Simple Injection Voltage Modification Methods for Improving the Performance of Saliency-based Sensorless Control without Prediction in a Single Shunt Current Sensing Drive System

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Abstract-- **This paper analyzes errors in the reconstructed current and injected voltage, when the saliency-based sensorless control is applied to the single shunt drive system (SDS), and proposes the methods to reduce the errors and improve the position estimation performance without predictive concept. Two methods of injection voltage modification for improving the performance of the sensorless control in SDS are presented, which include the pulsating voltage injection and the rotational voltage injection, respectively. Since the proposed methods do not apply the current prediction based on the motor voltage model, errors may exist compared to the existing prediction methods, but the calculation process for the sensorless control is considerably simple and the performance is not affected by the motor parameter errors. To verify the feasibility, the simulation and experimental results are presented about the saliency-based sensorless control with SDS in interior permanent magnet motor (IPMM) drives.**

Index Terms—**Sensorless control, Single shunt drive system, Current reconstruction, Voltage injection.**

I. Introduction

AC motor drive system applying a single current sensor and position sensorless control is attractive in low-cost applications such as home appliances, as in Fig. 1. The position sensorless control is largely classified into two categories: one is based on back electromotive force (EMF) and the other is based on the motor saliency. The back-EMF based sensorless estimates the rotor position based on the motor voltage model and has no difficulty in compatibility with single shunt drive system (SDS). However, in the saliency-based sensorless control with SDS, not only the current reconstruction error but also the injected voltage error in the current reconstruction dead zone deteriorates the position estimation accuracy.

In the saliency-based sensorless control, the admittance and position information are extracted by measuring the current fluctuation with respect to the injected high-frequency (HF) voltage. On the other hand, the SDS requires the voltage injection for the phase current reconstruction in the current reconstruction dead zone. When both two voltage injections are applied at the same time, two injected voltages are conflicted, which generates position estimation error. Also, the two current samplings occur respectively at two active voltage vectors in the SDS. In contrast to the phase current sensor system, the mid-point sampling is impossible in the SDS. Therefore, the SDS assumes that the current variations between two sampling points are negligibly small. However, the saliency-based sensorless control intentionally generates the current variations within one switching period by the HF voltage injection, so the current reconstruction errors in the SDS cannot be ignored any more when the saliency-based sensorless control is applied.

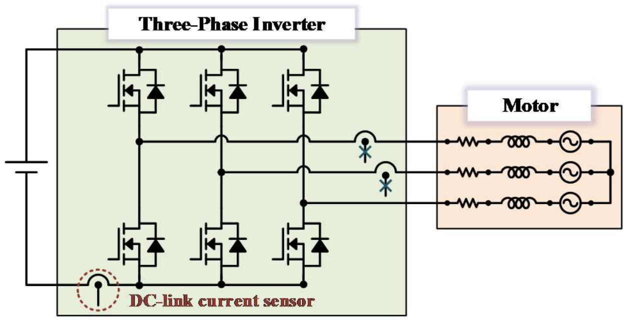


Fig. 1. Schematic diagram of the voltage source inverter and motor with a single current sensor.

The previous studies have attempted to compensate the errors in the injected voltage and the reconstructed current based on the voltage model of motor, which means that they applied the predictive concept [1-3]. Generally, the saliency-based sensorless control is dependent on the saliency of the motor, of which the position estimation performance is independent on the parameter accuracy. However, as introducing the predictive concept based on the motor voltage model, the parameter accuracy has effects on the position estimation accuracy. Therefore, this paper analyzes the error factors in the saliency-based sensorless control with SDS and proposes two methods to minimize the error factors. Since the proposed methods do not use a prediction concept, they can enhance the position estimation accuracy without the information of motor parameters.

II. Estimation Errors of High Frequency Voltage Injection Based Sensorless Control due to HF Voltage Injection in Single Shunt Drive System

A. Review of Square Wave Voltage Injection Based Sensorless Control

HF voltage injection sensorless methods vary according to the wave type of injection voltage and the injection method. This paper considers the case of the pulsating square wave voltage injection method on the synchronous reference frame [4]. Here, the HF square wave, of which frequency can be set to $F_{sw}/(2k)$ (F_{sw} is the switching frequency and k = 1,2,3…), is injected on the d-axis of the estimated synchronous rotor reference frame ($\hat{r}$), and the rotor position error ($\tilde{\theta}_r$) is extracted from the q-axis current variation($i_{qsh}^{\hat{r}}$).

$$v_{dqsh}^{\hat{r}*}[n] = \begin{bmatrix} v_{dsh}^{\hat{r}*} \\ v_{qsh}^{\hat{r}*} \end{bmatrix} = \begin{bmatrix} v_{inj}^{*}[n] \\ 0 \end{bmatrix}$$

$$where \;\; v_{inj}^{*}[n] = \begin{cases} V_h, & n = 1,2,...,k \\ -V_h, & n = k+1, k+2, ..., 2k \end{cases} \tag{1}$$

$$\tilde{\theta}_r[n] = \frac{i_{qsh}^{\hat{r}}[n]}{v_{inj}^{*}[n-2]} \frac{L_d L_q}{T_{samp}(L_q - L_d)} \tag{2}$$

where V_h is the amplitude of the injected square wave voltage and T_{samp} denotes the one switching period. If the voltage injection is applied to the d-axis with no error, the q-axis current has no current ripple by the injected HF voltage.

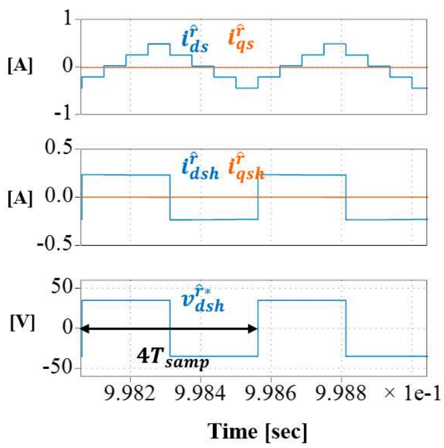


Fig. 2. Current ripples when the HF voltage is injected on the synchronous d-axis with no rotor position error.

Fig.2 shows the d- and q-axes currents and ripples according to the injected square wave voltage injection, where the injected frequency is set to $F_{sw}/4$. Also, the phase currents are simultaneously measured by the phase current sensors at the center point of zero voltage vector, which enables the almost perfect current measurements as the center point value of the changing current by the voltage vector. If the accurate rotor position is estimated, the q-axis has no ripple component by the injected voltage as shown in Fig. 2. As the rotor position error occurs, it causes the ripple component on the q-axis current, and the sensorless control method modifies the rotor position to make the q-axis ripple eliminated.

B. Review of Minimum Voltage Injection Method for Current Reconstruction in Single Shunt Drive System

Current reconstruction methods in SDS varies according to the modification method of voltage vectors. This paper adopts the minimum voltage injection (MVI) method of [5]. Here, to reconstruct the three phase currents, the voltage vector is divided into two parts in one switching period. During the half switching period, the voltage vector is projected to the measurable region in the voltage hexagon for measuring the two currents among three phase currents, where the projection makes the modification magnitude of the voltage vector minimum. And, to compensate the voltage vector modification in the measurement half switching period, the compensation voltage vector is applied during the remaining half cycle. Fig. 3 shows the example of the MVI scheme, where $V_{dqo}{}^{s*}$ is the original voltage vector reference for the vector control, $V_{dqm}{}^{s*}$ means the measurement voltage vector, and $V_{dqc}{}^{s*}$ denotes the compensation voltage vector.

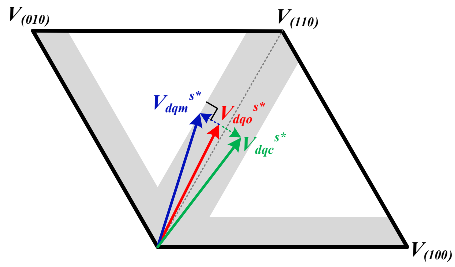


Fig. 3. Original, measurement, and compensation voltage vectors in the minimum voltage injection method for the current reconstruction [5].

In all current reconstruction method including the MVI method, the current sampling is done at each active voltage vector. Since the three phase currents change at the active voltage vector region, not only the center point value is not measured, but also the two current samplings for the three phase current reconstruction occur at separate points. In other word, the SDS is bound to have errors in the current measurement. The conventional researches of [1-3] proposed the prediction method for improving the measurement accuracy, but it depends on the parameter accuracy.

C. Deterioration of Current Measurement Accuracy with HF Voltage Injection based Sensorless Control in SDS

As mentioned above, the current measurement in SDS has inevitable errors because the phase currents change during one switching period according to the voltage vectors and the mid-point sampling, which can be applied in phase current sensor system, is impossible [6]. Meanwhile, the HF voltage injection for sensorless control deteriorates the current measurement errors in SDS.

Inherently, the HF voltage injection based sensorless control makes the phase currents vary according to the injected voltage frequency. Since the resolution of the current sesnsor is limited, the amplitude of the phase current variation should be kept to be over a certain level. It means that the current variation during the one switching period becomes more rapid as the injected voltage frequency increases, which can be a factor to deteriorate the current measurement accuracy in SDS.

Fig. 4 shows the voltage vector diagram when the HF voltage for the position sensorless drive is injected with the MVI method. Here, V_{HFinj}^{s*} denotes the injected HF voltage. By summing the V_{dqo}^{s*} and the V_{HFinj}^{s*}, the total voltage reference V_{dq}^{s*} at each control period is obtained, and the measurement and compensation voltage references, V_{dqm}^{s*} and V_{dqm}^{s*}, are generated considering the current reconstruction dead zone in SDS.

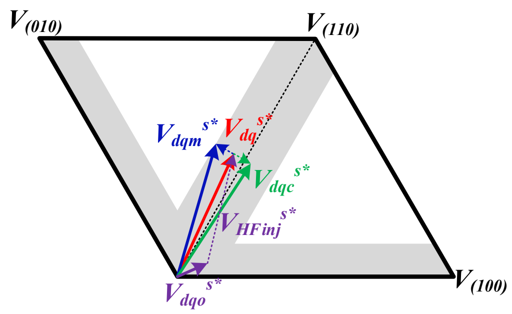


Fig. 4. Conventional pulsating HF voltage injection concept in SDS.

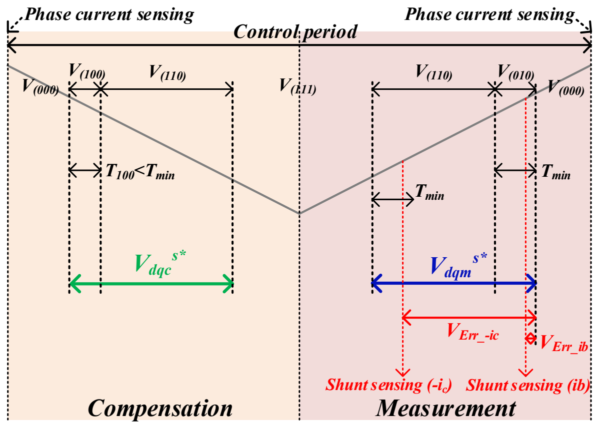
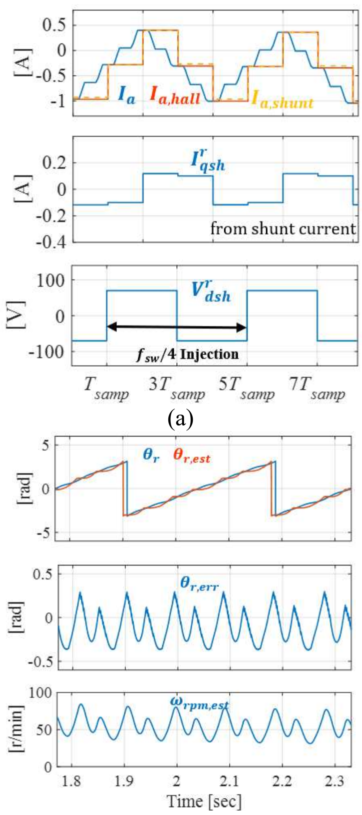


Fig. 5. Voltage vector durations of Fig. 4.

Normally, the HF votlage injection sensorless control is applied for the low speed region so the voltage reference for current control V_{dqo}^{s*} is smaller than the injected HF voltage V_{HFinj}^{s*}. Especially, as the injected voltage frequency is set near the switching frequency such as $F_{sw}/2$, or $F_{sw}/4$, the magnitude of V_{HFinj}^{s*} becomes much bigger than V_{dqo}^{s*}. Fig. 5 shows the voltage vector durations of Fig. 4 and the current sensing points within one switching period. Here, V_{dqo}^{s*} is ignored and omitted assumed that the operation region is limited to the low-speed region and T_{min} means the required minimum measurement time including the settling time, dead time, and AD conversion time. If the phase current sensing is performed by hall sensor or phase shunt sensor, the current variations by the injected HF voltage within one switching period can be measured simultaneously at the peak point of PWM carrier, where the current variation is almost zero because of zero voltage vector and low EMF voltage. On the other hand, the SDS measures the dc link current at the red dashed lines in Fig. 5. In each case, the other phase current is captured, and the phase current rapidly changes because the sensing points are placed at the active vector regions. Also, since the two measuring points are far apart, the current reconstruction based on the three-phase current balancing condition causes the additional errors.

D. High Frequency Injection Voltage Distortion due to Voltage Injection for Current Reconstruction in SDS

In Fig. 4, the HF injection votlage, V_{HFinj}^{s*}, is divided to the compensation and measurement voltage vectors, V_{dqc}^{s*} *and* V_{dqm}^{s*}. To accurately measure the current variation by V_{HFinj}^{s*}, the current sensing point should be placed after V_{dqc}^{s*} and V_{dqm}^{s*} like the phase current sensing case. However, in SDS, the current sensing points are on the voltage vector duration of V_{dqm}^{s}, which means that the effective HF injection voltage affecting the measured current variation is distorted. One example of the HF injection voltage distortion is also shown in Fig. 5. The c-phase current is measured before V_{HFinj}^{s*} is fully applied as much as V_{Err_ic} and the case of the b-phase current corresponds to V_{Err_ib}.



(b)

Fig. 6. Position and speed estimation performance of the conventional HF voltage injection sensorless of $F_{sw}/4$. (a) phase current sensing error, high-frequency current and voltage, (b) position and speed estimation at 50r/min under rated load.

With the current sensing error, this injected voltage distortion in the HF voltage injection sensorless control causes the position estimation error. Fig. 6(a) shows the current measurement accuracy in each case of the phase current sensing system and SDS, where the injected voltage frequency is set to $F_{sw}/4$. The phase current sensor (hall sensor) measures the a-phase current with no error ($I_{a,hall}$), but the a-phase current reconstructed from the dc shunt sensor ($I_{a,shunt}$) has some error with real current value (I_a). Fig. 6(a) shows the q-axis current variation between the successive current samplings in SDS when the HF injection voltage is applied to the exact d-axis with no angle error. Due to the current measurement error and the injection voltage distortion, the q-axis current includes the ripple component of the injected frequency, and it is contrast with the case of Fig. 2 where the phase current sensor is applied. When the HF voltage injection sensorless algorithm is used in SDS, the position and speed estimation performance is presented in Fig. 6(b). The ripple error component of the 6th harmonics exists in both position and speed estimation.

III. Proposed Injection Voltage Modification Method

In SDS, it is impossible to completely eliminate current measurement and injection voltage errors as in a phase current measurement system without the prediction scheme based on motor parameters. This paper proposes two voltage injection methods in SDS that can minimize the error of HF voltage injection sensorless without predictive control.

The first one applies the pulsating voltage injection of [4] as in Figs. 2 and 4. The other one adopts the rotating voltage injection [7], where the HF voltage is injected to the fixed three points. Both two methods can minimize the error components of current measurement and voltage distortion without the prediction scheme.

A. Proposed Injection Voltage Modification Method for Pulsating HF Voltage Injection Sensorless

In the conventional pulsating HF voltage injection sensorelss such as Fig. 4, the measurement voltage vector includes the HF voltage injection term, which makes the phase current change rapidly and the sensing points take apart from each other. The proposed method concentrates the HF injection voltage on the compensation voltage vector and makes the measurement voltage vector corrected by the MVI concept for the phase current reconstruction. The following equations represent the proposed injection voltage modification strategy.

$$V_{dq}^{s*} = V_{dqo}^{s*} + V_{HFinj}^{s*},\quad V_{dqm}^{s*} = V_{dqo}^{s*} + V_{MVI},\quad V_{dsc}^{s*} = V_{dq}^{s*} - V_{dqm}^{s*} \tag{3}$$

Fig. 7 shows the voltage vector diagram example of the proposed injection voltage modification method for the pulsating HF voltage injection sensorless, where the voltage vector durations are presented in Fig. 8.

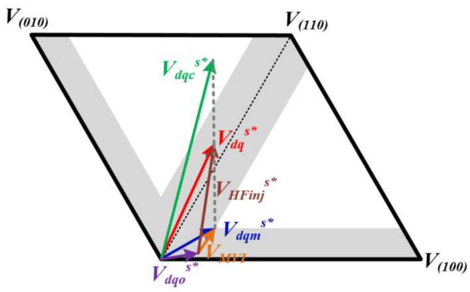


Fig. 7. Modified pulsating HF voltage injection concept in SDS.

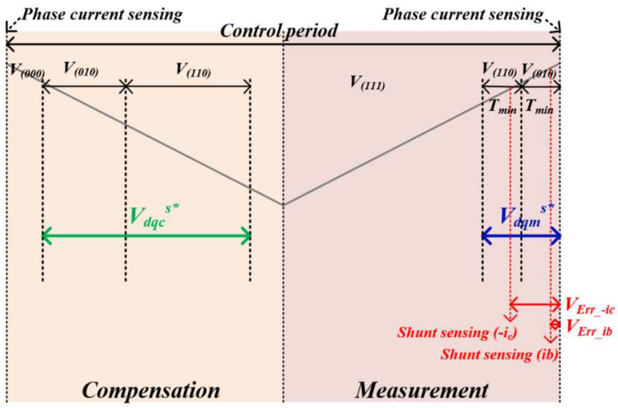


Fig. 8. Voltage vector durations of Fig. 7.

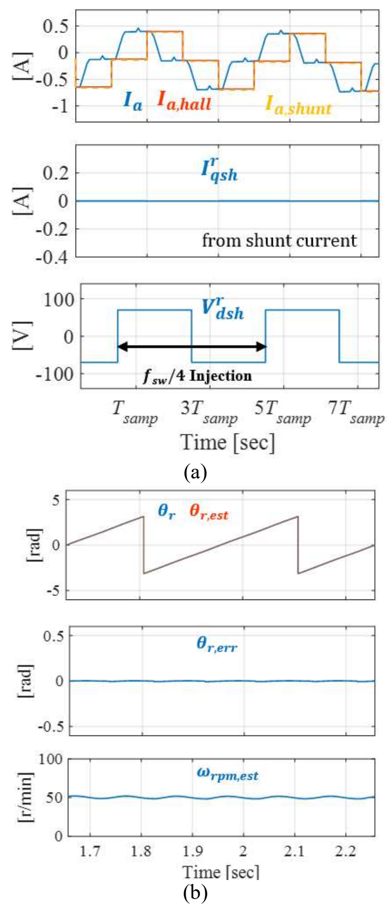


Fig. 9. Position and speed estimation performance of the proposed pulsating HF voltage injection sensorless of $F_{sw}/4$. (a) phase current sensing error, high-frequency current and voltage, (b) position and speed estimation at 50r/min under rated load.

In Fig. 8, the offset voltage is also modified to place the current sensing points close to the carrier peak point, which contributes to minimizing the current sensing errors with the case of the phase current sensor. Compared with the case of Fig. 5, the current sensing points are set to be closer and the voltage errors are reduced. As a result, the position estimating performance of the pulsating HF voltage injection sensorless is improved as shown in Fig. 9.

B. Proposed Injection Voltage Modification Method for Rotating HF Voltage Injection Sensorless

The proposed second scheme adopts the rotating HF voltage injection sensorless method [7]. Unlike the above pulsating voltage injection method, the HF injection voltage is placed in the measurement voltage region, and the compensation voltage region covers only the voltage for vector control. However, for the phase current reconstruction at the rotating HF voltage, the rotating HF injection voltage is set to be in the non-dead zone region and minimize the current and voltage errors like the case of the pulsating HF voltage injection case. Figs 10 and 11 show the voltage vector diagram and its voltage vector duration.

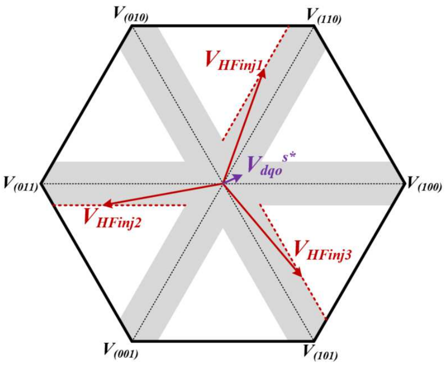


Fig. 10. Modified rotating HF voltage injection concept in SDS.

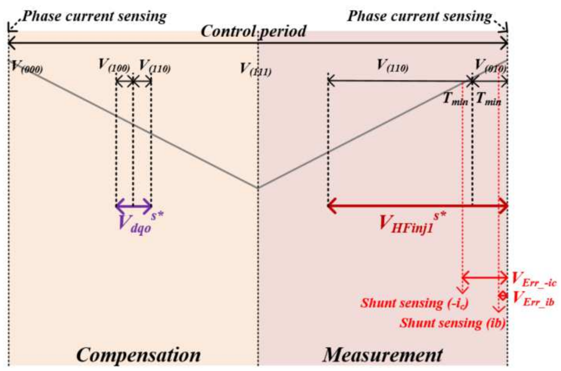
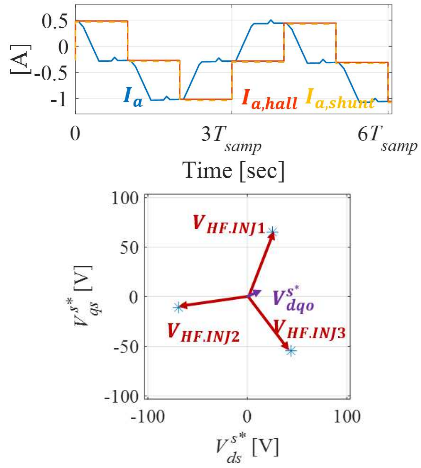
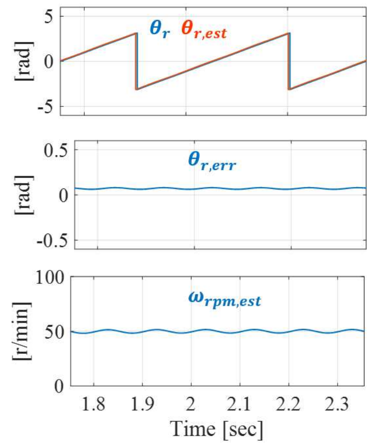


Fig. 11. Voltage vector durations of Fig. 10.

The rotating HF voltage can be placed on the dashed lines of Fig. 10, which makes the two current sensing points as close as possible. Also, the maximum offset voltage is applied in the measurement voltage region like the case of the pulsating HF voltage injection sensorless. As a result, the position estimating performance is improved as shown in Fig. 12.



(a)



(b)

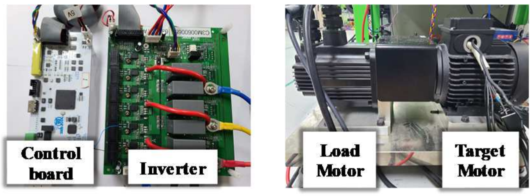
Fig. 12. Position and speed estimation performance of the proposed rotating HF voltage injection sensorless of $F_{sw}/3$. (a) phase current sensing error and injected rotating HF votlage, (b) position and speed estimation at 50r/min under rated load.

TABLE I
PARAMETERS OF MOTOR AND DRIVE SYSTEM

Symbol	Parameter	Nominal Value
PP	Pole Pair	4
V_{dc}	DC Link Voltage	$200V$
F_{SW}	Switching Frequency	$10kHz$
$I_{s,rated}$	Rated Current	6.7 A
R_s	Stator Resistance	0.9Ω
L_d	D-axis Inductance	$9.4mH$
L_q	Q-axis Inductance	$18.1mH$
λ_f	Flux Linkage	$183mV/(rad/s$

IV. EXPERIMENTAL RESULTS

To verify the proposed two methods, the experiments have been carried out. The parameters of the used IPMM and inverter system are listed in Table I, and the experimental setup is shown in Fig. 13.



(a) (b)

Fig. 13. Experimental setup (a) Inverter (b) Dynamo.

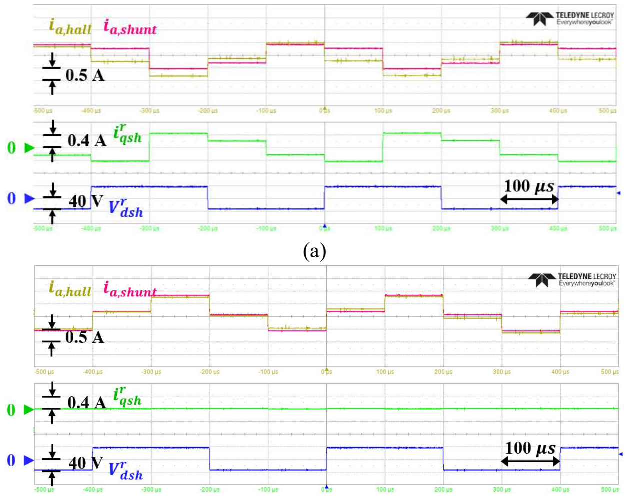


Fig. 14. Experimental results: Current sensing error, HF q-axis current, and the d-axis HF voltage in (a) the conventional pulsating HF voltage injection case and (b) porposed pulsating HF voltage injection case.

Fig. 14 shows the current sensing errors, HF q-axis current, and the d-axis HF voltage of the conventional and proposed pulsating HF voltage injection methods in SDS. Here, the HF voltage is exactly injected to the synchronous d-axis using the position information from the encoder. In Fig. 14(a), the current sensing error due to the injected HF voltage clearly exists, and it makes the q-axis HF current component occur although the HF voltage is injected exactly to the d-axis. On the other hand, the current sensing error of the proposed pulsating HF voltage injection case significantly decreases compared with the conventional one, so the q-axis HF current component becomes almost zero, which means the accurate position estimation in the HF voltage injection sensorless control.

Fig. 15 shows the steady state performance of the conventional pulsating HF voltage injection sensorelss control (a), the proposed pulsating HF voltage injection seosrless control (b), and the proposed rotating HF voltage injection sensorless control in SDS. Here, the frequency of the injected HF frequency is set to be $F_{sw}/4$ in Fig. 15(a) and (b), and $F_{sw}/3$ in Fig. 15(c). Also, the rotating speed is fixed to 50[r/min] under no load condition. In the conventional method of Fig. 15(a), the position error of 6^{th} harmonics clearly occurs due to the current reconstruction error and the voltage distortion. However, in the two cases of Fig. 15(b) and (c), the performance of the position and speed estimation is noticeably improved.

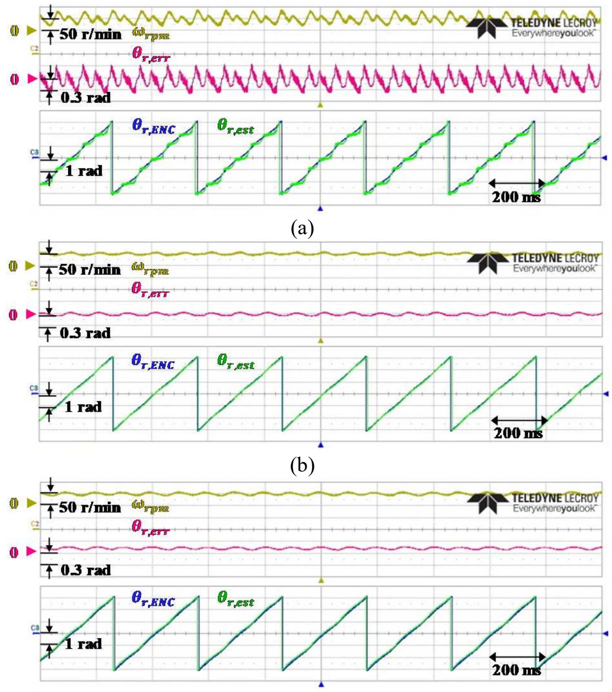


Fig. 15. Experimental results: Steady state performance (a)Conventional HF voltage injection sensorless, (b)the proposed pulsating HF voltage injection sensorless, and (c) the proposed rotating HF voltage injection sensorless in SDS.

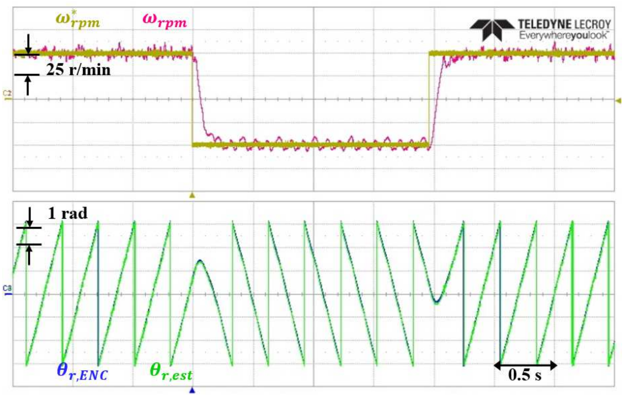


Fig. 16. Experimental results: Dynamic performance of the proposed pulsating HF voltage injection method (-50➔50 [r/min], 0.5 [p.u.] load condition)

Fig. 16 shows the dynamic performance of the proposed pulsating HF voltage injection sensorless control, where the speed control mode is applied and the speed reference is changed from 50 via -50 to 50 [r/min]. The load condition is set to 0.5[p.u.]. Regardless of the load condition and the step speed change, the proposed method maintains the enhanced angle and speed estimation performance.

V. Conclusions

This paper proposed an enhanced saliency-based sensorless control in SDS by only modifying the injection voltage to minimize the current reconstruction and voltage errors. The proposed methods can be implemented in the conventional carrier based PWM by just rearranging the original voltage, the measurement voltage, the compensation voltage, and the HF injection voltage on the measurement and compensation regions. The proposed methods do not apply the prediction concept and are independent on the motor parameters.

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