A New Circuit Design and Control to Reduce Input Harmonic Current for a Three-phase AC Machine Drive System having a very Small DC-link Capacitor

Hyunjae Yoo
Electric Power Control Part, Digital Business Division
Samsung Heavy Industries Co., Ltd.
Hwasung-City Gyeonggi-Do Korea
hyunjae.yoo@samsung.com

Seung-Ki Sul
School of Electrical Engineering & Computer Science
Seoul National University
Seoul, Korea
sulsk@plaza.snu.ac.kr

***Abstract*— This paper presents a new circuit topology to meet the input harmonic current standard for an ac machine drive system which has a very small dc-link capacitor. The proposed circuit topology is based on a harmonic current injection method, and it keeps up size and cost competitiveness of an ac machine drive system having a very small dc-link capacitor. Also, this paper proposes an appropriate control algorithm and a stability analysis for the proposed circuit topology. Experimental results reveal the validity of the proposed circuit topology and its control method. Also, it is confirmed that the harmonic current standard can be satisfied with the proposed circuit and its control method.**

I. INTRODUCTION

Recently, reducing the size of a dc-link capacitor has been key issues especially for low/medium power applications [1-6]. If the size of a dc-link capacitor in an ac machine drive system is reduced, not only the size of a capacitor itself is reduced, but also a pre-charging circuit can be saved. Moreover, an electrolytic capacitor which is less reliable than a film one because of its comparably short lifetime, can be replaced by film capacitors which generally have much longer lifetime. Thus, the reliability of an ac machine drive system can be enhanced [7-8]. Furthermore, the system having a very small dc-link capacitor contains much less input harmonic current contents than the drive system having a large one. Nevertheless, this system has a few inherent drawbacks such that the dc-link voltage may easily become unstable and it is not possible to supply enough energy during even short term input voltage interruption. Moreover, though the input harmonic currents are reduced, still the harmonics cannot meet the standards such as IEC 61000 [9-10] without adding any additional hardware.

As the dc-link voltage instability can be covered by adopting one of recent active researches, the stable operation regardless of the quite small capacitance of the dc-link can be achieved. Also, the issue related to the energy storage role during short term input voltage interruption is not always essential to every application. Applications such as a fan, a pump or a compressor, that a re-starting operation right after the input voltage interruption would not be a severe problem, may not need this energy storage role. However, the applicability of this drive system having a very small dc-link capacitor cannot be expanded if the international input harmonic current standard is not satisfied.

A lot of researches based on a harmonic current injection method have been presented in the past to reduce input harmonic current of a conventional diode rectifier-fed inverter system [11-21]. These methods have possibilities to comply with the given harmonic current standard with keeping up size and cost competitiveness of the drive system having a very small dc-link capacitor. In [19-20], new topologies using zero sequence coupling between machine and grid sides has been introduced. These topologies can greatly reduce the overall system cost as far as the neutral point of an ac machine is accessible. However, the ac machine should share the voltage for controlling the machine itself and that for controlling injection current. Therefore, the machine may not be operated at its rated speed simultaneously injecting harmonic current into the input ac side. Large size dc reactors for a harmonic current injection circuit have been replaced by smaller size ac ones in [21] to reduce the overall cost of the drive system. However, it still has a lot of passive elements in the current injection circuit as well as the dc side current smoothing purpose inductor.

This paper presents a new circuit topology to comply with the harmonic current standard with minimizing the additional hardware cost. The proposed harmonic current injection circuit consists of one switch arm, a single phase inductor and three bi-directional switches. The proposed circuit minimizes passive device which are less competitive in terms of size and cost than active one. The proposed circuit also makes it possible that the current rating of each element is reduced. In

978-1-4244-4783-1/10/$25.00 ©2010 IEEE

this paper, an appropriate control method of an injection current and a stability analysis for the proposed circuit configuration are also proposed.

II. AC Machine Drive System Having a Very Small DC-Link Capacitor

An example of ac machine drive system having a very small dc-link capacitor is shown in Fig. 1. Though the input side rectifier that is connected to the ac source can be composed of either a diode rectifier or a PWM rectifier, the former one is only taken into account in this paper. The input ac line current waveform under constant load condition can be described theoretically as shown in Fig. 2[6]. Input harmonic contents of the drive system having a very small dc-link capacitor are much less than that of the drive system having a large dc-link capacitor [6]. Nevertheless, it still cannot comply with the international harmonic current standards. Thus, additional hardware to meet the standard is necessary. There are plenty of possibilities of hardware composition such as a PWM rectifier, a VIENNA rectifier [22,23], active or passive filters [24,25], a harmonic current injection method and etc. Note here, the target harmonic current standard [9,10] does not require strict THD specification but does limit only each order of harmonic current magnitude. Hence, in this paper, a harmonic current injection method has been adopted for the drive system having a very small dc-link capacitor since it is more competitive than others in terms of size and cost.

III. Configuration of Current Injection Topology

Fig. 3 shows the basic configuration of the conventional current injection topology for a three-phase diode rectifier fed ac machine drive system. It consists of a harmonic current controller part and a current injection circuit part. Two boost converters, one series connected switch leg, a machine side zero sequence current controller and etc. can be such examples of the harmonic current controller part. A star-delta transformer with a neutral point, a zigzag auto-transformer, a resonant filter and etc. can be such examples of the injection circuit part. Fig. 4 shows a simplified block diagram of harmonic current injection topology. The desired harmonic current is synthesized by two current sources (I_h), and it is divided into 1/3 by the injection circuit part. Fig. 5 shows its harmonic current injection principle. Fig. 5(a) and 5(b) show input current waveforms for the drive system having large capacitance and that having very small capacitance respectively. Fig. 5(c) shows an injection current waveform based on the 3rd harmonic. Its optimal magnitude based on FFT analysis can be derived as (1) [11-13].

$$I_{h\_mag} = 0.74 \cdot I_{d\_mag} \tag{1}$$

Lastly, Fig. 5(d) shows a resultant input current waveform which is the summation of Fig. 5(b) and Fig. 5(c) sub-period by sub-period (1/6 period). Note that, the input current should be near square wave before a harmonic current is injected as shown in Fig. 5(b), or otherwise, an injection current should contain too much harmonic content to shape an input current into sinusoidal as expected from Fig. 5. Thus, inductors on the ac side or the dc side are necessary if the dc-link capacitance

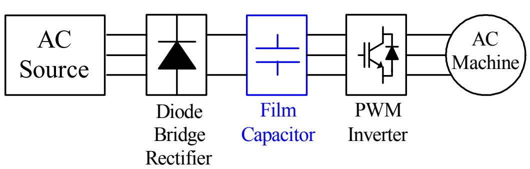


Figure 1. AC machine drive system having a very small dc-link capacitor.

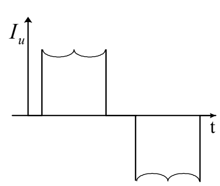


Figure 2. Input ac line current waveform.

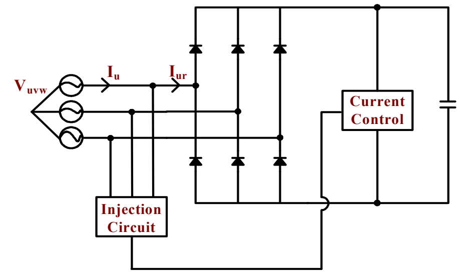


Figure 3. Basic configuration of the conventional current injection topology.

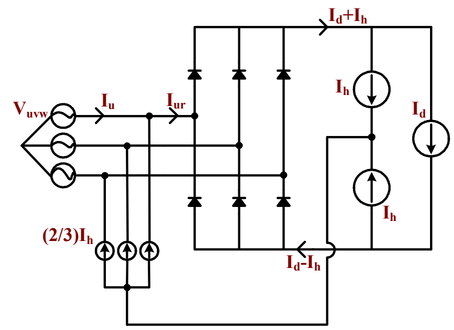


Figure 4. Simplified configuration of the current injection method.

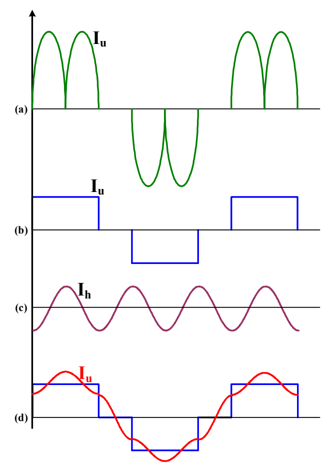


Figure 5. Current shaping principle of the conventional current injection method

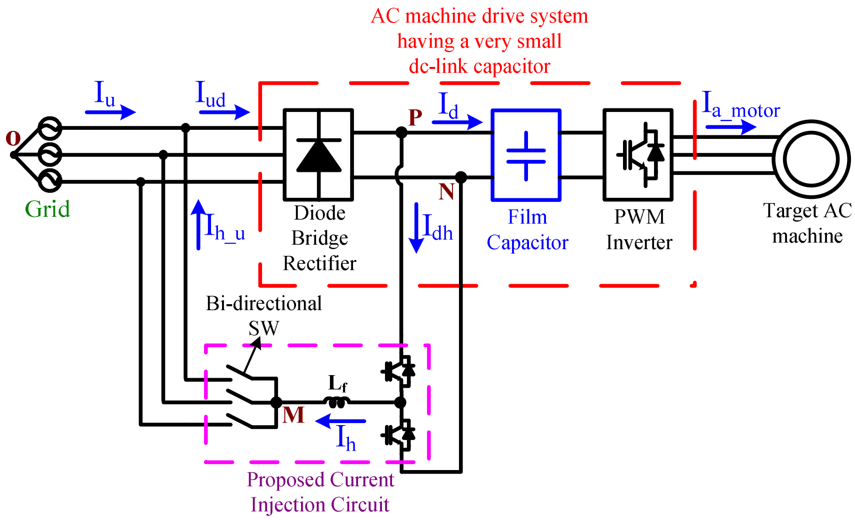


Figure 6. Configuration of the proposed harmonic current injection circuit.

is large enough to reduce a lot of low order harmonic contents preliminary. However, the input current waveform of a drive system having a very small dc-link capacitor is already near square wave as shown in Fig. 2. Therefore, an additional inductor except a current control purpose one is not necessary.

IV. Proposed Circuit and its Control Method

In order to reduce an input harmonic current, the harmonic current injection method has been adopted to keep up size and cost competitiveness. This harmonic current injection method has a large variety of circuit composition. This paper proposes a new circuit composition which optimizes size and cost but complying with the given harmonic current standard.

A. Circuit Configuration

Fig. 6 shows the configuration of the proposed harmonic current injection circuit for an ac machine drive system having a very small dc-link capacitor. Injection of a harmonic current is achieved by one switch arm and a single phase inductor, and three bi-directional switches. The proposed circuit makes it possible that the three phase input current can be shaped simultaneously with only a single phase inductor. Also, by using three bi-directional switches instead of passive elements such as an LC tuned filter, a star delta transformer and a zig-zag auto-transformer, not only the injection of the three phase input side is possible but also the magnitude of circulating current via the current injection circuit and the diode rectifier is reduced to 1/3 of that of the circuit using passive elements. Hence, the current ratings of all elements including the single phase inductor in the proposed circuit are reduced by 1/3 of the conventional one. Thus, the circuit has competitiveness in terms of size and cost over other conventional circuit based on passive elements.

B. Current Path Generation through Three bi-directional Switches

As shown in Fig. 6, three bi-directional switches are located between the three phase grid side and the single phase inductor to constitute the injection current path. Each switch is turned ON when the magnitude of input phase voltage is medium among three phases, and that is described in detail in [14-15,20].

C. Proposed Optimal Current Reference Generation

The main idea of the injection current reference generation method is the same as introduced in [18], but the proposed optimal current reference generation method is able to save both the complex calculation effort and the discrimination effort of magnitude and phase of the input voltages. The optimal injection current reference for the proposed current injection circuit can be simply obtained from

$$i_{opt\_ref} = \frac{v_{mid}}{V_p} \cdot I_p \quad (2)$$

where, i_{opt_ref} : optimal injection current reference, : input phase voltage whose magnitude is medium value among three input phase voltages, V_p : peak input voltage magnitude, I_p :peak input current magnitude. The current reference forms quasi-triangular wave and its magnitude is 1/3 of that introduced in [18] as mentioned in the previous section A.

D. Proposed Current Control Method

The injection current control can be easily achieved by a simple Proportional Integral (PI) control method. An equivalent circuit diagram of the current injection control circuit is shown in Fig 7. The controller consists of one switch arm, a single phase inductor and three bi-directional switches which directly connected to the grid side. Thus, the current controller should consider the grid side voltage change according to the switching sequence of three bi-directional switches in order to get desired control performance. In other words, the inductor current can be decided by voltage difference between the dc-link voltage and the voltage between the neutral point of three bi-directional switches and

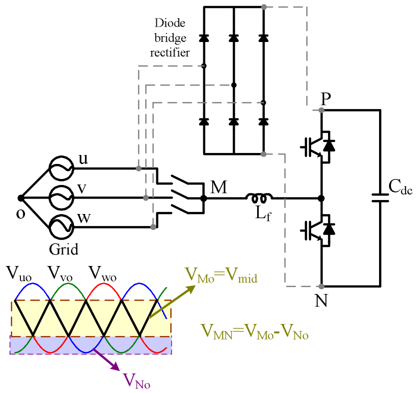


Figure 7. Voltage relation of the proposed current injection circuit.

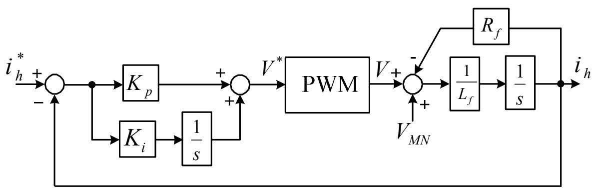


Figure 8. An injection current controller without considering voltage V_{MN}.

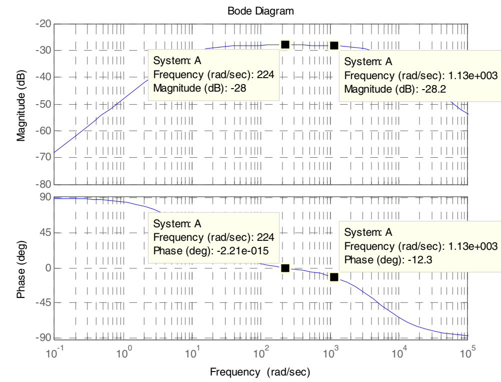


Figure 9. Bode plot of unwanted band pass filter.

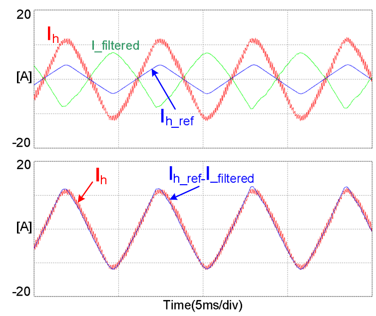


Figure 10. Simulation result of current control performance without considering voltage disturbance.

the minus point of the dc-link voltage (V_{MN}) shown in Fig. 7. A block diagram of the current control system where this voltage is not considered is shown in Fig. 8. Its mathematical representation is also given by (3). Substituting the proportional and integral gains of current controller, (4) into (3), then (5) can be derived.

$$i_h = \frac{K_p s + K_i}{s^2 L_f + (R_f + K_p)s + K_i} i_h^* - \frac{s}{s^2 L_f + (R_f + K_p)s + K_i} V_{MN} \tag{3}$$

$$K_p = L_f \omega_{cc} \qquad K_i = R_f \omega_{cc} \tag{4}$$

$$i_h = \frac{\omega_{cc}}{s + \omega_{cc}} i_h^* - \frac{s}{s^2 L_f + (R_f + L_f \omega_{cc})s + R_f \omega_{cc}} V_{MN} \tag{5}$$

The first term in (5) is desired current control dynamic, and the second term in (5) is unwanted band pass filtered dynamic resulted from the disturbance voltage (V_{MN}). A Bode plot of this unwanted filtered dynamic where cut-off frequency of the current controller (ω_{cc}) is given by $2\pi \cdot 800$ [rad/s] is shown in Fig. 9. The phase difference of the unwanted filtered dynamic where the fundamental frequency of the disturbance voltage (V_{MN}) is given by 180Hz (3rd harmonic), can be obtained from Fig. 9. Also, its magnitude can be obtained from (6). A simulation result where the disturbance voltage has not been considered is shown in Fig. 10. The actual current (I_h) cannot track its reference (I_{h_ref}) in spite of applying large controller gains (800Hz), but is almost the same as the current reference minus unwanted filtered value as analyzed above.

$$-28.2 = 20\log\frac{x}{465} \qquad I_{filtered} = 10^{(-\frac{28.2}{20} + \log 465)} \approx 18[A] \tag{6}$$

Therefore, the voltage (V_{MN}) should be considered to get rid of this unwanted filtered dynamic. Even though this voltage (V_{MN}) can be directly measured, it results in additional cost for a measurement circuit. Hence, this paper also introduces a voltage disturbance estimation method using given measured information. The disturbance voltage (V_{MN}) shown in Fig. 7 can be expressed by (7).

$$V_{MN} = V_{Mo} - V_{No} \tag{7}$$

The voltage between the neutral point of three bi-directional switches and that of the input three phase voltages can be defined by (8) because each bi-directional switch is turned ON when the magnitude of the corresponding input phase voltage is medium value. Also, the voltage between the dc-link minus point and the neutral point of the input phase voltage can be defined by (9) because of the commutation action of the three phase diode bridge rectifier.

$$V_{Mo} = V_{mid} \tag{8}$$

$$V_{No} = V_{\min} \tag{9}$$

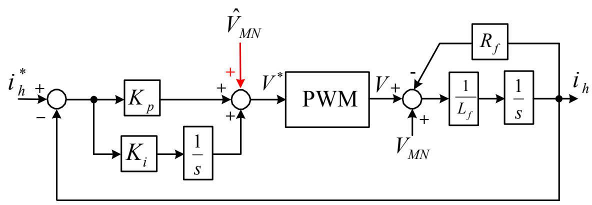


Figure 11. Block diagram of the proposed injection current control.

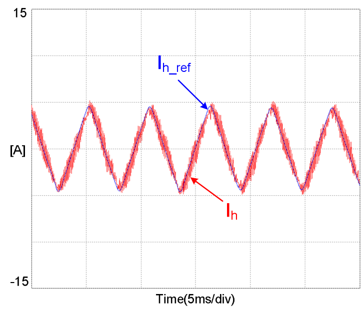


Figure 12. Proposed injection current control performance.

where V_{mid} is the input phase voltage whose magnitude is the medium value and $V_{\min}$ is the input phase voltage whose magnitude is the minimum value

Actually, these voltages cannot be defined clearly if the size of a dc-link capacitor is relatively large. In this system however, they can be defined because the size of a dc-link capacitor is very small and thus the dc-link voltage roughly follows to the maximum value among three input line-to-line voltages. As a consequence, this disturbance voltage can be estimated only by compounding input phase voltage information which is already known. A block diagram of the proposed injection current control including this input voltage disturbance rejection by feed-forward manner is shown in Fig. 11. Its simulation result is also shown in Fig. 12. The actual current tracks its reference much better than the previous case.

V. STABILITY ANALYSIS

The proposed current injection circuit and its control algorithm make it possible to reduce an input harmonic current. However, if the stability of this system cannot be guaranteed, it is very hard to apply the system into a practical system. Hence, a stability of the drive system including the proposed harmonic current injection circuit is analyzed in this section. As mentioned above, an ac machine drive system having a very small dc-link capacitor is subject to being unstable. Thus, the stability and the minimum size of the dc-link capacitance which makes the system stable have been analyzed in [26]. Fig. 13 shows an equivalent circuit diagram of a diode rectifier front ended typical ac machine drive system under a constant load condition neglecting the PWM inverter action. The load is modeled as a current source (P_{load}/v_{dc}), and L_{src}, R_{src} stand for the equivalent line impedance. Also, C_{dc} stands for the dc-link capacitance. Thus, the dynamic equation of the system is derived in (10).

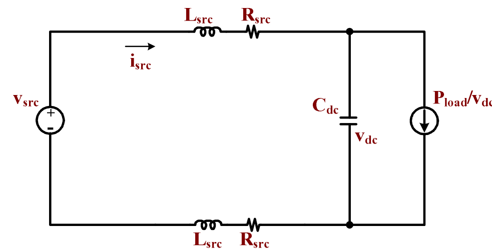


Figure 13. Equivalent circuit diagram of typical diode rectifier front ended ac machine drive system.

$$\begin{aligned} 2\cdot L_{src}\cdot\frac{di_s}{dt} &= v_{src}-2\cdot R_{src}\cdot i_{src}-v_{dc} \\ C_{dc}\cdot\frac{dv_{dc}}{dt} &= i_{src}-\frac{P_{load}}{v_{dc}} \end{aligned} \qquad (10)$$

The source current and the capacitor voltage can be expressed by (11) which contain dc and ac components respectively.

$$\begin{aligned} i_{src} &= \bar{i}_{src}+\tilde{i}_{src} \\ v_{dc} &= \bar{V}_{dc}+\tilde{v}_{dc} \end{aligned} \qquad (11)$$

where $\bar{i}_{src}$ and $\bar{V}_{dc}$ are mean values of the source current and the dc-link voltage respectively, $\tilde{i}_{src}$ and $\tilde{v}_{dc}$ are the source current and the dc-link voltage variations respectively. If the dc-link voltage variation term is relatively small enough, the load current (P_{load}/v_{dc}) can be linearized at the operating point as derived in (12).

$$\begin{cases} L\cdot\dfrac{d\tilde{i}_{src}}{dt} = -R\cdot\tilde{i}_{src}-\tilde{v}_{dc} \\ C_{dc}\dfrac{d\tilde{v}_{dc}}{dt} = \tilde{i}_{src}+\dfrac{P_{load}}{\bar{V}_{dc}^{\,2}}\cdot\tilde{v}_{dc} \end{cases} \qquad (12)$$

Then, the resultant characteristic equation is given by (13)

$$P(s)=s^2+\left(\frac{R}{L}-\frac{P_{load}}{C_{dc}\bar{V}_{dc}^{\,2}}\right)s+\left(\frac{\bar{V}_{dc}^{\,2}-RP_{load}}{LC_{dc}\bar{V}_{dc}^{\,2}}\right)=0 \qquad (13)$$

where, $R=2\cdot R_{src}$, $L=2\cdot L_{src}$.

Consequently, if the dc-link capacitance value satisfies the condition (14), the system is remained in stable operation area [26].

$$C_{dc}>\frac{L\cdot P_{load}}{R\cdot\bar{V}_{dc}^{\,2}} \qquad (14)$$

The stability of the proposed drive system including harmonic current injection circuit can be analyzed with the same criterion. Its equivalent circuit diagram is shown in Fig. 14, and also its dynamic equation is given by (15).

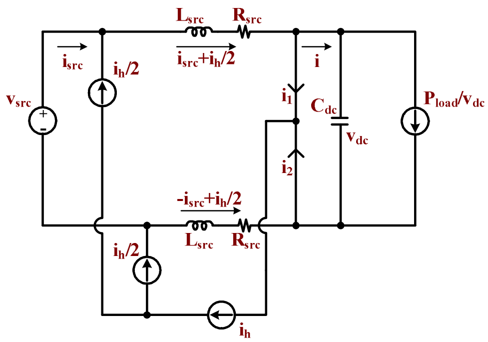


Figure 14. Equivalent circuit diagram of typical diode rectifier front ended ac machine drive system including proposed current injection circuit.

$$L_{src}\frac{d(i_{src}+i_h/2+i_{src}-i_h/2)}{dt}=v_{src}-R_{src}(i_{src}+i_h/2+i_{src}-i_h/2)-v_{dc}$$

$$2L_{src}\frac{di_{src}}{dt}=v_{src}-2R_{src}i_{src}-v_{dc}$$

$$C_{dc}\cdot\frac{dv_{dc}}{dt}=i-P_{load}/v_{dc} \tag{15}$$

where i_h is an injection current, and i is a dc-link current. If the injection current i_h satisfies (16), then the characteristic equation of the drive system including the harmonic current injection circuit becomes the same as (13).

$$i_1+i_2=i_h \tag{16}$$

As a result, if the original drive system having a very small dc-link capacitor satisfies the condition (14) and the harmonic current controller also satisfies (16), the overall drive system is stable.

VI. Experimental Results

An experimental setup for the proposed current injection circuit is shown in Fig. 15. It includes an ac machine drive system having a very small dc-link capacitor, bi-directional switches, a single phase inductor, one switch arm and its drive circuit, a target ac machine and a control board. Several core parameters of the experimental setup are listed in Table I.

Fig. 16 shows an experimental result of the drive system having a very small dc-link capacitor without applying the harmonic current injection where the target machine has been operated at its rated speed yielding 83% of its rated power. It shows the input current, the dc-link voltage, the injection current reference, the injection current, the dc side current, the switch arm current and the machine current waveforms respectively. Abbreviation of each waveform is represented in Fig. 6. The input ac current (I_u) forms quasi-square wave as expected in Fig. 2 which still contains a lot of low order harmonic components. The dc-link voltage (V_{dc}) follows to the maximum value of three-phase line-to-line voltage. The injected harmonic current (I_h) is zero in this case.

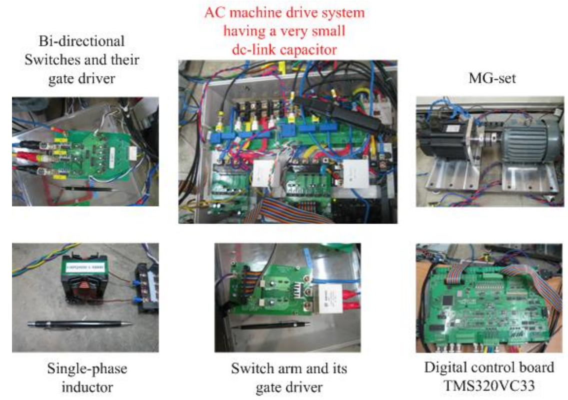


Figure 15. Experimental setup.

TABLE I
System Parameters

Input voltage	380Vrms
DC-link capacitance	6.6μF
Machine's rating	3.7kW
Bi-directional switches	50A, 1200V
One switch arm	50A, 1200V
Single phase inductor	5mH, 7Arms

The dc-link current (I_d) contains a dc-link voltage ripple component as well as mean dc value since the system is operating under the constant load condition. Also, the switch arm current (I_{dh}) is zero in this case. Lastly, the machine current forms sinusoidal at its rated operating frequency.

Fig. 17 shows the same waveforms where the proposed harmonic current injection has been applied. The injection current reference is obtained from (2) which forms quasi-triangular wave. The input ac current (I_u) forms almost sinusoidal wave due to the proposed harmonic current injection (I_h). The switch arm current (I_{dh}) contains an injected harmonic current component in this case. Lastly, the machine current is not affected by the proposed harmonic current injection method but controlled independently. Consequently, the harmonic contents of the input ac current (I_u) has been reduced considerably without affecting the performance of the machine control.

Fig. 18 shows that the frequency spectrum analysis results (FFT) of all harmonic currents of the above two cases. The results have been compared with the target harmonic current standard (IEC 61000-3-2). Fig. 18(a) shows the result for the case without harmonic current injection.

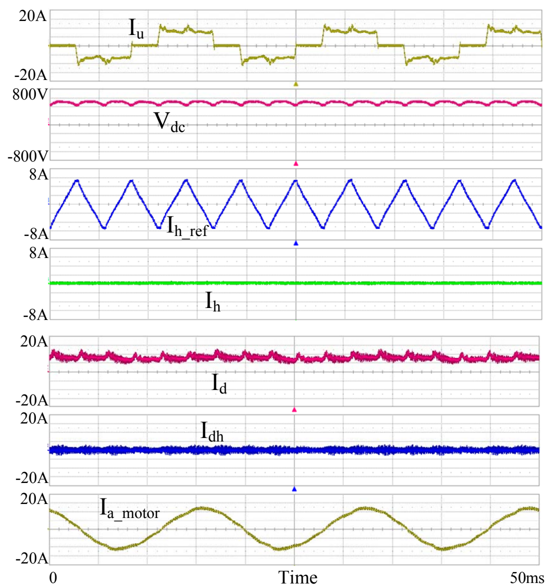


Figure 16. Experimental result for an ac machine drive system having a very small dc-link capacitor.

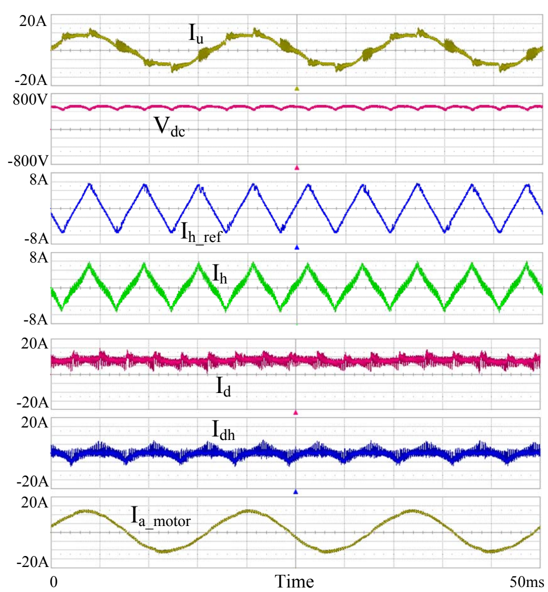


Figure 17. Experimental result for the proposed harmonic current injection circuit.

Almost all harmonic current orders are not satisfied with the standard. However, as shown in Fig. 18(b), all harmonic current orders of the input ac current have been suppressed conspicuously. Also, it is confirmed that the given harmonic current standard is satisfied by the proposed harmonic current injection method.

Fig. 19 and Fig. 20 are experimental results to verify the validation of the stability analysis. The harmonic current injection has been started at 0.2s abruptly while the drive system having a very small dc-link capacitor is operating at its 75% of the rated power as shown in Fig. 19. The dc-link voltage and the machine current are stable both before and after the injection even under abrupt harmonic current

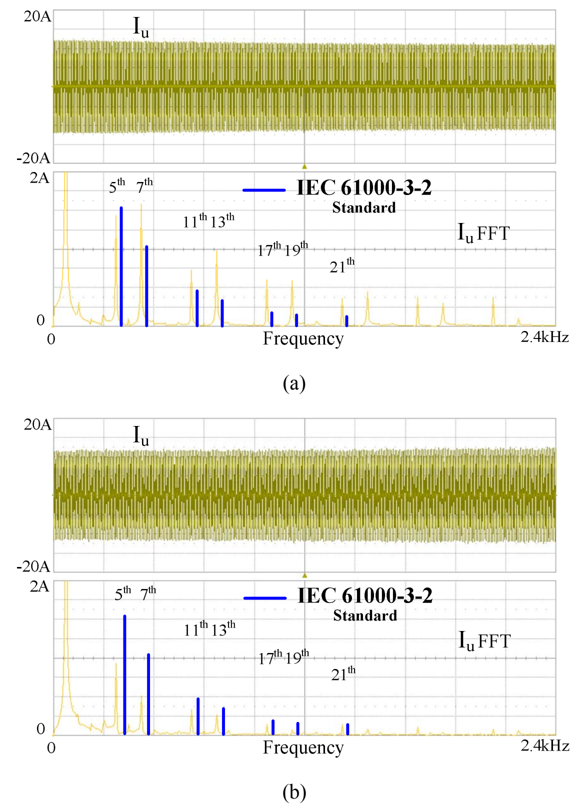


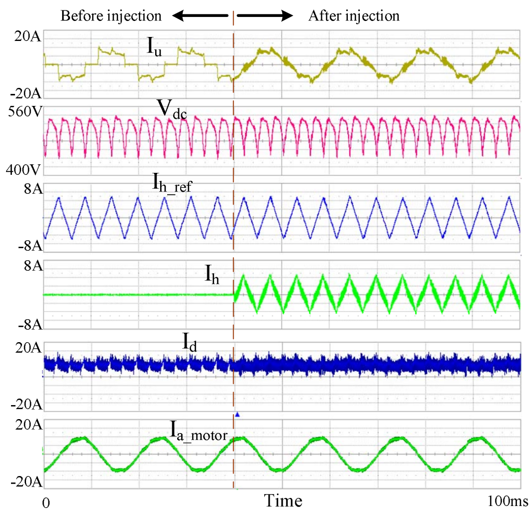
Figure 18. Frequency spectrum results for the input line current: (a) without harmonic current injection; (b) with proposed harmonic current injection.

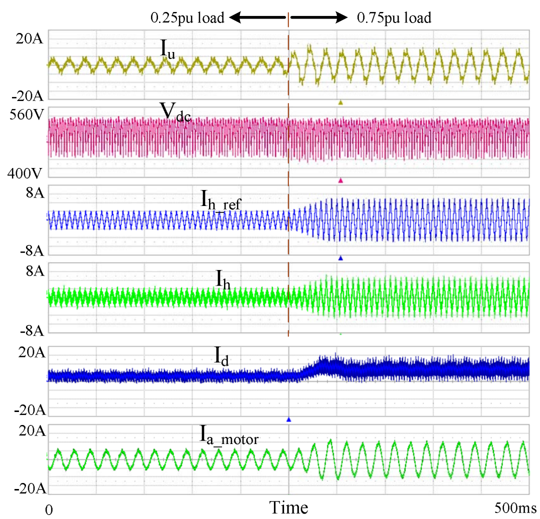
injection because the dc-link capacitor has been designed based on (14) and the harmonic current control system satisfies (16). Fig. 20 shows another experimental result for the case that the load has been abruptly changed while the harmonic current is injecting. The system is also stable both before and after the abrupt load variation. Therefore, it is verified that the stability analysis in the previous section is valid.

VII. CONCLUSION

In this paper, a new circuit topology to reduce an input harmonic current of a three-phase ac machine drive system having a very small dc-link capacitor, has been proposed based on a harmonic current injection method. In order to minimize the additional cost and size of this harmonic current injection circuit, the proposed harmonic current injection circuit minimizes the size and the number of passive elements. Thus only a single phase inductor as a passive element has been used. Moreover, the current rating of the proposed injection circuit is 1/3 of that of the conventional current injection topologies. This also minimized the additional cost considerably.

This paper also presents an appropriate current control method for the proposed current injection circuit considering the voltage disturbance due to the switching of the bi-directional switches. Lastly, the stability of ac machine drive system including the proposed current injection circuit has been analyzed. By experimental results and their frequency analyses, it is confirmed that not only the harmonic current





standard can be satisfied with the proposed harmonic current injection circuit and its control method, but also the stability analysis of the proposed drive system is valid.

REFERENCES

[1] B. K. Bose, D. Kastha, "Electrolytic capacitor elimination in power electronics system by high frequency active filter," in Conf. Rec. of 1991 IEEE IAS Annual Meeting, vol. 1, 1991.

[2] J. S. Kim, S. K. Sul, "New control scheme for AC-DC-AC converter without DC link electrolytic capacitor," in Proc. IEEE PESC 93, pp.300-306, 1993.

[3] M. Hinkkanen and J. Luomi, "Induction motor drives equipped with diode rectifier and small dc-link capacitance," IEEE Trans. Ind. Electron., vol. 55, no. 1, pp. 312-320, Jan. , 2008.

[4] K. Oietilainen, L. Harnefors, A. Petersson, et al., "DC-link stabilization and voltage sag ride-through of inverter drives," IEEE Trans. Ind. Electron., vol. 53, no. 4, pp. 1261-1268, Aug. 2006.

[5] Bon-Gwan Gu, Kwanghee Nam, "A DC-link capacitor minimization method through direct capacitor current control," IEEE Trans. on Industry Applications, vol.42, no. 2, pp. 573-581, March/April, 2006

[6] H. Yoo, S. Sul, H. Jang and Y. Hong, "Design of a variable speed compressor drive system for air-conditioner without electrolytic capacitor," IEEE 42nd IAS Annual meeting, pp. 305-310, Sep., 2007.

[7] Afroz M. Imam, "Condition Monitoring of Electrolytic Capacitors for Power Electronics Applications," Georgia Institute of Technology, Ph. D. Dissertation, 2007.

[8] Siyoung Kim, Seung-Ki Sul and T. A. Lipo, "AC/AC Power Conversion Based on Matrix Converter Topology with Unidirectional Switch," IEEE Trans. on Industry Applications, vol. 36, no. 1, pp. 139-145, Jan./Feb., 2000.

[9] IEC 61000-3-2 : 2005.11.

[10] IEC 61000-3-12 : 2004-11.

[11] N. Mohan, M. Rastogi, and R. Naik, "Analysis of a new power electronics interface with approximately sinusoidal 3-phase utility currents and a regulated dc output," IEEE Trans. on Power Delivery, pp. 540-546, Apr. 1993.

[12] N. Mohan, "A novel approach to minimize line-current harmonics in interfacing power electronics equipment with 3-phase utility systems," IEEE Trans. on Power Delivery, pp. 1395-1401, Jul. 1993.

[13] R. Naik, M. Rastogi, and N. Mohan, "Third-harmonic modulated power electronics interface with three-phase utility to provide a regulated DC output and to minimize line-current harmonics," IEEE Trans. on Industry Applications., vol. 31, pp. 598-602, May/June 1995.

[14] P. Pejovic, "A novel low-harmonic three-phase rectifier," IEEE Trans. on Circuits and Systems, vol. 49, pp. 955-965, July 2002.

[15] J. C. Salmon, "Operating a three-phase diode rectifier with a low-input current distortion using a series-connected dual boost converter" IEEE Trans. on Power Electronics, vol. 11, no. 4., pp. 592-603, July 1996.

[16] P. Pejovic and Z. Janda, "An Analysis of Three-Phase Low-Harmonic Rectifiers Applying the Third-Harmonic Current Injection," IEEE Trans. on Power Electronics, vol. 14, no. 3, pp. 397-407, May 1999.

[17] S. Kim, P. N. Enjeti, and P. Packebush, "A new approach to improve power-factor and reduce harmonic in a three-phase diode rectifier type utility interface," IEEE Trans. on Industry Applications, vol. 30, no. 6, pp. 1557-1564, Nov./Dec. 1995.

[18] P. Pejovic and Z. Janda, "Optimal Current Programming in Three-Phase High-Power Factor Rectifier based on two Boost Converters," IEEE Trans. on Power Electronics, vol. 13, no. 6, pp. 1152-1163, Nov. 1998.

[19] N. R. Raju, "A low-harmonic diode rectifier-fed drive using zero-sequence coupling between machine and grid," IEEE 42nd IAS Annual meeting, pp. 1582-1584, Sep., 2007.

[20] H. Yoo and S. Sul, "A novel approach to reduce line harmonic current for a three-phase diode rectifier-fed electrolytic capacitor-less inverter," IEEE APEC, 2009.

[21] J. Itoh and I. Ashida, "A novel three-phase PFC rectifier using a harmonic current injection method," IEEE Trans. on Power Electronics, vol. 23, no. 2., pp. 715-722, Mar. 2008.

[22] J. W. Kolar and F. C. Zach, "A Novel Three-Phase Utility Interface Minimizing Line current Harmonics of High-Power Telecommunications Rectifier Modules," IEEE Trans. on Industrial Electronics, vol. 44, no. 4, pp. 456-467, Aug. 1997.

[23] C. Qiao and K. M. Smedley, "Three-phase unity-power-factor star-connected switch(VIENNA) rectifier with unified constant-frequency integration control," IEEE Trans. on Power Electronics, vol. 18, no. 4, pp. 952-957, July 2003.

[24] R. P. Stratford, "Rectifier harmonics in power systems," IEEE Trans. on Industry Applications, vol. 1A-16, no. 2, pp. 271-276, Mar./Apr. 1980.

[25] F. Z. Peng, H. Akagi, and A. Nabae, "A new approach to harmonic compensation in power systems-A combined system of shunt passive and series active filters," " IEEE Trans. on Industry Applications, vol. 26. pp. 983-990, 1990.

[26] W. Lee and S. Sul, "DC-link voltage stabilization for reduced dc-link capacitor inverter," IEEE conf. ECCE 09, pp. 1740-1744, Sep. 2009.