Implementation of Digital Adaptive Hysteresis Current Control Technique

A. Faruk BAKAN, A. Talha DUDAK

Yildiz Technical University, Istanbul, Turkey
fbakan@yildiz.edu.tr, talhad@yildiz.edu.tr

Abstract

Current control performance and stability are very important in motor drive, UPS, active filter and PV inverter applications. Designing a current controller is a time consuming work. Control analysis is required to ensure stable operation and to improve dynamic response. However, such detailed analysis is not needed in the hysteresis current control method. The hysteresis method is an analog-based simple method. This method has a high dynamic response and very good stability compared to other current control methods. However, the method is not widely used because of the variable switching frequency. Variable switching frequency causes difficulty in filter design and EMI problems in some applications. In this study, the problems encountered in hysteresis current control are investigated and a method is presented to solve these problems. The effects of the parameters used in band calculation are simulated in detail. With the developed digital current control method constant frequency is maintained.

Keywords: Hysteresis current control, power electronics, fixed frequency

1. Introduction

Closed loop current control is implemented in power electronics applications requiring fast dynamic response. The dynamic response of linear controllers is generally low. In practice increasing controller gains, especially proportional term is not possible due to noise, sensor delay, switching ripple and dead time. This limits the dynamic response of the system. Engineers working on the control of power electronic systems spend a significant time on designing these controllers, but dynamic response times can not be achieved at the desired levels. Linear controller design is generally done in frequency domain, the system is considered linear and nonlinear effects are ignored. This design procedure does not give optimum results. It is also possible to control power electronic systems with nonlinear controllers. In this case the design process is even more difficult.

The hysteresis current control method is a nonlinear current control method. This method is preferred because of its fast dynamic response and ease of implementation. In the basic hysteresis control a constant hysteresis band is used and the switching decision is made depending on the comparison of the current error. It is quite easy to implement hysteresis current control with analog circuits. Due to variable switching frequency, this method is not widely preferred in power electronics applications.

**This study has been supported with the project number 115E951 by TÜBİTAK.*

In case of digital implementation, the load of the microcontroller increases due to the very frequent demand for ADC conversion and comparison. Also, measurement problems may occur due to noise problems.

There are many studies in the literature about hysteresis control. In [1] and [2] the average switching voltage value is used for adjustable band hysteresis control. It is assumed that the back-emf value of the load is approximately equal to the average voltage value in a switching and this voltage value is obtained using the DSP's timer unit. The frequency is kept approximately constant.

In [3], a method is proposed based on the dead-beat principle to obtain constant frequency. In order to maintain frequency constant, band is changed at every switching. However, the experimental results show that the frequency can not be kept constant.

In [4], a new control method is used to set the upper and lower bandwidths by using the zero transition time of the previous current error. Implementation of the method has been done with FPGA. The method gives the upper and lower bands calculated by the sign of the slope of the absolute current error to the state machine and then the switching signals are generated by means of a logic circuit. The switching frequency is not kept constant at transient conditions. A quite complex hardware is required in [5]. The method is parameter dependent. The calculation is done by means of an analog circuit. The use of large number of components increases cost, makes it difficult to implement, and reduces reliability. In [6], a new method is been developed, which is synchronized with a clock signal and has a fixed frequency. The method was developed for three-phase systems and applied to the motor control.

In [7], the system is started with an initial band. After the switching period is completed, the period is measured and the new band is updated using the old band value and the old switching period and the reference period. The band is constantly updated to keep the switching frequency constant. But the method in the transient state and fast changing current references is not satisfactory. It is assumed that the system will find the correct value after a switching. However, this condition does not occur under certain conditions and it may take a long time to find the correct band. In [8], a simple, self-adjusting analog estimation of the hysteresis band is added to the PLL control to obtain the fixed switching frequency. This was done using both feedback and feedforward control methods. There is a self-tuning feature against parameter changes.

In [9]-[11], the band is adjusted by PLL control in the hysteresis current control method developed for three-phase systems.

In [12], a hysteresis current controller developed for a three-phase VSI is presented. It measures only two phase currents. To reduce the switching frequency, the derivative of the current error and the voltage vectors are used. The methods proposed in [13]-[16] are dependent on parameters.

In [17], an analytical approach is proposed for hysteresis current control. The programmed ramp comparator was used to keep the switching frequency constant. The advantage of the proposed controller is the prior knowledge of the appropriate amplitude and slope of the carrier waveform. There is no need proportional-integral (PI) controller and hysteresis delimiter in feedback. System parameters are used for these operations. The switching frequency is not kept constant. In [18], it was aimed to select the appropriate switching frequency of the hysteresis band. Sampling time is kept long so that high switching frequency is avoided. But the current control quality is low and switching frequency is variable. In [19], it is desired to obtain a fixed frequency operation using predictive current control (PCC).

In this study, a digital hysteresis current control method is developed for power electronics converters. The basic idea of the method is based on the basic hysteresis technique and capable of operating at a fixed frequency. By changing the band, the frequency is kept constant. The hysteresis band was controlled adaptively by measuring the switching frequency. In the study, the parameters affecting the system were examined and a solution is proposed. The proposed method improves the current control performance in power electronics applications and seems to be a good alternative to the fixed frequency PWM methods.

2. Adaptive Hysteresis Current Control Method

In the hysteresis control method, by switching upper and lower switches inductance current i_L is followed the reference. In Fig.1, the basic circuit diagram of the method is shown in a grid inverter. A grid inverter that transfer energy to the grid, the current waveform is sinusoidal in the same phase with the grid voltage. In the basic hysteresis current control method with constant band, the switching frequency varies. The frequency variation is related to the mains voltage, dc bus voltage and inductance values. Besides, dead time also effects switching frequency. The problem of the variable switching frequency is shown in Fig. 2. Simulation is realized with PSIM program with the following paramaters given in Table 1.

Table 1. Simulation parameters

Sampling time	delt	200 ns
Reference current	Iref	$100.\sin(2\pi 50t)$ A
Dc bus voltage	VdcP = VdcN	400 V
Hysteresis band	DI	100 A
Resistance	rL	5 mohm
Inductance	L	300 uH
Mains voltage	vS	$311.\sin(2\pi 50t)$ V

The switching frequency for a fixed hysteresis band is variable, and it changes between 1100-3400 Hz. The reason of the large frequency variation is the rise and fall times of the current in each switching period.

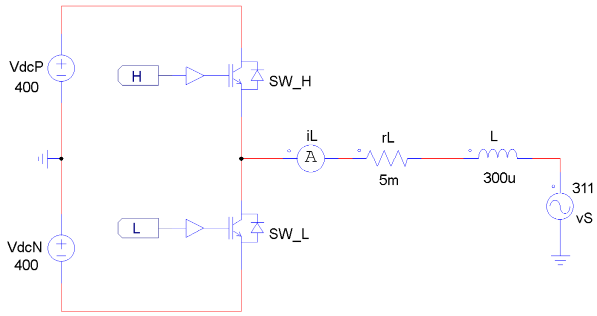

Fig. 1. Two-level single-phase voltage source inverter.

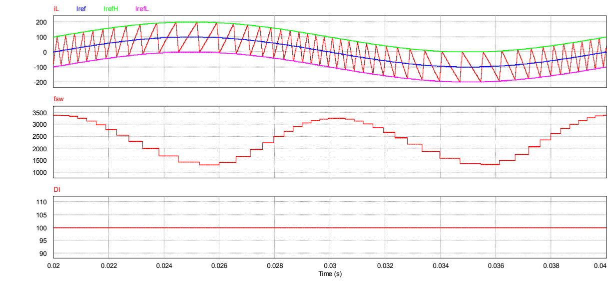

Fig. 2. The variable switching frequency problem in fixed band in hysteresis current control method.

In order to obtain constant switching frequency in hysteresis control the band is varied. In Fig. 3, definitions for constant frequency hysteresis current control is shown. Using these definitions, the value of the band that provides the constant switching frequency is obtained mathematically.

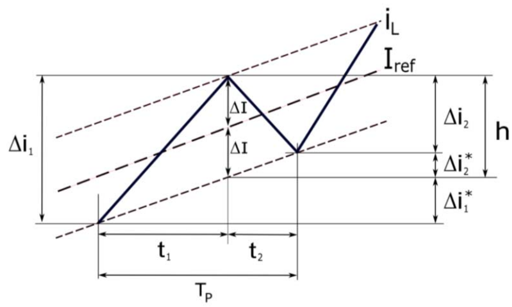

Fig. 3. Definitions for constant frequency hysteresis current control.

The definitions used in the calculation of the band are given below.

T_p : switching period
t_1 : upper switch conduction duration
t_2 : lower switch conduction duration
Δi_1 : increment of the inductance current during t_1
Δi_2 : decrement of the inductance current during t_2
$\frac{di^*}{dt}$: derivative of the current reference
Δi_1^*: increment of the current reference during t_1
Δi_2^* : decrement of the current during t_2
ΔI : hysteresis band
h : ripple in the inductance current
m_1 : slope of the inductance current during t_1

m_2 : absolute value of the slope of the inductance current during t_2

m_{ref} : slope of the current reference

To find a h value for a fixed period $T_p = t_1 + t_2$, t_1 and t_2 can be written in terms of m_1, m_2 and m_{ref} . The amount of increase in inductance current during t_1

$$\Delta i_1 = h + \Delta i_1^* \tag{1}$$

$$\Delta i_1 = \frac{di_L}{dt} t_1 = m_1 t_1 \tag{2}$$

$$m_1 = \frac{V_L(t_1)}{L} = \frac{V_{dcP} - V_s}{L} \tag{3}$$

is obtained. The amount of increase in current reference during t_1

$$\Delta i_1^* = \frac{di^*}{dt} t_1 = m_{ref} t_1 \tag{4}$$

is found. Using (1) and (4), the following equations are obtained.

$$m_1 t_1 = h + m_{ref} t_1 \tag{5}$$

$$t_1 = \frac{h}{m_1 - m_{ref}} \tag{6}$$

A similar way is followed for obtaining t_2.

$$h = \Delta i_2 + \Delta i_2^* \tag{7}$$

$$\Delta i_2 = \frac{di_L}{dt} t_2 = m_2 t_2 \tag{8}$$

$$m_2 = -\frac{V_L(t_2)}{L} = \frac{V_{dcN} + V_s}{L} \tag{9}$$

is obtained. The amount of increase in current reference during t_2

$$\Delta i_2^* = \frac{di^*}{dt} t_2 = m_{ref} t_2 \tag{10}$$

using (7), (8) and (10)

$$h = m_2 t_2 + m_{ref} t_2 \tag{11}$$

$$t_2 = \frac{h}{m_2 + m_{ref}} \tag{12}$$

is obtained. Using (6) and (12), the period is calculated.

$$T_p = t_1 + t_2 \tag{13}$$

$$T_p = \frac{h}{m_1 - m_{ref}} + \frac{h}{m_2 - m_{ref}} \tag{14}$$

hysteresis band for fixed period

$$h = \frac{T_p \cdot (m_2 + m_{ref}) \cdot (m_1 - m_{ref})}{m_1 + m_2}, DI = \frac{h}{2} \tag{15}$$

are obtained. To test the method, the circuit shown in Fig. 4 is simulated in the PSIM. Two comparators and one RS flip flop are used in the control circuit. The inductance current rises when the positive switch of the inverter leg is in conduction. When the inductance current exceeds the IrefH value, the output of the comparator connected to the RESET pin of the RS flip-flop is logic 1. In this case, PWM becomes logic 0 and the current begins to fall. When the inductance current falls below the IrefL value, the output of the comparator connected to the SET pin of the RS flip-flop becomes logic 1. In this case, PWM becomes logic 1 and the current starts to increase. The implementation of the analog hysteresis method with two comparators and one RS flip flop is a classical method that has been applied for many years. For last years this analog-based control is built entirely within the DSPs. Today, most of the DSPs include comparators, DACs and flip flops. The DI band is calculated by the DSP at each Ts and IrefH and IrefL are found using Iref and DI, and these values are applied to the comparator inputs by loading into the DACs. The next operation is accomplished by means of the hardware. The load of the DSP is only the DI band calculation. The calculation time (Ts) can be selected from 10-100us. Thus, the method does not create a processing load on the DSP. Simulations have been carried out with the hysteresis band given in equation (15) for the fixed frequency. The results are given in Fig. 4. It is aimed that the current at the output of the inverter follow a sinusoidal reference. In the proposed method, the DI hysteresis band is changed to keep the switching frequency constant.

In Fig. 4, the parameters given in Table 1 is used. Only DI band is calculated at every T_s sampling period, IrefH and IrefL values are loaded to the DACs.

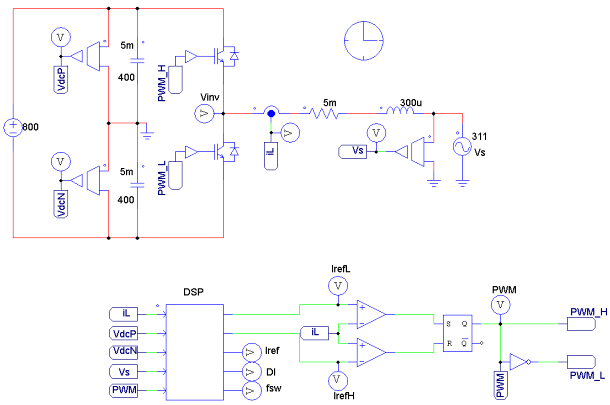

Fig.4. Fixed frequency hysteresis method in a grid inverter.

3. Simulation Results

Simulations are made in for 3 kHz switching frequency which can be considered to be low for power electronics applications. As power and voltage increase in power electronic applications, the need for reducing the switching frequency occurs. It is more difficult to control at low switching frequency. It is predicted that the hysteresis control method will be more attractive especially in low frequency and high power applications.

The simulations are implemented to investigate the sampling time, dc bus voltage, inductance parameter and dead time effects. As shown in Fig. 5, the switching frequency can be kept constant to a large extent by the proposed method. The frequency is kept constant by changing the hysteresis band for a period. The hysteresis band was updated every 1us. This is a quick update. In this case the calculation and updating of the band will take a significant time of the processor. It is assumed that all parameters are known and measured correctly. If the parameters are not correct, the frequency can not be kept constant at the desired value. Ts = 1us is nearly equivalent to an analog system.

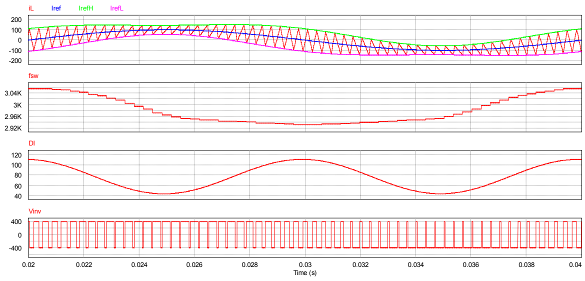

Fig. 5. In the new method, the frequency is fixed by changing the band (Ts=1us)

Simulations are repeated with Ts = 20us to reduce the processor load. It is seen that the results in Fig. 6 are similar to Ts = 1us. It is concluded that selecting too small sampling period is not required. fsw_ref fluctuates in a very small range around 3 kHz. In practice, it can be predicted that differences will occur due to dead time, errors in parameter values, etc. In Fig. 7, there is no significant change in the switching frequency when Ts period is 200us. Therefore, this method can be easily performed with DSP using large Ts durations. By selecting a Ts that corresponds to the change rate of the reference current, the optimum value can be obtained in terms of calculation load and accuracy.

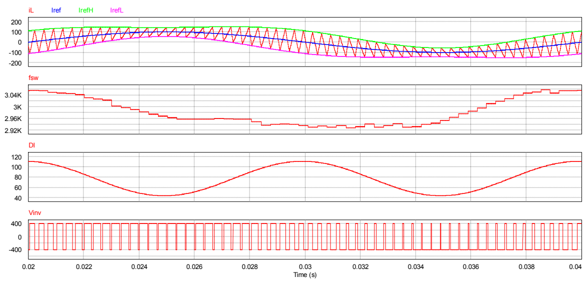

Fig. 6. Simulation results for Ts=20us

In Fig. 8, the effects of voltage ripple on VdcP and VdcN are simulated. The amount of dc bus voltage ripple can be seen from inverter output voltage. In the calculation of the hysteresis band, VdcP, VdcN and the rate of change of the current reference are added to the calculator. It is appeared that when the voltages are taken into account, there is no significant error in the switching frequency. In Fig. 9, the simulations are given for the voltage ripple of VdcP and VdcN are not taken into account. It is seen that large variations occur in the frequency.

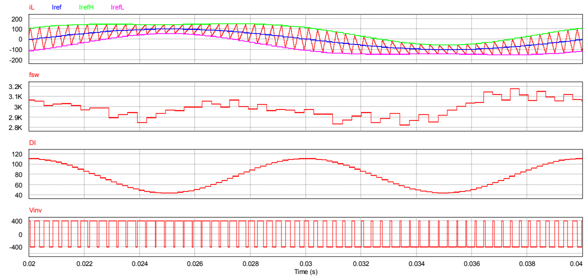

Fig. 7. Simulation results for Ts= 200us.

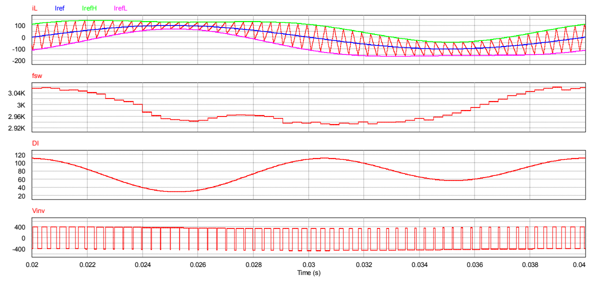

Fig. 8. The waveforms for VdcP and VdcN are not constant.

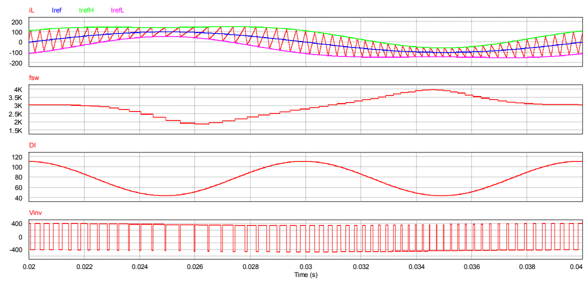

Fig. 9. The waveforms for VdcP and VdcN are not constant but in the calculation VdcP=VdcN=Vdc/2 is used.

The switching frequency varies depending on the internal resistance of the inductance. In Fig. 10 it is shown that if the rL value increases the operating frequency is below the targeted switching frequency. The value chosen in simulation is quite higher than the practical value. It can be assumed that there will not be such a high resistance value in practice. Due to overheating of the inductance over time, the resistance value may increase and affect the frequency. In Fig. 11, it is shown that the frequency fluctuation increases when the derivative of the current reference is not used. This becomes particularly important when the rate of change of the reference current is high. If the parameter mref is not used in calculations, especially at high fundamental frequencies such as 400Hz applications and nonlinear loads, a large error in switching frequency may occur.

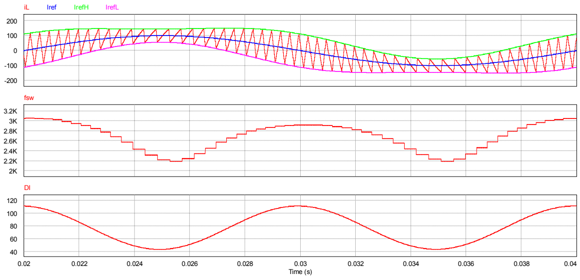

Fig. 10. Simulation results with rL = 250 mohms

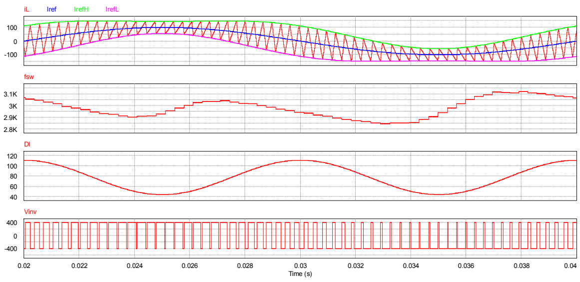

Fig. 11. The waveforms for mref is taken zero in calculations.

If the wrong value of the inductance is used in calculations frequency is not correct. This case is shown in Fig.12 and Fig.13.

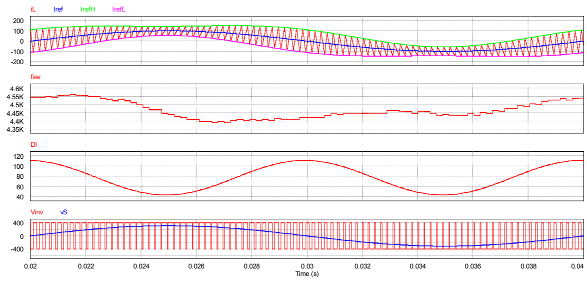

Fig. 12. The waveforms for L=200uH (wrong value is used in calculation).

In Fig. 14, simulations are given for high switching frequency reference. It is seen that there is a fluctuation on the switching frequency. When the calculated band is applied, the switching frequency is slightly lower than the reference value.

Another issue that needs to be examined is the dead time effect. In practice, it is required to use a dead time between the drive signals of the switches in the inverter phase leg. Due to the dead time, there is a considerable change in the switching frequency. When the current is around zero, the switching frequency remains around the reference value. In other regions, the frequency is lower than the reference value. Dead time is seen to be more effective at high switching frequencies. In Fig. 15, the results are shown for 20 kHz switching frequency.

In the regions where the current reference is maximum and minimum due to the dead time, the inductance current exceeds the band. The current falls below the lower band in the positive alternance. On the negative alternance, it is out of the upper band. Since the sum of the fall and rise times gives the switching period, the overflows in these durations lead to a decrease in the switching frequency. In Fig. 16, this situation is shown.

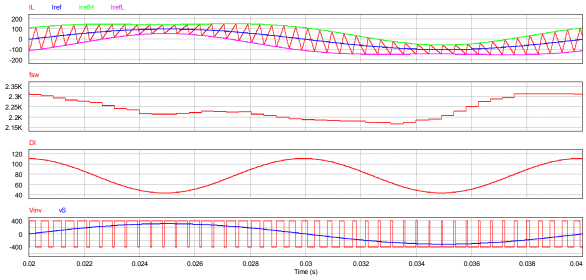

Fig. 13. The waveforms for L=400uH (wrong value is used in calculation).

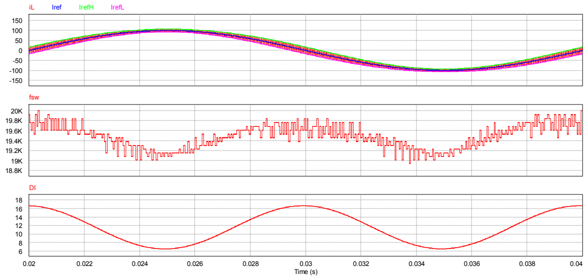

Fig. 14. The waveforms for fsw_ref=20kHz

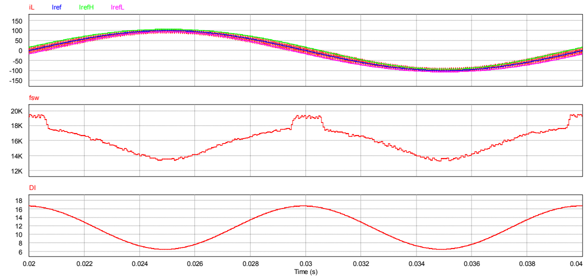

Fig. 15. The waveforms for dead time = 2us.

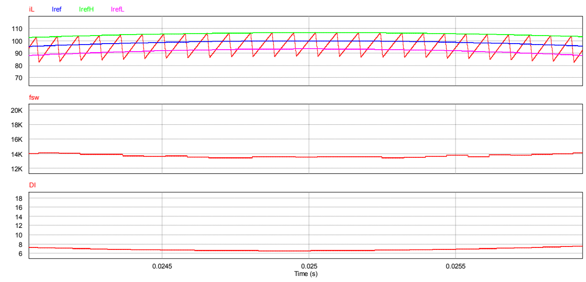

Fig. 16. The zoomed waveforms for dead time = 2us.

As can be seen, there are many factors that lead to the variation of the switching frequency in the constant frequency hysteresis method. These effects need to be eliminated in order to keep the frequency constant. Some work have been done in the literature to eliminate these effects. A simple method given in the literature [6] corrects the band in every switching period. The method tries to keep the switching frequency constant without using a mathematical equation. Therefore, it does not have parameter dependency. The new band value is updated according to the previous switching period to keep the frequency constant. As can be seen from the simulation results, there is a significant change in the switching frequency. Especially in fast changing current references, the frequency error increases. However, in terms of parameter independency, the method is very advantageous. The fixed frequency method that calculates the new band using the previous switching period is expressed in equation (16).

$$DI = \frac{DI\_old}{Tpm} \times Tp \quad (16)$$

DI is the calculated band, DI_old is the previous calculated bandwidth, Tp is the fixed reference switching period, and Tpm is the measured previous period.

The results in Fig. 17 are obtained when the equation (16) is used in the simulation instead of the equation (15).

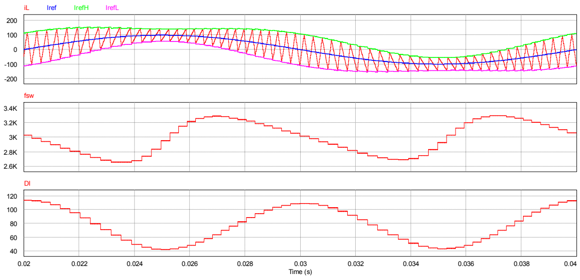

Fig. 17. The waveforms for method [6]

In this method, the change in switching frequency in the case of dead time is shown in Fig. 18. It is understood that there is no major variation in the switching frequency.

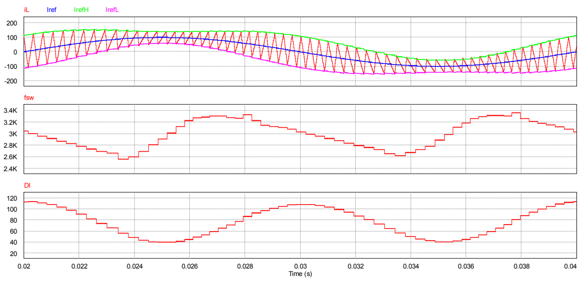

Fig. 18. The waveforms for method [6] (dead time = 2us)

4. Conclusions

In this study, an improved digital hysteresis current control method is proposed to solve the problems of analog hysteresis current control. In the proposed method, the required band value is calculated to obtain constant switching frequency. A sampling period is determined at an acceptable level based on the rate of change of the reference current. The effects of the parameters used in band calculation equation are simulated in detail. Lastly a method which is parameter independent [6] is given for a performance comparison. It is concluded that the proposed method improves current control performance in power electronic applications and can be used as an alternative to fixed frequency PWM methods.

5. References

[1] D. G. Holmes, R. Davoodnezhad, B. P. McGrath, "An improved three-phase variable-band hysteresis current regulator", IEEE Trans. Power Electron., vol. 28, no. 1, pp. 441 – 450, Jan 2013.

[2] R. Davoodnezhad, D. G. Holmes, B. P. McGrath, "A novel three-level hysteresis current regulation strategy for three-phase three-level inverters," IEEE Trans. on Power Electron., vol. 29, no. 11, pp. 6100-6109, Nov. 2014.

[3] S. Buso, S. Fasolo, L. Malesani, P. Mattavelli, "A dead-beat adaptive hysteresis current control," IEEE Trans. on Ind. App., vol. 36, no. 4, pp. 1174-1180, July/August 2000.

[4] H. Mao, X. Yang, Z. Chen, Z. Wang, "A hysteresis current controller for single-phase three-level voltage source inverters," IEEE Trans. on Power Electron., vol. 27, no. 7, pp. 3330-3339, July 2012.

[5] C. N. Ho, V. S. P. Cheung, H. S. Chung, "Constant-frequency hysteresis current control of grid-connected VSI without bandwidth control," IEEE Trans. on Power Electron., vol. 24, no. 11, pp. 2484-2495, Nov. 2009.

[6] L. Malesani, L. Rossetto, P. Tomasin, A. Zuccato, "Digital adaptive hysteresis current control with clocked commutations and wide operating range," IEEE Trans. on Ind. App., vol. 32, no. 2, pp. 316-325, March/April 1996.

[7] W. Stefanutti, P. Mattavelli, "Fully digital hysteresis modulation with switching-time prediction," IEEE Trans. on Ind. App., vol. 42, no. 3, pp. 763-769, May/June 2006

[8] L. Malesani, P. Mattavelli, P. Tomasin, "Improved constant-frequency hysteresis current control of VSI inverters with simple feedforward bandwidth prediction," IEEE Trans. on Ind. App., vol. 33, no. 5, pp. 1194-1202, Sep./Oct. 1997.

[9] S. Buso, L. Malesani, P. Mattavelli, "Comparison of current control techniques for active filter applications," IEEE Trans. on Ind. Electron., vol. 45, no. 5, pp. 722-729, Oct. 1998.

[10] L. Malesani, P. Mattavelli, P. Tomasin, "High-performance hysteresis modulation technique for active filters," IEEE Trans. on Power Electron., vol. 12, no. 5, pp. 876-884, Sep. 1997.

[11] L. Malesani, P. Tenti, "A novel hysteresis control method for current-controlled voltage-source PWM inverters with constant modulation frequency," IEEE Trans. on Ind. App., vol. 26. no. I, pp. 88-92, Jan./Feb. 1990.

[12] E. Aldabas, L. Romeral, A. Arias, M.G. Jayne, "Software-based digital hysteresis-band current controller," IEE Proc.-Electr. Power Appl., Vol. 153, No. 2, pp. 184-190, Mar. 2006.

[13] F. Liu, A. I. Maswood, "A novel variable hysteresis band current control of three-phase three-level unity PF rectifier with constant switching frequency," IEEE Trans on Power Electron., vol. 21, no. 6, pp. 1727-1734, Nov. 2006.

[14] A. K. Panda, R. Patel, "Adaptive hysteresis and fuzzy logic controlledbased shunt active power filter resistant to shoot-through phenomenon," IET Power Electron., Vol. 8, Iss. 10, pp. 1963–1977, 2015.

[15] A. Fereidouni, M. A. S. Masoum, K. M. Smedley, "Supervisory nearly constant frequency hysteresis current control for active power filter applications in stationary reference frame," IEEE Power and Energy Technology Systems Journal, vol. 3, no. 1, pp. 1-12, March 2016.

[16] B. K. Bose, "An adaptive hysteresis-band current control technique of a voltage-fed PWM inverter for machine drive system," IEEE Trans. on Ind. Electron., vol. 31, no. 5, pp. 402-408, Oct. 1990.

[17] K. M. Rahman, M. R. Khan, M. A. Choudhury, "Implementation of programmed modulated carrier HCC based on analytical solution for uniform switching of voltage

source inverters," IEEE Trans. on Power Electron., vol. 18, no. 1, pp. 188-197, Jan. 2003.
[18] L. Prakash, A. Meenakshi Sundaram, K. Durairaj, "Digital implementation of a constant frequency hysteresis controller for dual mode operation of an inverter acting as a PV-grid interface and STATCOM", Turkish Journal of Electrical Engineering & Computer Sciences, vol. 24, no. 5, pp. 4406-4428, June 2016.
[19] R. Mikail, I. Husain, Y. Sozer, M. S. Islam, T. Sebastian, "A fixed switching frequency predictive current control method for switched reluctance machines," IEEE Trans. on Ind. App., vol. 50, no. 6, pp. 3717-3726, Nov./Dec. 2014.