torque and flux axis separately, sampled current information of at least 2 phases is required. However, since cost-effectiveness is one of the top priorities in home appliance products or general-purpose motor control systems, current measurement circuit is composed with resistors to reduce the expense of current sensors. Although losses from the resistors occur and consequently the measurable current is limited, it is easily implemented by installing resistors on the lines where current flows and current information can be obtained by measuring voltages across the resistors.

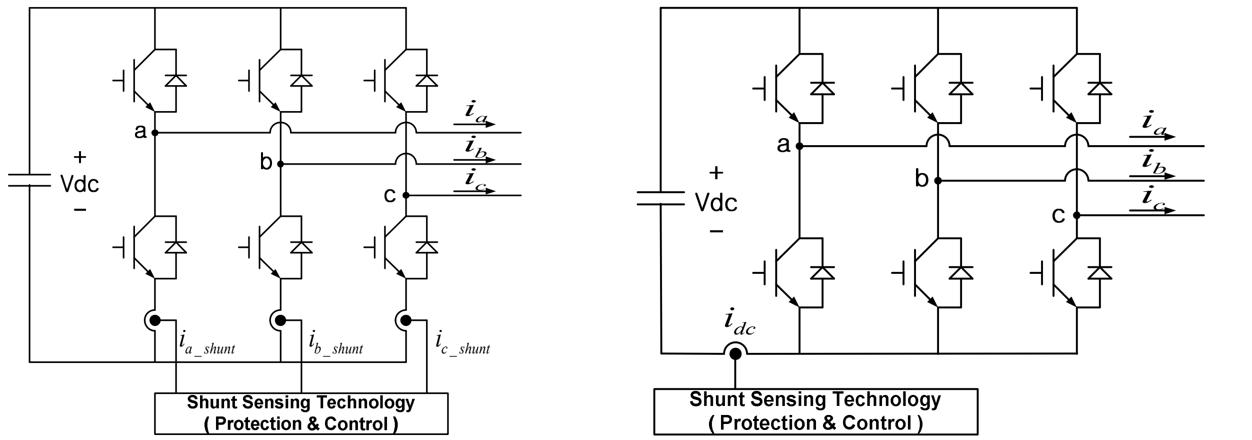
Fig. 1(a) and (b) shows typical output phase current sensorless inverter configurations and each circuit can be called Three Current-Shunt Inverter(TCSI) and Single Current-Shunt Inverter(SCSI), respectively [1]. In the SCSI, phase current reconstruction is relatively complicated because measurements have to be done twice during one sampling period with DC link current sensing or estimators must be introduced for acquisition of at least two phase current information. On the other hand, TCSI permits independent and simultaneous measurement for 3 phase current, less immeasurable areas exist in voltage vector plane and provides better current reconstruction performance at the expense of two additional shunt sensing ([4]).

In this paper, boundary conditions for phase current reconstruction for a TCSI system and voltage injection method is proposed to expand the boundaries. Limitations of phase current reconstruction in TCSI are resulted from practical concerns of inverter operation such as noise signal contained in the measured voltage, settling time of switching current, A/D conversion, dead time and etc. In conventional researches, the constraints are already well-known and considered in the current reconstruction process but theoretical analysis for the limitations has not been conducted.

On the basis of the boundary conditions derived from the analysis, this paper proposes voltage injection method to reconstruct phase current information. Observer based methods or calculation from measurable phase current information under certain assumptions have been reported ([5]~[6]). However, system parameters and conditions have significant effects on those methods and as a result reliability of the reconstructed current is inconsistent. With voltage injection method, immeasurable areas can be expanded to the theoretically extreme extent and accuracy of current measurement is secured. Although current ripple could be larger due to the injected voltage and compensation for the injection, it can be minimized with minimum magnitude voltage injection. Simulation results are provided to support the effectiveness of the works.

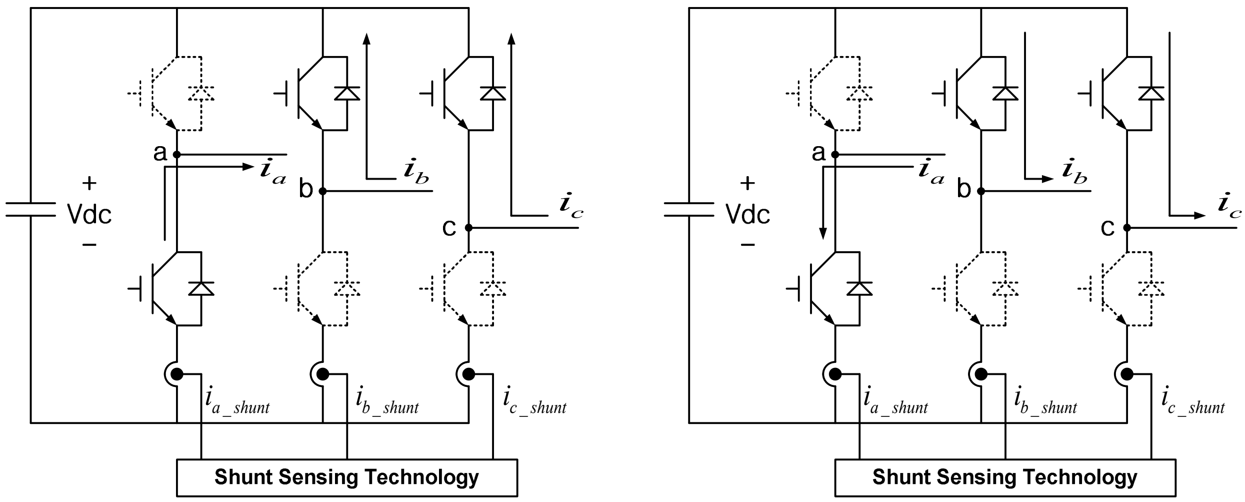
II. Boundary Condition for Phase Current Reconstruction

To improve phase current reconstruction performance, comprehension for the limitation of three shunt sensing is necessary. In this section, the process for acquiring phase current information is covered and boundaries are derived.



(a) TCSI (b) SCSI

Fig. 1. Typical output phase current sensorless inverter configuration



(a) (b)

Fig. 2. Current route for (a) positive / (b) negative current in phase ‘a’ when switching state is (0,1,1)

A. Derivation of Immeasurable Areas

In TCSI, current information of each phase can be obtained when lower switches are on-state regardless of the current direction. Fig. 2 depicts the moment when the lower switch in phase ‘a’ is conducting while the upper switches in phase ‘b’ and ‘c’ are conducting. It is possible that the current direction of phase ‘b’ and ‘c’ is in the other way, which is different from the case shown in Fig. 2. However, the current of phase ‘a’ is always same as the shunt current when lower switch is conducting.

Based on the analysis, measurable phase current information according to switching states is arranged in table. 1. For the instantaneous control of the phase current of the motor, which is the prerequisite of the high performance AC motor drive, current information of at least two phases is required during control period. Therefore, when voltage is synthesized with switching only (1,1,0), (0,1,1), (1,0,1) or (1,1,1) during one whole sampling period, high performance AC drive is impossible and the area, which is actually lines, can be expressed on the voltage vector plane as in Fig. 3.

TABLE 1
Obtainable phase current information depending on switching states with shunt sensing(switching state ‘1’ means that the corresponding switch is conducting)

Switching state (Sa, Sb, Sc)	Obtainable currents ($i_{a\ shunt}$, $i_{b\ shunt}$, $i_{c\ shunt}$)
(1, 0, 0)	(x, i_b, i_c)
(1, 1, 0)	$(\mathrm{x}, \mathrm{x}, i_c)$
(0, 1, 0)	(i_a, x, i_c)
(0, 1, 1)	$(i_a, \mathrm{x}, \mathrm{x})$
(0, 0, 1)	(i_a, i_b, x)
(1, 0, 1)	$(\mathrm{x}, i_b, \mathrm{x})$
(0, 0, 0)	(i_a, i_b, i_c)
(1, 1, 1)	$(\mathrm{x}, \mathrm{x}, \mathrm{x})$

However, due to the practical issues mentioned previously, minimum duration of each voltage vector except (1,1,1) zero vector must be assured to obtain accurate phase current information from the shunt current measurement. When voltage vector is located in sector 1 as defined in Fig. 3, switching pattern of SVPWM is determined as shown in Fig. 4. For given switching states, all of the three phases’ currents can be measured during (0,0,0) state while (1,0,0) state provides the information of phase ‘b’ and ‘c’. Therefore, for the high performance drive system, summation of (0,0,0) state and (1,0,0) states must be longer than the minimum duration ,T_{min}.

$$T_0 + T_1 > T_{min} \quad (1)$$

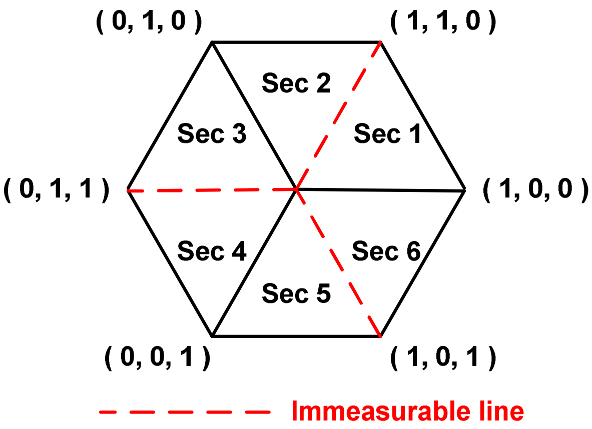


Fig. 3. Immeasurable lines of three shunt sensing with ideal measurement.

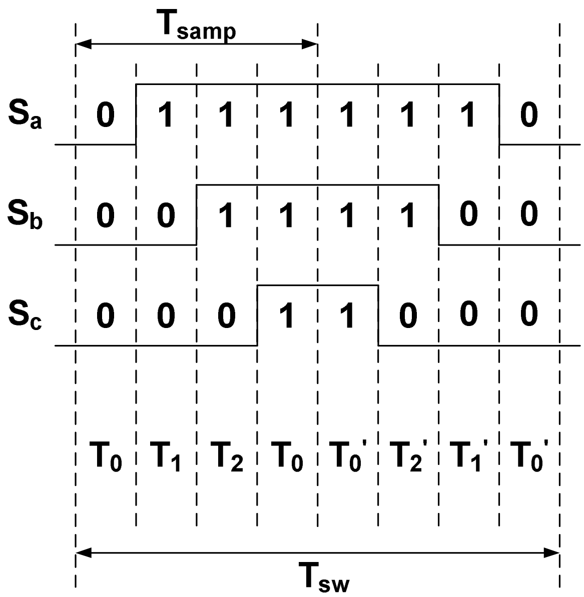


Fig. 4. Switching patterns of SVPWM in sector 1.

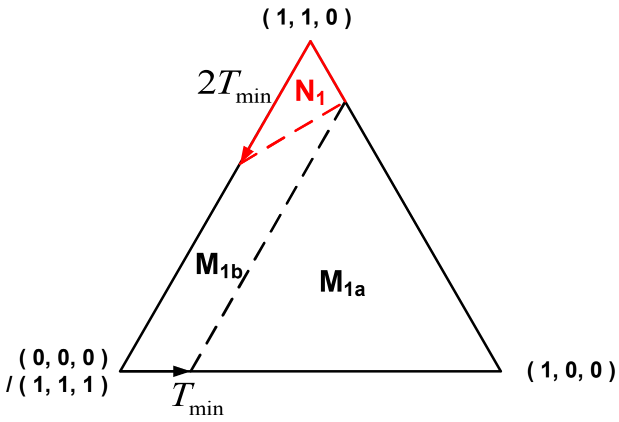


Fig. 5. Measurable/immeasurable areas on voltage plane in sector 1.

Fig. 5 displays the boundary conditions to guarantee the measurement of at least two phases’ currents. M_{1a} is the area when T_1 is over T_{min} whereas M_{1b} is the area when T_1 is less than T_{min} but the summation, $T_o + T_1$, is over Tmin. As a result, N1 is the immeasurable area in sector 1 and the whole immeasurable areas are presented in Fig. 6.

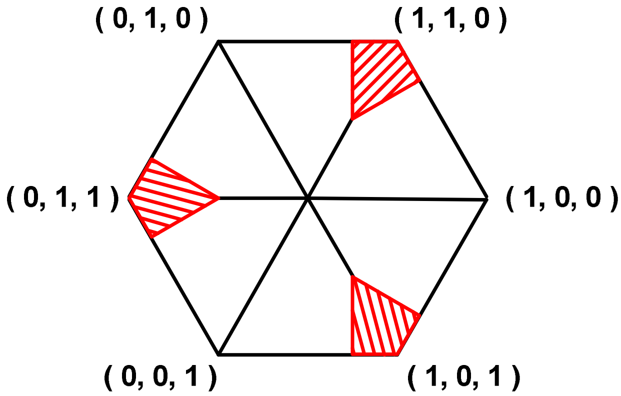


Fig. 6. Entire immeasurable areas in TCSI(hatched areas).

B. *Identification of Measurable Areas*

TABLE 2
Conditions for simulation

DC link (Vdc)	300[V]
Load resistance (Rs)	0.5[Ω]
Load inductance (Ls)	5[mH]
Shunt resistance (Rshunt)	12.5[mΩ]
Sampling frequency (fsamp)	10[kHz]
Minimum duration (Tmin)	8[us]

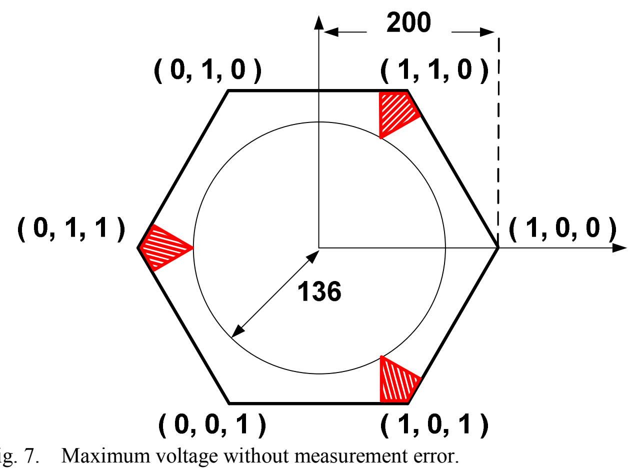


Fig. 7. Maximum voltage without measurement error.

Simulation has been conducted with R-L load to identify the analysis. Conditions are given in table 2 and Fig. 7 represents the voltage hexagon based on the conditions. According to the hexagon, the maximum magnitude of voltage reference without measurement error is determined to be 136[V]. Inside the circle area, perfect phase current reconstruction is guaranteed and current control performance is same as normal output phase current sensing system. Simulated results of reconstructing phase currents are shown in Fig. 8.

Fig. 9 displays the results of reconstructing phase currents when the magnitude of voltage reference crosses the immeasurable areas. It is expected that there are measurement errors occurring three times per one operating period for three phases and the corresponding results are obtained.

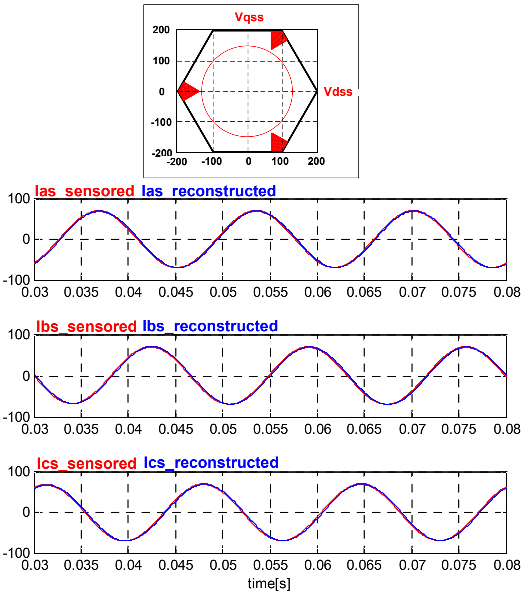


Fig. 8 Current reconstruction with voltage reference magnitude of 135[V].

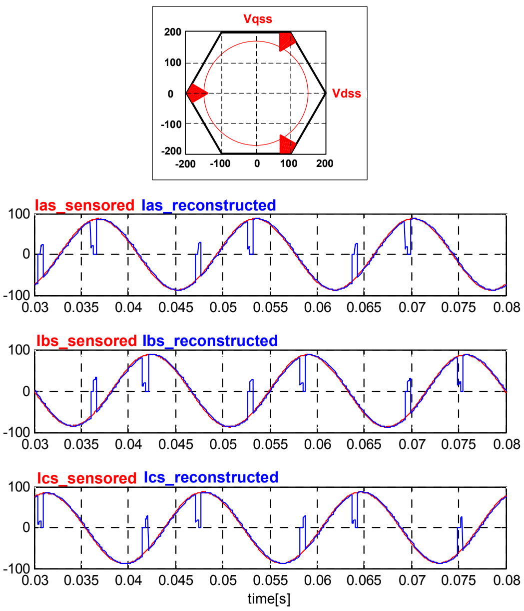


Fig. 9 Current reconstruction with voltage reference magnitude of 170[V].

III. EXPANSION OF MEASURABLE AREAS

The immeasurable areas can be reduced by injecting/compensating voltages. Sector 1 of voltage plane has been exemplified to provide explanation in detail. When the voltage lies in the immeasurable area, different voltage can be injected depending on the location of the voltage vector. First of all, when the voltage vector is placed in the area S1 of Fig. 10, surrounded by ABGE, minimum voltage can be injected since perfect compensation is possible. However, when voltage reference is enclosed by IGH, which is area S2 in the figure, minimum voltage injection is impossible. Therefore, voltages parallel with line AD are injected and compensated for the area S2. When the voltage vector lies in the area S3, enclosed by BIH, voltage can be injected so that the modified reference for measurement is on the point A.

To see the effect of the voltage injection, simulation results are displayed in Fig. 11. As it is shown, the measurable areas are expanded successfully.

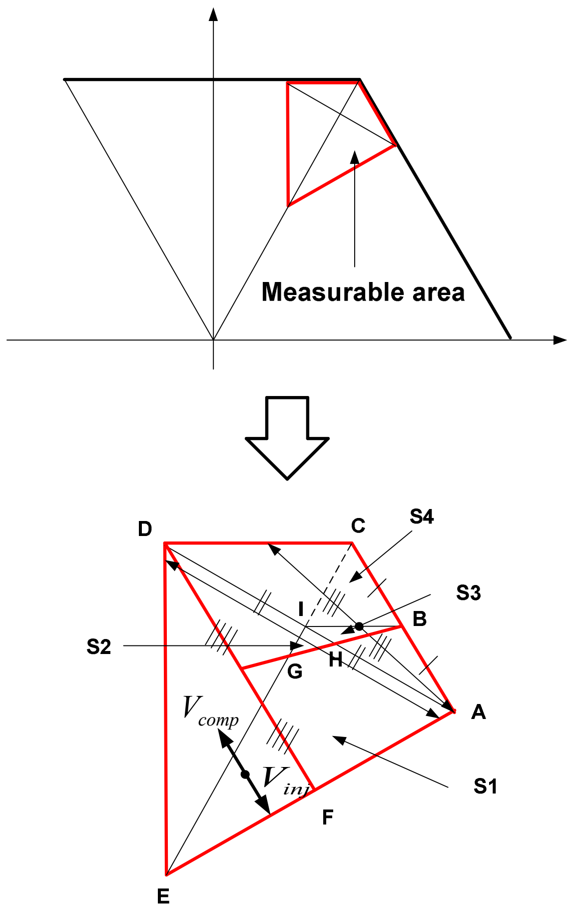


Fig. 10 Expansion of measurable area by injecting/compensating voltages.

IV. CONCLUSIONS

In this paper, the boundary conditions for phase current reconstruction of Three Current Sensing Inverter (TCSI) are derived and proved by simulation. For given system conditions, immeasurable areas are identified and phase current reconstruction is limited. However, by injecting/compensating voltages during switching period, the immeasurable area can be expanded to some extent. To minimize side effects of voltage injection, minimum magnitude voltage is selected and effectiveness of the proposed method is verified by computer simulation.

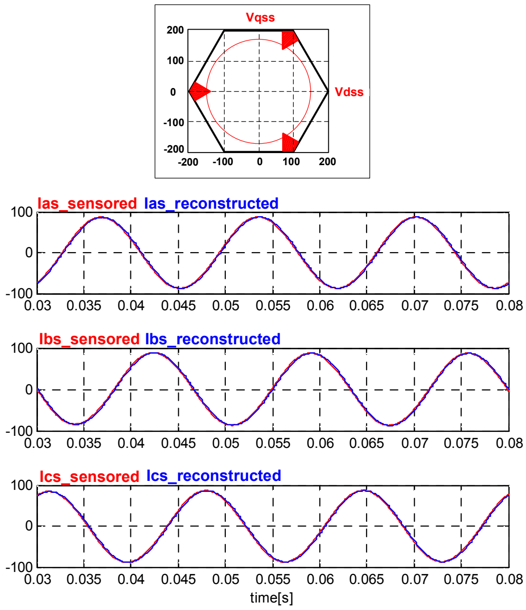


Fig. 11 Current reconstruction with voltage reference magnitude of 170[V] by injecting/compensating voltage.

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