เอกสารอ้างอิง

[1] E. J. Dade, J. V. Gozalea, J. A. Linarase, J. Jordan, D. Ramirez, "**25kW/50 kHz Generator for Induction Heating**," IEEE Trans. Industrial Electronics, Vol. 47, No. 2, pp. 282-286, April 2000.

[2] J. Davies, P. Simson, **Induction Heating Handbook.** McGraw-Hill Book Company (UK) Limited , 1979.

[3] I. Khann, J. Tapson, I. Vries, **"Automatic Frequency Control of an Induction Furnace,"** IEEE Conf., Africon'99, Vol. 2 , pp. 913-916, September 1999.

[4] M. K. Kazaimierczuk, D. Czarakowski, **Resonant Power Converters.**, John Wiley & Sons, INC, USA, 2000.

[5] R. E. Best, **Phase-Locked Loops Design, Simulation, and Application.** McGraw-Hill Book Company (UK) Limited, 2005.

ภาคผนวก

ภาคผนวก ก.

โปรแกรม(MCS-51)ที่ใช้ในการควบคุมกระแส ดีซี ลิงค์ ให้คงที่

```
$regfile = "89C51AC2.DAT"
$ramstart = 0
$ramsize = 256
$crystal = 24000000
Ckcon = &B00000000



'/////////////////////////////////////////
Declare Sub Get_adc3
Declare Sub Get_adc4
Dim Adc_result As Byte , Adc_resultm As Byte
Dim I As Byte , J As Byte
Declare Sub Int_adc

Dim Out_p As Single , Out_i As Single , Out_i_old As Single , Out_i_new As Single
Dim Out_pi As Single
Dim Error As Single
Dim Out_pit As Integer
Dim Led_status As Bit

'/////////////////////////////////////////

  ' Led_port Alias P2.6                          'show Led when on Int0

  ' On Int0 Int0_int                          'INT0 = P3.2
  ' Enable Int0
  ' Enable Interrupts

  ' Led_status = 1                            'define start Led
  ' Led_port = Led_status



   Call Int_adc
   Out_i_old = 0
   Out_pi = 0
```

```
Do

    Call Get_adc3
    Call Get_adc4

    Error = Adc_resultm - Adc_result                'Find I_error

    Out_p = Error * 0.1
    Out_i = Error * 0.05

    Out_i_new = Out_i_old + Out_i                   'PI Controller
    Out_pi = Out_p + Out_i_new

    If Out_pi > 255 Then
      Out_pi = 255
      'Out_i_old = Out_i_old

    Elseif Out_pi < 0 Then
      Out_pi = 0
      'Out_i_old = Out_i_old

    Else
      Out_i_old = Out_i_new
    End If

    Out_pit = Out_pi
    Out_pit = 255 - Out_pit
    P0 = Out_pit                               'OUTPUT to DAC

Loop




End
'///////////////////////int_adc/////////////////////////
Sub Int_adc:
    Adcf = &B01100000
```

```
    Adcon = &H20
End Sub

'//////////////////////get adc1,2,3////////////////////
Sub Get_adc4:


    Adcon = Adcon And &HF8                            ' clr ch

    Adcon = Adcon Or 4                                ' selec ch j
    Adcon = Adcon Or &H08                             ' start convertion and 8bit mode
      Do
            J = Adcon
            J = J And &H10
            Loop Until J = &H10                       ' wait adc convert complete
            Adcon = Adcon And &HEF
      Adc_resultm = Addh

End Sub



'/////////////////////////end////get_adc/////////////////

'//////////////////////get adc1,2,3////////////////////
Sub Get_adc3:


    Adcon = Adcon And &HF8                            ' clr ch

    Adcon = Adcon Or 3                                ' selec ch j
    Adcon = Adcon Or &H08                             ' start convertion and 8bit mode
      Do
            J = Adcon
            J = J And &H10
            Loop Until J = &H10                       ' wait adc convert complete
            Adcon = Adcon And &HEF
      Adc_result = Addh
```

```
End Sub

'//////////////////////////end////get_adc//////////////////////////////////////

'//////////////////// INT0 SERVICE PROGRAM/////////////////

'Int0_int:                                    'Begin Int0 Service


'Start:

 '   Out_pit = Out_pit + 1
  '  P0 = Out_pit


   '     If Out_pit < 255 Then
    '    Goto Start

    'End If

'Do

 '    Led_status = Not Led_status
  '   Led_port = Led_status
   '  Wait 1

'Loop

'Return

'//////////////// END INT0 SERVICE PROGRAM////////////////
```

ภาคผนวก ข.

โปรแกรมของ MCS-51(AT89LP4052)ที่ใช้ควบคุมระบบ

```
SPDR        EQU   86H          ; SPI Data Register
TCONB       EQU   91H          ; Watch-Dog Control Register
RL0         EQU   92H          ; Timer0 Reload Low Byte
RL1         EQU   93H          ; Timer1 Reload Low Byte
RH0         EQU   94H          ; Timer0 Reload High Byte
RH1         EQU   95H          ; Timer1 Reload Low Byte
ACSR        EQU   97H          ; Analog Comparator Control & Status Register
WDTRST      EQU   0A6H         ; Watch-Dog Reset Register
WDTCON      EQU   0A7H         ; Watch-Dog Control Register
SADDR       EQU   0A9H
SPSR        EQU   0AAH         ; SPI Status Register
IPH         EQU   0B7H
SADEN       EQU   0B9H
P1M0        EQU   0C2H         ; Port-1 Mode:0 Register
P1M1        EQU   0C3H         ; Port-1 Mode:1 Register
P3M0        EQU   0C6H         ; Port-3 Mode:0 Register
P3M1        EQU   0C7H         ; Port-3 Mode:1 Register
SPCR        EQU   0D5H         ; SPI Control Register

I_OLD       EQU   30H
I_NEW       EQU   31H
P_NEW       EQU   32H
COUNT       EQU   33H

START       BIT   30H
STOP_PO     BIT   31H
CH_FF       BIT   20H          ; 1 I 0 V

                  ORG   0000H
                  LJMP  MAIN


MAIN:
                  MOV   P3M0,#00000000B      ; P3 = Quasi-bidirectional
                  MOV   P3M1,#00000000B
                  MOV   P1M0,#00000000B      ; P1 = Quasi-bidirectional
                  MOV   P1M1,#00000000B
```

```
                MOV     P1,#80H
                MOV     I_OLD,#00
                MOV     TMOD,#00000001B

LOOP:
                JB      P3.2,$
                JNB     P3.2,$
                MOV     TL0,#00
                MOV     TH0,#00
                MOV     RL0,#00
                MOV     RH0,#00
                MOV     COUNT,#00
                LCALL   CH_PO
                MOV     A,TL0

                MOV     PSW,#00
                SUBB    A,#20
                JC      NOT_ADJ
; CH  OVER
                JB      CH_FF,FOR
                MOV     A,P1
                SUBB    A,#1
                CJNE    A,#0,GO_LOOP
                MOV     A,#1
                AJMP    GO_LOOP

FOR:            MOV     A,P1
                ADD     A,#1
                CJNE    A,#254,GO_LOOP
                MOV     A,#253
                AJMP    GO_LOOP

GO_LOOP:        MOV     P1,A
NOT_ADJ:        LCALL   WAIT1
                AJMP    LOOP

DOI:            JB      P3.4,$
```

```
                    JNB     P3.4,$
                    SETB    TR0
                    ;SETB   P1.0
;DDD:               INC     COUNT
                    JB      P3.4,$
                    CLR     TR0
                    ;CLR    P1.0
                    RET

DOV:                JB      P3.5,$
                    JNB     P3.5,$
                    SETB    TR0
                    ;SETB   P1.1
;III:               INC     COUNT
                    JB      P3.5,$
                    CLR     TR0
                    ;CLR    P1.1
                    RET
CH_PO:              JB      P3.2,$
                    JB      P3.3,$

LPP:                JB      P3.2,DO_SET
                    JB      P3.3,DO_CLR
                    AJMP    LPP
DO_SET:             clr     CH_FF
                    ACALL   DOI
                    RET
DO_CLR:             setb    CH_FF
                    ACALL   DOV
                    RET

WAIT1:                MOV     R3,#255
LL:                 LCALL   WAIT
                    DJNZ    R3,LL
                    RET

WAIT:                MOV     R2,#0FFH
```

```
DJNZ    R2,$
RET
END
```

ภาคผนวก ค.

รูปภาพเครื่องมือที่ใช้สำหรับทดลอง

1. ออสซิลโลสโคป YOKOGAWA รุ่น DL1740E

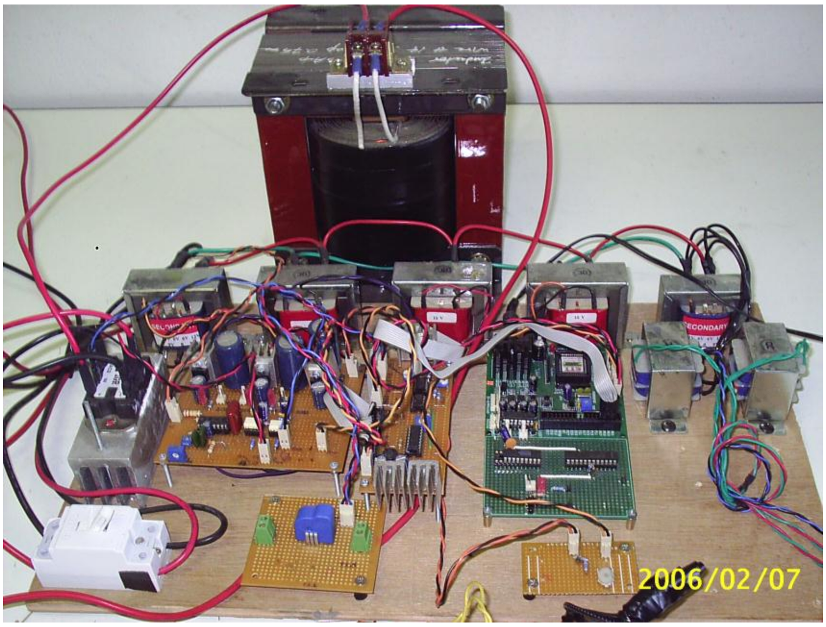
2. สายวัดสัญญาณแรงดัน (DIFFERTIAL PROBE) YOKOGAWA รุ่น 700925

3. สายวัดสัญญาณกระแส FLUKE

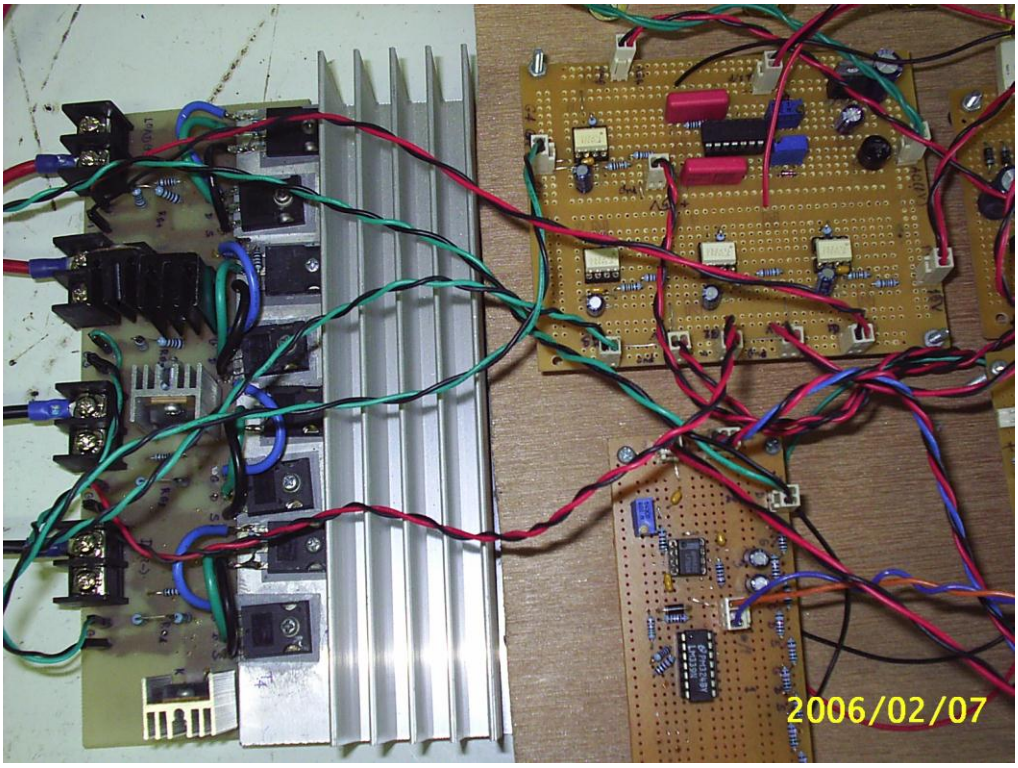
4. ตัววัดอุณหภูมิ (Temperature range -30 to 900 $°C$)

5. มัลติมิเตอร์ FLUKE รุ่น 179

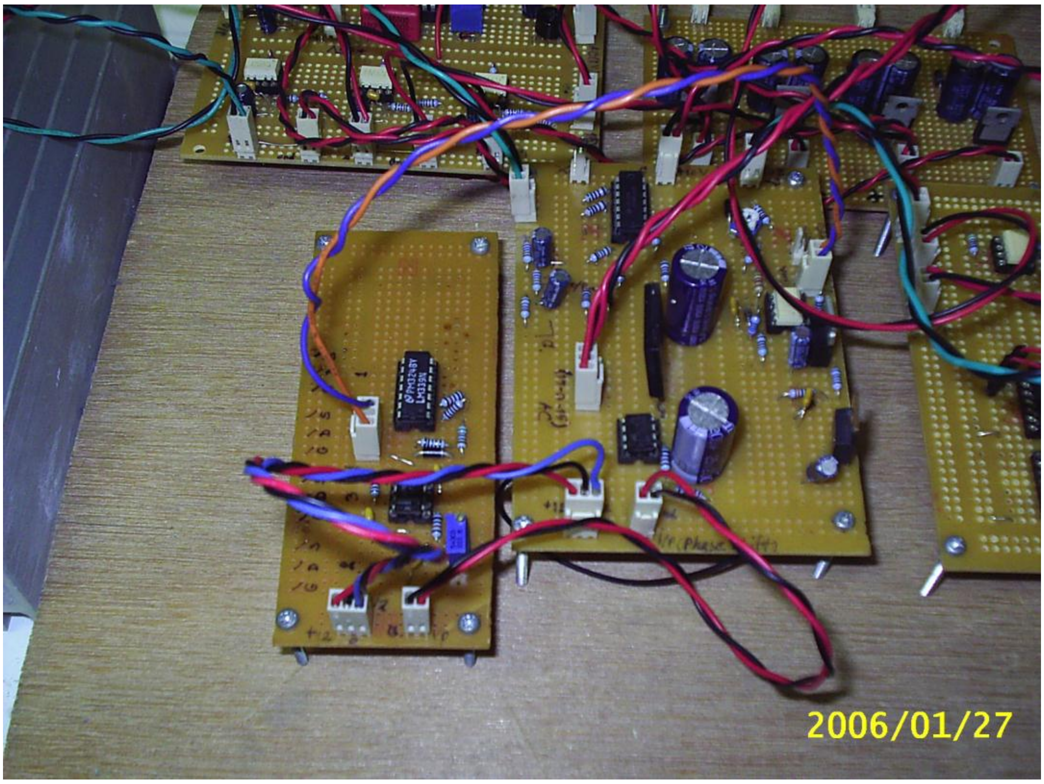
6. แหล่งจ่ายกระแสและตัวควบคุมกระแสให้คงที่



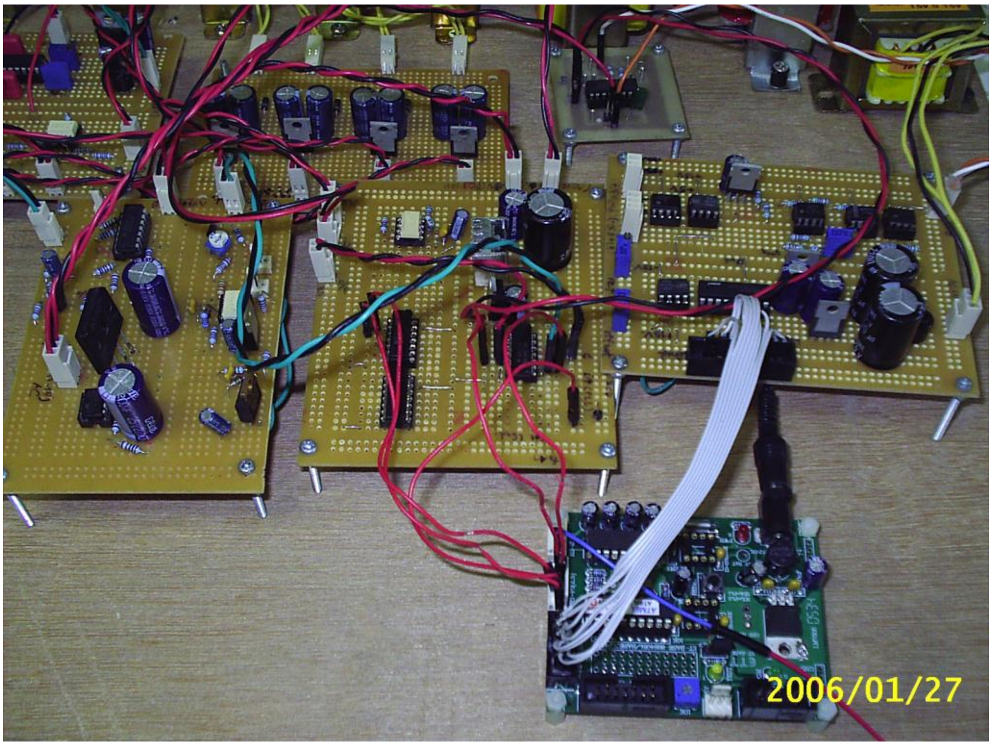
7. ชุดขับมอสเฟต



8. ชุดเลื่อนเฟสแรงดันและวงจรตรวจจับแรงดันศูนย์

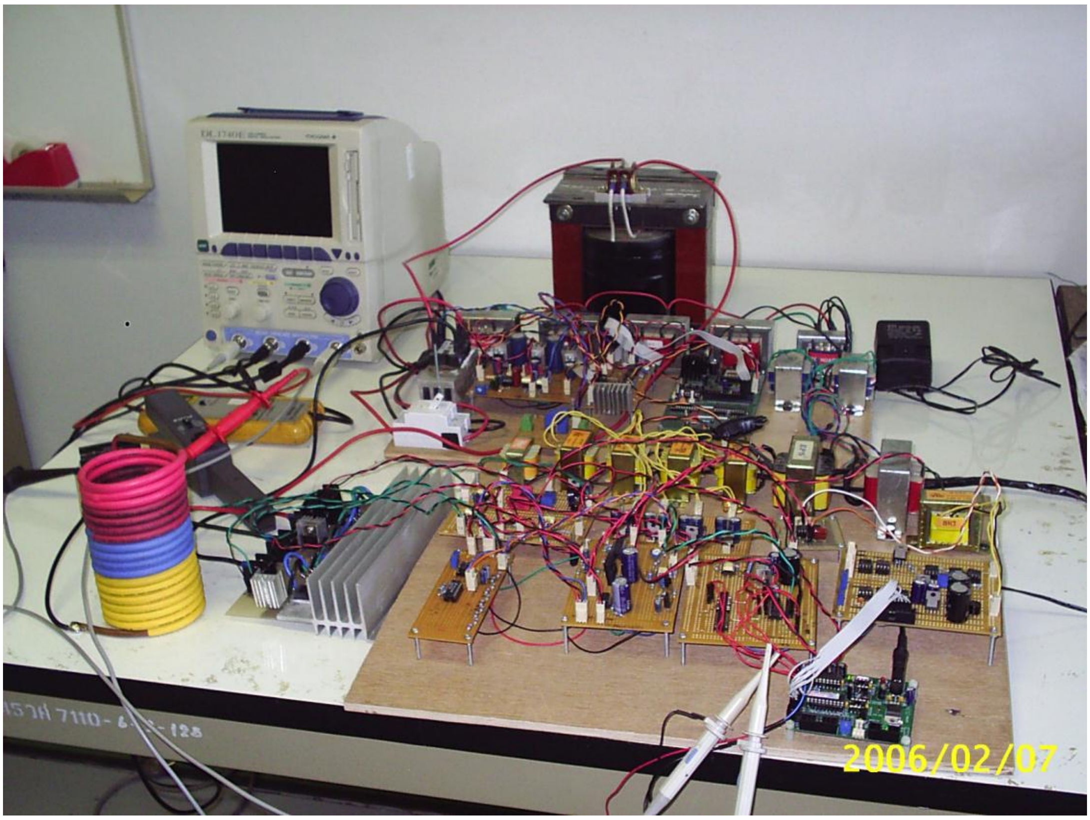


9. ชุดเฟสล็อกลูป



10. ขดลวดเหนี่ยวนำสำหรับการทดลอง

11.ชุดเครื่องต้นแบบให้ความร้อนแบบเหนี่ยวนำชนิดแหล่งจ่ายกระแสที่มีระบบควบคุมการสวิตซ์ที่สภาวะเรโซแนนซ์แบบอัตโนมัติ



ภาคผนวก ง.

ผลงานวิจัยที่ได้รับการตีพิมพ์เผยแพร่

1. P. Thongprasri, S. Kittiratsatcha, "**Automatic Resonant Frequency Control using Phase-Locked Loop for an Induction Furnace**," The 2006 ECTI International Conference (ECTI-CON 2006), Ubonratchathani, Thailand, May 10-13, 2006.


ECTI-CON 2006
THE 2006 ECTI INTERNATIONAL CONFERENCE
ECTI Association
ECTI 2006
Enter to the Proceeding
Proceedings of the 2006 Electrical Engineering/ Electronics, Computer, Telecommunications and Information Technology (ECTI) International Conference
May 10-13, 2006
Ubonburi Hotel, Ubon Ratchathani, THAILAND
ECTI Association
IEEE-LEOS Thailand Chapter
IEEE MTT/AP/ED THAILAND CHAPTER
NECTEC
Seagate
IEEE CAS Society
LEOS

Automatic Resonant Frequency Control using Phase-Locked Loop for an Induction Furnace

P. Thongprasri, S. Kittiratsatcha
Department of Electrical Engineering, Faculty of Engineering
King Mongkut's Institute of Technology Ladkrabang
Chalongkrung Rd., Ladkrabang, Bangkok THAILAND 10520

ABSTRACT

This paper proposes the computer simulation on PSCAD program of a current-fed parallel resonant inverter. The inverter is able operate at resonant switching frequency through out the heating period even the load condition is changed. This guarantees that the maximum power is transferred to the heating element all the time. The control principle uses Phase Frequency Detector to detect the phase difference of the tank circuit. The Phase Locked Loop is used to control the switching frequency. The proposed control scheme is designed to operate from 720 Hz to 870 Hz. Different kinds of loads are performed in the simulation.

Keywords: Parallel resonant, PLL, Induction heating.

1. INTRODUCTION

Both series resonant inverter and parallel resonant inverter are widely used in the induction heating and induction melting. In series resonant inverter system, the induction coil is in series with the resonant capacitor. While the parallel type the induction coil is connected in parallel with the resonant capacitor. In this paper, we choose the parallel resonant inverter because it is popular induction heating and melting applications in the medium frequency range (1-10kHz.) and medium power (10-10,000 W) [1]. This configuration can operate during the unloaded condition. It causes no damage when the load is short circuit as well as it does not require high voltage rating resonant capacitor [2]. The induction heating/melting is widely use in surface hardening, welding, heating, cutting applications. It has higher efficiency compared to the conventional power supply because it generates heat in short duration and also controls heat in the specific area. There are no pollutions such as smoke or acoustic noise. Generally the parallel resonant inverter has poor power factor (PF < 0.3 lagging) [3][5]. If the power factor is controlled to unity, the maximum power will transfer to load and there is no loss during switching. At this condition we call 'resonant condition'. When the metal load heats up, the electric and magnetic properties of the material are changed (e.g. conductivity or permeability). Consequently the resonant frequency of the tank circuit changes [4]. Thus if we can control the inverter to operate in resonant mode even the load has changed, the maximum power will also transfer to the load all the time.

2. PARALLEL RESONANT INVERTER

A parallel resonant inverter is shown in Fig. 1. It is consist of a three-phase controlled rectifier with an

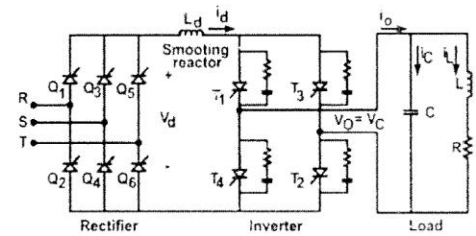


Fig.1: A Current-fed Parallel Resonant Inverter.

inductor, L_d. There is a close loop controller to control the dc link current with low ripple level by adjusting the firing angle of the SCRs. The RC snubber is added to reduce dv/dt across SCRs. When the coil is unloaded, the resonant frequency is at the natural resonant frequency. If the metal load is inserted in the coil, the inductance of the coil may be increasing or decreasing which depends on the material property. This brings the resonant frequency alters from the natural resonant frequency.

Moreover the resonant frequency has changed when the objects in the coil is heated up. This paper proposed a means how to control a current-fed inverter to operate at the resonant frequency for melting application. This method uses a phase-locked loop to keep tracking the resonant frequency. A Phase Frequency Detector (PFD) detects the frequency and phase differences of current and voltage across the load. The ability of PFD to detect this Phase Error, θ_e, is in the range of $-2\pi < \theta_e < 2\pi$ [6]. Also PFD can detect the phase shifting whether it is lead or lag. In general, the structure of PFD is a D flip-flop. But in this paper, we use RS flip-flop to eliminate reset delay problem. The simulation is performed using PSCAD program. The results show the validity of the proposed controller.

3. PHASE FREQUENCY DETECTOR

This section describes the operation of a PLL-based controller to keep tracking the resonant frequency. A PFD is used to detect the phase shift of current and voltage of the tank circuit. It operates in three modes which are when U_1 and U_2 are in phase, θ_e will be zero as shown in Fig. 2(a). θ_e is greater than zero if U_1 leads U_2 as shown in Fig. 2(b). Similarly, θ_e is less than zero if U_1 lags U_2 as shown in Fig. 2(c).

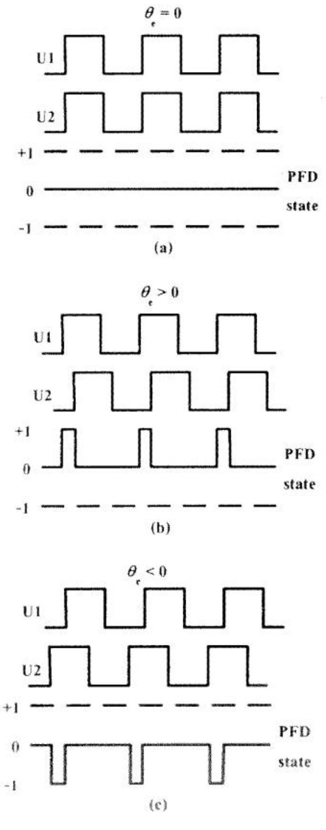


Fig.2: Ideal Waveforms of PFD when U_1 and U_2 are in Phase (a), U_1 leads U_2 (b) and U_1 lags U_2 (c).

Fig. 3 depicts the typical form of PFD which uses D-type flipflops. The output of PFD using D-type flipflop also has modes by determining the state of 'UP' and 'DOWN' as follows:

UP = 1, DOWN = 1 :D-type flipflop is reset by AND gate
UP = 0, DOWN = 0 : OUT is zero
UP = 1, DOWN = 0 : OUT is positive
UP = 0, DOWN = 1 : OUT is negative

There is a problem in the state UP = 1 and DOWN = 1. There will be delay in the RESET state. To eliminate this problem, the RS-type flipflop is implemented to correct this problem as shown in Fig. 4.

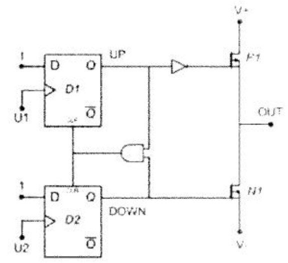


Fig.3: A Ttypical PFD using D-type Flipflop.

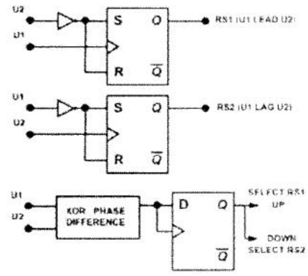


Fig.4: A Proposed RS-type Flipflop PFD.

4. PLL BASED CONTROLLER

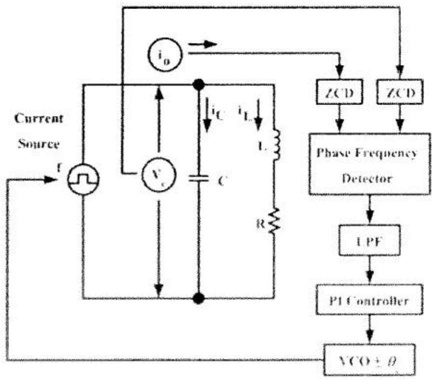


Fig.5: A Block Diagram of a PLL-Based Automatic Resonant Frequency Control System.

Fig. 5 is a block diagram of PLL-based controller integrated with the current-fed inverter. The current and voltage across tank circuit is detected by zero-crossing detector (ZCD). The output from ZCD then fed to the PFD. At this stage we know the phase error between current and voltage. The average of the phase error is taken by using a low pass filter. This error is then fed to a

PI controller. The command signal is the input of a voltage-controlled oscillator (VCO). The output is the sinusoidal waveform and the frequency is adjustable depend on the phase error whether it is lead or lag. The outputs of VCO are switching signals of the inverter. Consequently, the tank circuit is in the resonant condition all the times. This statement is verified by the simulation results. PSCAD program is used for the computer simulation. From the simulation, we study the operation at unload. The resonant frequency is at natural resonant frequency. If the inductance of the coil increases, the resonant frequency is decreasing. If the coil inductance decreases, the resonant frequency will shift to higher frequency. The simulations confirm that the proposed controller can track the resonant frequency even though the load conditions of induction furnaces have changed.

5. SIMULATION RESULTS

Appendix A depicts the schematic diagram of the current-fed inverter and the proposed controller in the PSCAD program. The quality factor Q in the simulation is approximated 15 (In general, Q must be greater than 5 [1]). The simulations are separated in two conditions which are with and without automatic controller. Each condition has three types of loads which are No-load, High inductance load and low inductance load. At no-load condition, the parameters of the tank circuits are L = 4.45mH, R = 1.45 ohm and C = 9 uF. The resonant frequency is at 795.278 Hz. The second condition is High inductance value, the tank circuit parameters are L = 5.42 mH, R = 1.61 ohm and C = 9uF. For this type of load, the resonant frequency is shifted from 795.278 Hz at no-load condition to 720.278 Hz. If the load (heating object) makes the inductance decreasing, the resonant frequency is higher compared to the no-load condition. In this case, the tank circuits parameters are L = 3.72 mH, R = 1.33 ohm and C = 9uF. The resonant frequency is at 870.278 Hz. Fig. 6 – 8 depict the simulation results at different load condition and with or without automatic control.

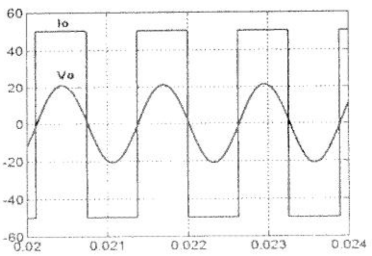


Fig.6(a): The Simulation Results of I_o and V_o at No-load Condition without Automatic Control.

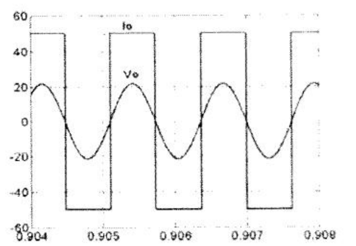


Fig.6(b): The Simulation Results of I_o and V_o at No-load Condition with Automatic Control.

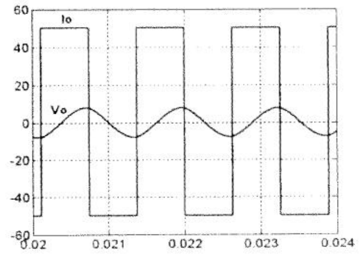


Fig.7(a): The Simulation Results of I_o and V_o at High Inductance Load Condition without Automatic Control.

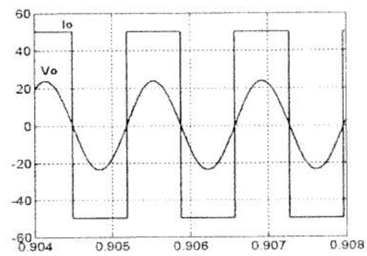


Fig.7(b): The Simulation Results of I_o and V_o at High Inductance Load Condition with Automatic Control.

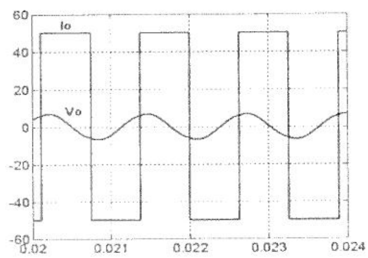


Fig. 8(a): The Simulation Results of I_o and V_o at Low Inductance Load Condition without Automatic Control.

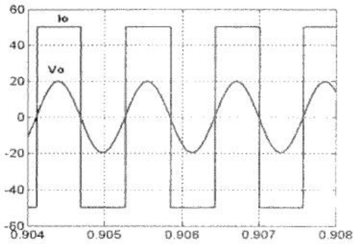


Fig.8(b): The Simulation Results of I_o and V_o at Low Inductance Load Condition with Automatic Control.

6. CONCLUSION

Phase Frequency Detector Locked Loop is showing the capability to control the switches of an inverter to operate at resonant condition even though the load condition is changed. PFD is able to detect phase of current and voltage of tank circuit whether it is leading or lagging. The switching frequency is able to shift up or shift down to match with the different load conditions. By implementing the automatic resonant frequency control, the maximum power is delivered to heated load through out the heating time. While the conventional induction furnace without automatic resonant frequency control, the inverter operates out of resonant condition when the load is heated up. The experimental results will be included in the future work.

7. REFERENCES

[1] Arieh L. Shenkman, Boris Axelrod and Vadim Chudnovsky"A New Simplified Model of the Dynamics of the Current-Fed Parallel Resonant Inverter", IEEE Trans. Industrial Electronics, vol. 47, NO. 2, April 2000, pp.282-286

[2] Enrique J. Dade, Jose V. Gonzalez, Juan A. Linares, Jose Jordan, Diego Ramirez,"25-kW/50-kHz Generator for Induction Heating", IEEE Transactions on Industrial Electronics, Vol.38, NO. 3, IUNE 1991, pp.203-209.

[3] L. Hobson, and D.W. Tebb,"Transistorized power supplies for induction", Int. J. Electronics, vol. 59, No. 5, June 1985, pp.543-552.

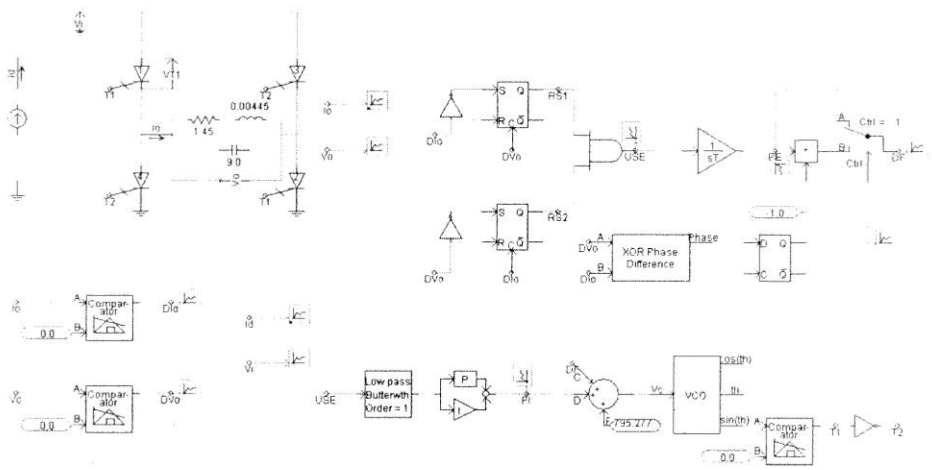
[4] D. L. Loveless, "An Overview of Solid-State Power Supplies for Induction Heating", Metal Production, vol.33, August 1995.

[5] Irshad Khann, Jonathan Tapson, Ian de Vries, "Automatic Frequency Control of an Induction Furnance", IEEE 1999.

[6] McGraw-Hill ,"Phase-Locked Loops Design Simulation and applications", 1999.

[7] Mozhgan Mansuri, Dean Liu and Chih-Kong Ken Yang,"Fast Frequency Acquistion Phase-Frequency Detectors for GSa/s Phase Locked Loops", University of California at Los Angeles, Stanford University.

8. APPENDIX A



ประวัติผู้เขียน

นายไพโรจน์ ทองประศรี เกิดเมื่อวันที่ 19 มิถุนายน พ.ศ.2514 ที่จังหวัดสุพรรณบุรี สำเร็จการศึกษาปริญญาตรีวิศวกรรมศาสตรบัณฑิต สาขาวิศวกรรมอิเล็กทรอนิกส์ จากภาควิชาวิศวกรรมอิเล็กทรอนิกส์ คณะวิศวกรรมศาสตร์ สถาบันเทคโนโลยีพระจอมเกล้าเจ้าคุณทหารลาดกระบัง ในปีการศึกษา 2537 และเข้าศึกษาต่อในระดับปริญญาโท หลักสูตรวิศวกรรมศาสตรมหาบัณฑิต สาขาวิศวกรรมไฟฟ้า ภาควิชาวิศวกรรมไฟฟ้า คณะวิศวกรรมศาสตร์ สถาบันเทคโนโลยีพระจอมเกล้าเจ้าคุณทหารลาดกระบัง ในปีการศึกษา 2547

ประวัติการทำงาน

2535-2536 อาจารย์พิเศษ แผนกอิเล็กทรอนิกส์ โรงเรียนกรุงเทพเทคนิคนนท์ จังหวัดกรุงเทพมหานคร

2536-2537 อาจารย์พิเศษ แผนกไฟฟ้า โรงเรียนเทคโนโลยีภาคตะวันออก(อีเทค) จังหวัดชลบุรี

2537-2539 วิศวกร แผนกR&D บริษัทไทยเคิเบิ้ลทีวี จำกัด จังหวัดกรุงเทพมหานคร

2539-2540 อาจารย์พิเศษ แผนกไฟฟ้าและอิเล็กทรอนิกส์ โรงเรียนอักษรเทคโนโลยีพัทยา จังหวัดชลบุรี

2540-2545 วิศวกรอวุโส และหัวหน้าแผนกMaterial บริษัท PT. (Pet-Toy) จำกัด จังหวัดกรุงเทพมหานคร

2544-2545 อาจารย์พิเศษ แผนกไฟฟ้าอิเล็กทรอนิกส์ โรงเรียนวิศวกรรมเทคโนลียีบริหารธุรกิจ จังหวัดชลบุรี

2545-2547 ฝ่ายวิชาการประจำแผนกอิเล็กทรอนิกส์ และพัสดุแผนก ฝ่ายระบบสารสนเทศประกันคุณภาพการศึกษา โรงเรียนเทคโนโลยีทีพีไอ (ในเครือบริษัททีพีไอ จำกัด) จังหวัดระยอง

2545-2546 อาจารย์พิเศษแผนกไฟฟ้าอุตสาหกรรม สถาบันราชภัฏราชนครินทร์ วิทยาเขตชลบุรี จังหวัดชลบุรี

2547-ปัจจุบันรับทุนการศึกษา จาก SIG Cobibloc Ltd. (Head Office) (ลาศึกษาต่อระดับวิศวกรรมศาสตรมหาบัณทิต สาขาวิชาวิศวกรรมไฟฟ้า)