대전력 교류전동기 구동용 소프트 스위칭 인버터의 EMI 해석

EMI Analysis of Soft Switching Inverter on High Power AC Motor Drive

권순걸

Kwon, Soon-Kurl

요 약

대전력 전동기 구동장시스템에서 하드 스위칭 토폴로지는 심각한 스위칭 손실과 EMI잡음문제를 일으키며, 인버터 스위칭 주파수는 과도한 손실과 열적문제 때문에 제한되게 된다. 본 연구의 목적은 개선된 소프트 스위칭 토폴로지에 의해 스위칭손실과 EMI를 저감할 수 있는 대용량 교류전동기의 구동에 적합한 시스템을 개발하고자하며, 시뮬레이션과 실험을 통하여 그 타당성을 입증하였다.

ABSTRACT

In high power motor drive system, the hard-switching topology produces severs switching losses and EMI noises. Also the inverter switching frequency is thus limited because of excessive loss and thermal handling problem. The primary purpose of the proposed works on the induction motor drive system is to develop an advanced soft-switching inverter topology that is most suitable for high power induction motor drive applications. To make the optimal selection EMI comparison of the switching losses presented. To verify the proposed design procedure, detailed simulation analysis with theoretical and experimental approaches have been done using laboratory prototype.

Key Word : soft switching, inverter topology, motor drive, switching loss, hard switching

I. Introduction

Soft-switching inverter technologies have been around for more than 10 years. Although the soft-switching inverter itself has demonstrated many attractive features, it has not been designed and applied to practical induction motor drives. The mayor hurdle was due to improper circuit topologies in the early development. Recently, the load-side commutation techniques using the auxiliary resonant snubber circuits have shown great success in achieving high performance soft-switching inverters without experiencing some associated problems that were found in the early resonant dc link inverters. In order to choose an advanced type for motor drive applications, a complete review was performed in the project.

The traditional hard-switching inverters, although easy to design, have several problems during switching. Under turn-on condition, the device current not just rises from zero to the load current but also adds a current over-shoot because of the opposite-side diode reverse recovery and stray capacitor charging and discharging currents. Thus a current spike will occur with extremely high peak power consumption. During turn-off condition, the device voltage not just rises to the dc bus voltage, but also produces overshoot due to the leakage inductance in the loop.

Although this overshoot voltage can be reduced by a good circuit layout, the switch voltage rise rate (dv/dt) can be extremely high, causing other associated problems such as winding circulating current, bearing breakdown, etc. The hard-switching turn-on and turn-off also introduce switching losses and EMI noises. The inverter switching frequency is thus limited because of excessive loss and thermal handling problems. Low switching frequency further introduces acoustic noise and poor inverter output performance.

The soft-switching inverters can be zero-voltage or zero-current switching. Zero-voltage soft switching inverters have received more attention because they do not need bi-directional or reverse blocking device.

There are two major types of zero-voltage soft-switching inverters. One is the resonant dc link inverter which produces resonating voltage across the input of the inverter bridges, and the other is the resonant pole inverter which adds an auxiliary resonant branch for each inverter leg[1].

The primary purpose of the proposed works on the first phase is to develop an advanced soft-switching inverter topology that is most suitable for high power induction motor drive applications. The proposed circuit topology that provides reduced power loss and increased efficiency of the inverter system with soft-switching topology is presented.

In order to verify the proposed circuit, theoretical analysis and experimental results for the topology are contained.

Ⅱ. Three-Phase Auxiliary Resonant Snubber Inverter

The resonant snubber inverter (RSI) topologies have been proposed in the literature and the basic issue is to improve better efficient, reduced EMI and the size of the system. Recently, several RSI topologies were proposed to improve these problems by locating the

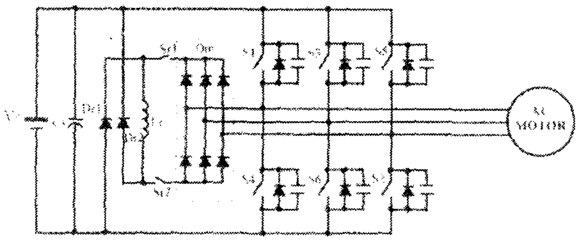


Fig. 1 Main circuit of ZVT Invert

그림 1 인버터 주회로

auxiliary resonant components on the load side. Inacmotor drives, the ac side soft-switching topologies havebeen issued an auxiliary commutated resonant pole (ARCP), and various delta or Yconnection topologies.

Of these topologies, Fig. 1 shows a three-phase motor drive applications. Since each phase resonant circuit consists of two auxiliary switches, diodes, and inductors, it adds significant cost in resonant components associated with control logic and their gate drive power supplies [2].

The proposed circuit topology is to reduce the parts count of the resonant snubber based soft-switching inverters as mentioned above. The idea of the proposed topology is mainly to reduce the number of the resonant inductor and blocking diodes. By placing the only one blocking diode with ultra fast characteristics to the auxiliary circuit, the diode reverse recovery current is much less and the number of the resonant components can be reduced.

Ⅲ. Switching Characterization Of The Selected IGBT

Fig. 2 shows switching characteristics test circuit for IGBT with inductive load instead of motor. The parameter values are summarized as follows:

- Inductor: 2mH(neglect the resistance in inductor)
- L.F. Capacitor : 2,700uF*4
- H.F. Capacitor : 1uF*4
- Shunt Resistor : 4.909 $m\Omega$

DC Link Voltage: 300 V

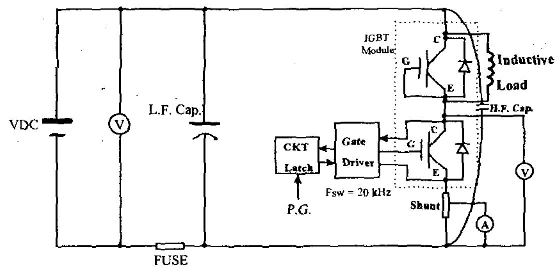


Fig. 2 Switching characteristic test circuit for IGBT with an inductive load

그림 2 IGBT의 스위칭 특성 실험 회로

3.1 Hard-switching Scheme

Although the new IGBTs have very high switching speeds and have more efficient switching characteristics at high frequencies (up to 20 kHz and beyond), these devices still have some switching losses during switching. These switching losses increase the product price and the heat-sink size.

A detailed comparison of the switching character-stics of hard and soft-switching inverters, including dv/dt, di/dt and switching losses follows. During switching, the energy dissipated in the IGBT can be obtained with the following equation as:

$$E_{on}=K\int_0^{t_{on}} I_c(t)\cdot V_{CE}(I_c)\cdot dt \qquad (1)$$

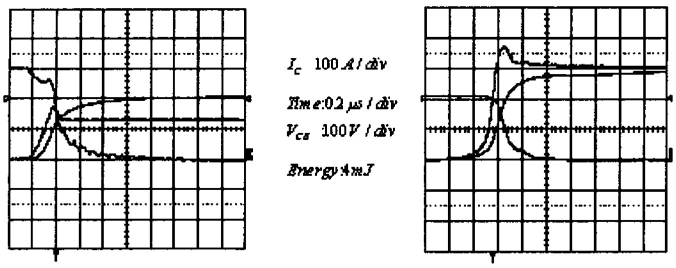
$$E_{off}=K\int_0^{t_{off}} I_c(t)\cdot V_{CE}(I_c)\cdot dt \qquad (2)$$

Where,

$$t_{on}=t_{d\_on}+t_r$$

$$t_{off}=t_{d\_off}+t_f$$

The turn-on time basically depends on the turn-on delay time and rising time. The turn-off time also can be determined by the turn-off delay time and falling time. At 20 kHz switching, the switching loss is calculated by multiplying the energy dissipated by the frequency (20 kHz). By using digital oscilloscopes with waveform processing capability, we can simplify switching loss calculations by a great extent. The total switching energy is the sum of the turn-on and-off switching energies.



(a) (b)

Fig. 3 Switching characteristics of the IGBT with hard switching at inductive load / (a) Turn-on @ Ion = 130 A (b) Turn-off @ Ioff = 200 A
그림 3 하드스위칭시 IGBT의 스위칭 특성

Fig. 3 shows switching characteristics of voltage, current and switching energy waveforms during turn-on and turn-off of IGBTs with hard switching. During turn-off, the dv/dt of 1,610 V/us and switching energy of 14.0 mJ were obtained at load current 200 A. Under turn-off, di/dt of 1,120 A/us and switching energy of 10.0 mJ at 130 A were marked.

3.2 ZVT Soft-switching Circuit And Its Control

Fig. 4 shows soft-switching control logic blocks of ZVT inverter for each leg. Fig. 4 shows soft-switching control logic blocks and their time sequence of ZVT inverter for each leg. The PWM output signals are sampled by comparing the PWM clock signal to the error signal from the current controller, based on the desired load current. All the design parameters are adjustable for resonant current control with different time delays[3].

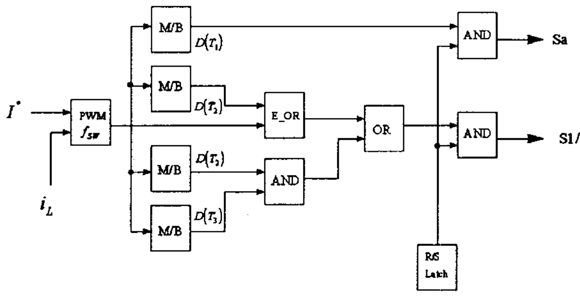


Fig. 4 Soft-switching control logic block diagram
그림 4 소프트스위칭 제어논리블록 다이어그램

Ⅳ. Soft-switching circuit components

4.1 Resonant capacitor

The selection of the resonant capacitor and inductor is very important because the overall inverter efficiency depends largely on the design and selection of these passive components. From the previous test results about compromising turn-off loss and reduction of dv/dt, the resonant capacitor is chosen as C=0.22 uF. The following expression can be used to find the exact value of the capacitor, and its results can be also compared with test results.

$$\frac{dV_{Cr}}{dt}=\frac{I_{Cr}}{2C_r} \qquad (3)$$

Where

$$I_{Cr}=I_{Lr}\pm I_L$$

To compromise the diode reverse recovery, related to di/dt during turn-off, the switching losses should be calculated as follows [3,4]:

$$P_D=I_D\cdot V_{Cr} \qquad (4)$$

Where

$$I_D=I_{C_r}\cdot\left(1-\frac{t}{t_f}\right)$$

$$V_{Cr}=\frac{1}{C_r}\int I_D\cdot dt$$

The resonant capacitor selected from the test, or calculation, should have low loss, low equivalent series inductance (ESL), low equivalent series resistance (ESR) and an excellent frequency response to handle the required turn-off current ratings. A polypropylene capacitor can be used in the soft-switching inverter as the widely used dielectric.

4.2 Resonant inductor

After selecting the resonant capacitor, the resonant inductor should be designed based on the resonant energy balance. The inductor needs sufficient capability during charging time so that the charged energy in the capacitor is fully discharged to the inductor. The time needed depends on turn-on delay time of IGBTs. From an energy balance point of view, because the amplitude of the resonant current is required to be larger than the load current for zero voltage switching, the energy relationship between the inductor and capacitor must satisfy the following condition:

$$\frac{1}{2} L_r \cdot I_{Cr}^2 \ge C_r \cdot (V_s - 2 \cdot V_{drop})^2 \qquad (5)$$

Where V_S is the dc bus voltage, and V_{drop} is the device drop voltage for each conducting device of the main device, about 2 to 3 V depending on the load current. Equation (5) means that the capacitor energy capability is limited by the function of inductor value and capacitor discharge current.

Therefore, the resonant value can be calculated as follows:

$$L_r = \frac{V_S - 2 \cdot V_{drop}}{I_{Lr}} \cdot t_{d-on}$$

Considering the turn-on delay time of PWM signal, this value can be obtained from the IGBT selected. In this design, the delay time of 2 us is chosen, and an inductor of 2 uH is thus calculated.

4.3 Auxiliary switch and diode

While selecting the auxiliary switches, two criteria should be followed the switches, two main factors, should have a higher peak current capability than the rated load current and a lower conducting drop voltage in the device. For this requirement, the MCT is the best device for a soft-switching operation. The MCT is designed with particular SCR characteristics having lower conduction losses and high peak current capability. This device is controlled for switching current on and off by negative and positive pulse signals, unlike IGBTs and MOSFETs. Since the auxiliary switch operates during transitions, the maximum duty ratio of the MCT is less than 3% of the switching frequency, considering the deadtime of IGBTs. In this design, MCTV75P60E1 with 75 A and 600 V is chosen for the MCT.

V. Experimental Results

In order to verify the proposed circuit topology, a soft-switching inverter was designed and implemented based on the design methodologies of the ZVT IGBT inverter that was tested on a single-phase full bridge inverter [4]. Detailed design parameters for the proposed soft-switching inverter are as follows:

1) Dual IGBT Module with 600 V - 400 A, as MG400J2YS50 was used for the inverter topology. This device has a turn-off time of 0.35 us.

2) The resonant capacitors used were the Polypropylene capacitors with 0.22 uF-600 V.

3) The resonant inductor value was 2 uH, with ferrite core having Bmax = 0.32 T, and with foil copper sheet winding type.

4) An auxiliary switch was chosen with MCT 75 A-600 V. This device was controlled with a negative pulsed signal for turn-on.

A blocking auxiliary diode was chosen with 50 A-600 V, as HFA50PA60C has a reverse recovery time of 19 ns.

The following test results show the circuit operation waveforms of the proposed soft-switching inverter corresponding to timing control of the auxiliary switch with different charging/ discharging time to resonant components, respectively.

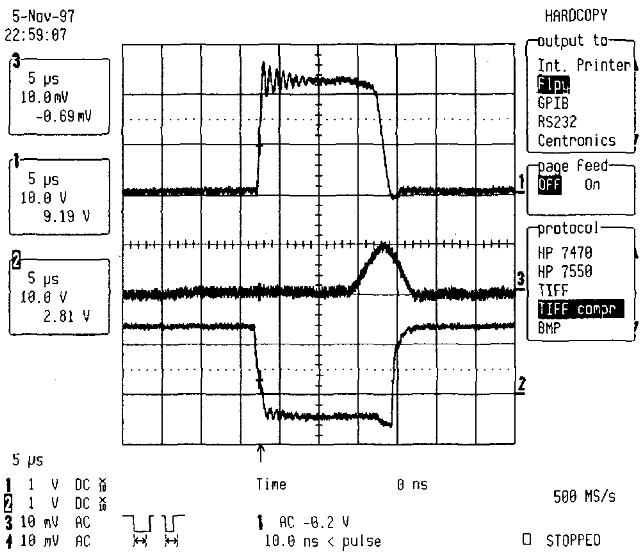


Fig. 5 Current and voltage waveforms for a single-phase inverter

그림 5 단상인버터의 전류전압파형

Fig 5 shows current and voltage waveforms for a single-phase inverter. These waveforms illustrate turn-on and turn-off switching characteristics of the main device under soft-switching condition with a large charging time of 3us and deadtime of 3 us. This figure also shows a resonant inductor current waveform when the main switch is turned on at zero voltage transition for other two switches of the leg.

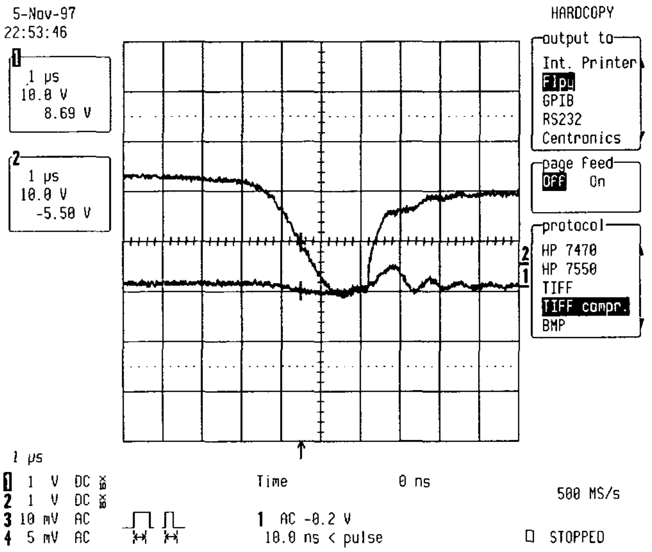


Fig. 6 Collector-emitter and gate-emitter voltage waveforms during turn-on

그림 6 점호시의 콜렉터-에미터 전압과 게이트-에미터 전압 파형

Fig. 6 shows experimental main switch device collector-emitter and gate-emitter voltage waveforms during turn-on. This figure indicates that the device is turned at a zero voltage condition.

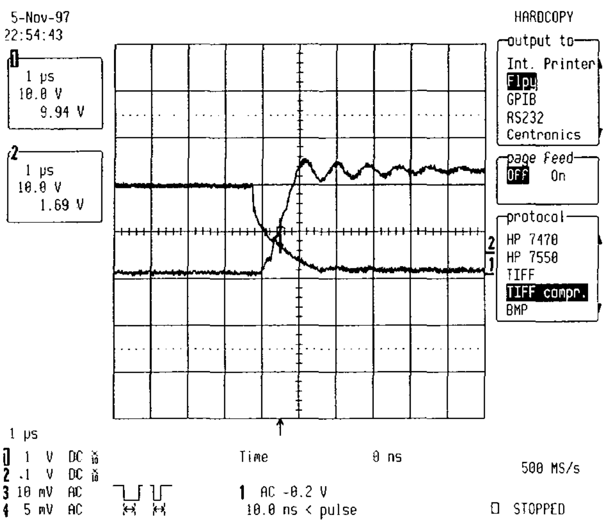


Fig. 7 Turn-off characteristics of the main device

그림 7 소호시의 주소자의 전압전류 특성

Fig. 7 shows turn-off voltage characteristics of the main device. During this period, the voltage collector-emitter rises slowly with a dv/dt rate of approximately 40 V/us at a lower input voltage. This means that the turn-off dv/dt is controlled by the external resonant capacitor across the main device. In order to reduce a rate of the turn-off dv/dt, that is, to improve the turn-off characteristics of the device, a larger capacitor should be added. The optimal magnitude of turn-off dv/dt is determined by Equation (3), which indicates the resonant capacitor values across each main device. For turn-on dv/dt rate, this approach is similar to its turn-off counterpart except that the direction is different.

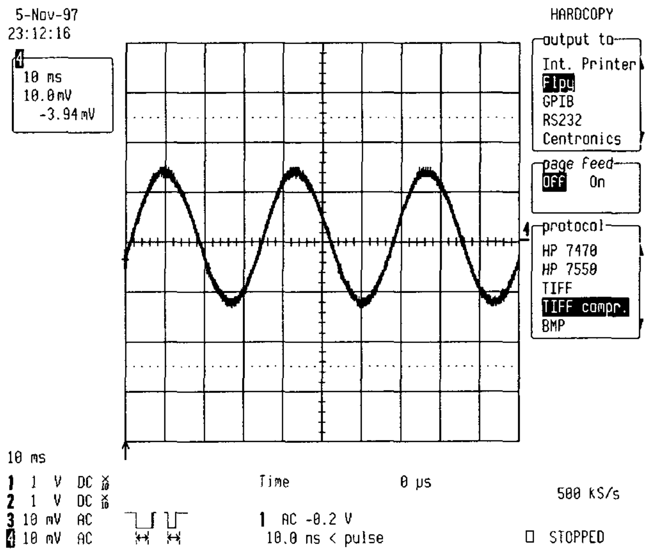


Fig. 8 Output current waveform of the proposed inverter

그림 8 제안한 인버터의 출력전류 파형

Fig. 8 shows the output current waveform of the proposed inverter with the inductor load instead of a motor load. Under soft-switching conditions with 20kHz switching frequency, the current reference fundamental frequency of 30Hz as the current reference is applied to the inverter. The current ripple is largely reduced with high frequency switching.

VI. Gate Drive Circuit

To design a gate drive circuit, several factors are required as following: one is the driving current and voltage capabilities due to determination of the isolation components as optocoupler, opto-coupler shielded, and optic fiber link. The second is a driving isolated power suppply as a 1W class. The last is a protecting function for the main device as de-saturation protection from short circuit of each leg. As considering of a given power level, the optocoupler of the gate driver is chosen as high dv/dt capability and speed operation. Also power to drive the MCT board is supplied by a small DC-DC converter with 1W.

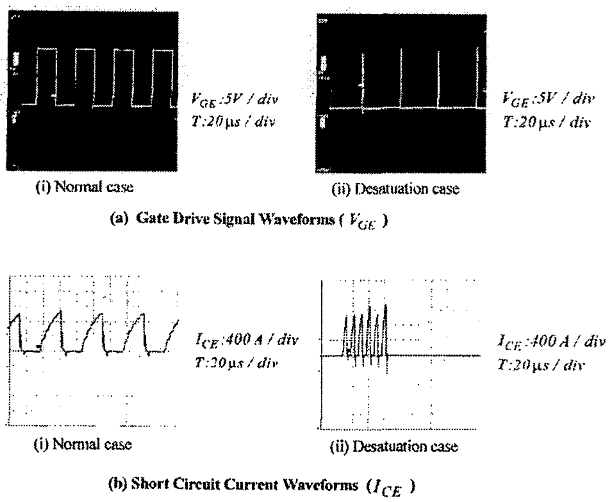


Fig. 9 Gate voltage and short circuit current waveforms
그림 9 게이트전압과 단락회로 전류 파형

Fig.9 shows gate voltage and short circuit current waveforms.

VI. Conclusion

This paper presented a design optimization of the zero-voltage-transition IGBT inverter based on the results of $\frac{dv}{dt}$, $\frac{di}{dt}$, and switching losses to select resonant components and switching control, through a comparison with the conventional hard switching scheme.

The design criteria of the auxiliary resonant subber inverter using load-side circuit for electric propulsion drives are discussed. In this regard, this paper attempted to develop a set of design criteria for the system. These comples design criteria problems are reduced by the various approaches under soft-switching for high power driver applications. In addition, the detailed simulation and experimental results were presented to verify the proposed design procedures based on a laboratory prototype to the greatest extent possible. As expected, high frequency EMI in the systemis greatly reduced by the soft-switching scheme. Therefore, the soft-switching inverter is one of the solutions to reduce the effect of the EMI to other systems.

접수일자 : 2002. 6. 28　　수정완료 : 2002. 7. 20

This project was sponsored by Kyung-nam University Research fund at 1998

References

[1] J. S. Lai et al, "A Novel Resonant Snubber Based Soft-Switching Inverter," *Conference Records of IEEE APEC*, pp. 797-803, Dallas, TX, March (1995)

[2] J. S. Lai et al, "A Delta-Configured Auxiliary Resonant Snubber Inverter, *IEEE,"* *Trans. on Industry Applications*, Vol. 32, No.3, May/June , pp.518-525 (1996)

[3] H. Mao and F. C. Lee, "Improvements on Zero-Voltage-Transition Three-Phase Rectifier /Inverter," *Proc. of 1995 VPEC Seminar*, Vol. 13, pp. 19-27, Virginia Tech, VA (1995)

[4] B. M. Song, T. Tang and J. S. Lai, "Design Improvement of the ZVT IGBT Soft-Switching Inverter for Induction Motor Applications," *Proc. of 1997 VPEC Seminar*, Vol 15, p75-82, Virginia Tech, VA (1997)

권순걸(Kwon, Soon-Kurl)
正會員
1973. 2. 영남대학교 전기공학과 졸업 (공학사)
1980. 2. 부산대학교 대학원 전기공학과 졸업 (공학석사)
1990. 2. 영남대학교 대학원 전기공학과 졸업 (공학박사)
1997. 1 ~ 1998. 1 미 버지니아 주립대학(VPI & SU) 방문교수
1983. 3 ~ 2002. 현재 경남대학교 전기전자공학부 교수