

Three Phase Rectifier

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Content

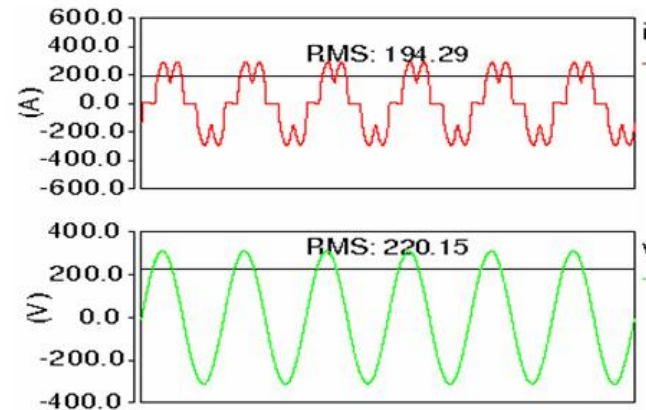
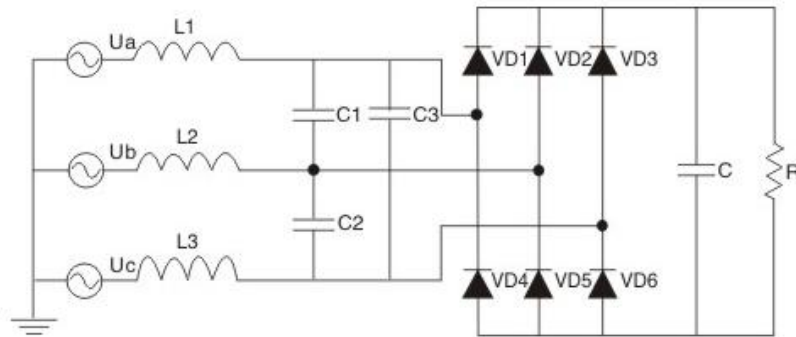
- **Introduction**
- **Hardware Design Review**
- **Software Design Review**
- **Close-Loop Controller Review**

Introduction

- Rectifier functions:
 1. The AC to DC conversion.
 2. Improve the power factor.
 3. Reduce the THDi.

Introduction

- **Three Phase PFC Topology - 6 Pulse + SCR + LC**

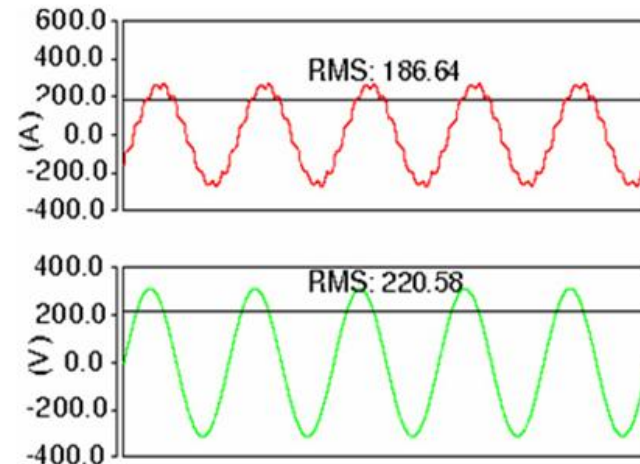
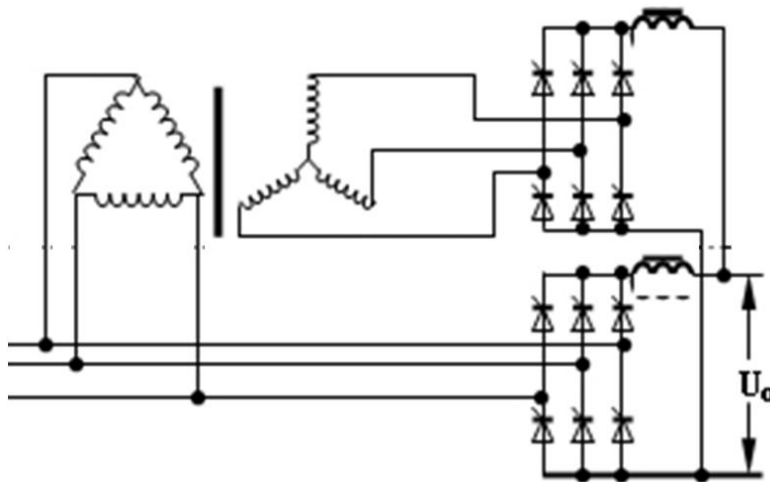


It is a non-controllable rectifier, the input current contains many harmonic waves. (ie, 5,7,11,13....)

So the PF and the THDi performance is bad.

Introduction

- **Three Phase PFC Topology - 12pulse + SCR + L**

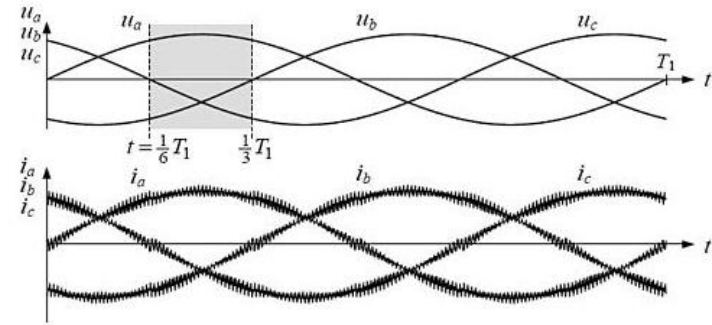
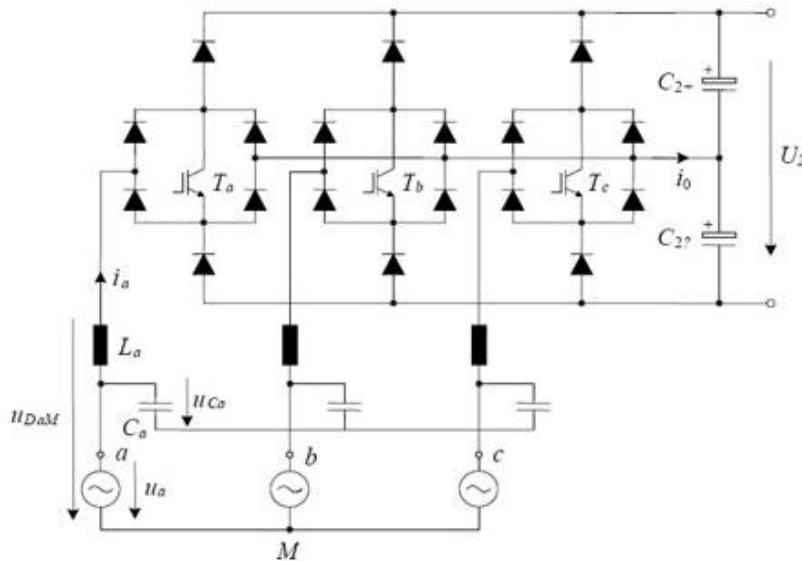


The 12-pulse rectifier is made up of 2 6-pulse AC-DC bridge, each 6-pulse AC-DC has a 3 phase input which have 30 degree phase error between the 2 bridges.

- Better PF and THDi than 6-pulse
- Easy to control and realize.
- Big size and low efficiency

Introduction

- Three Phase PFC Topology - Vienna topology

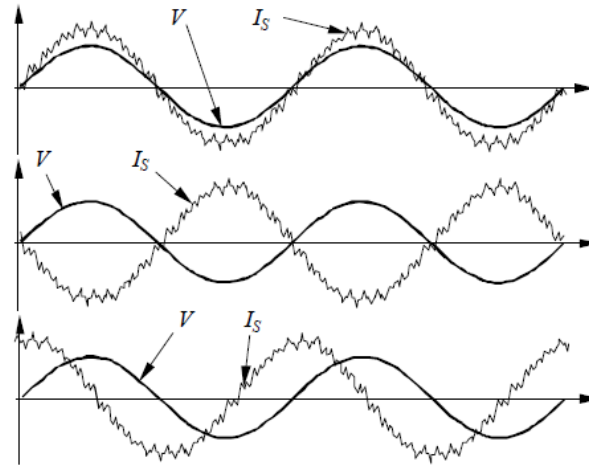
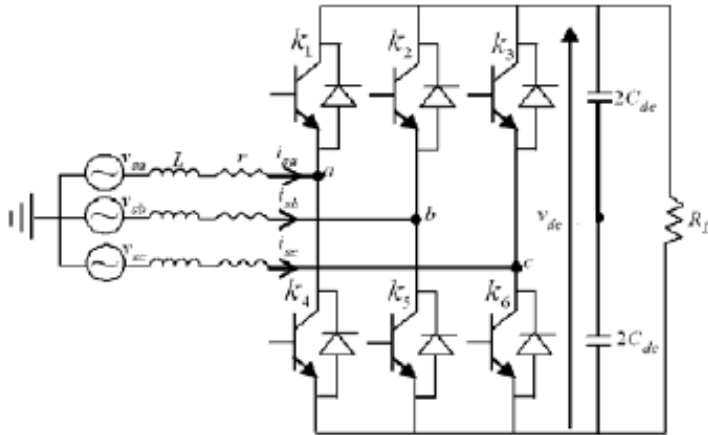


The Vienna topology is a controllable active power rectifier.

- Controllable output voltage and BUS balance
- High PF and low THDi
- High efficiency
- The controller is complicated
- Worse EMI than passive AC-DC

Introduction

- **Three Phase PFC Topology - 3 phase 2-level PWM rectifier**

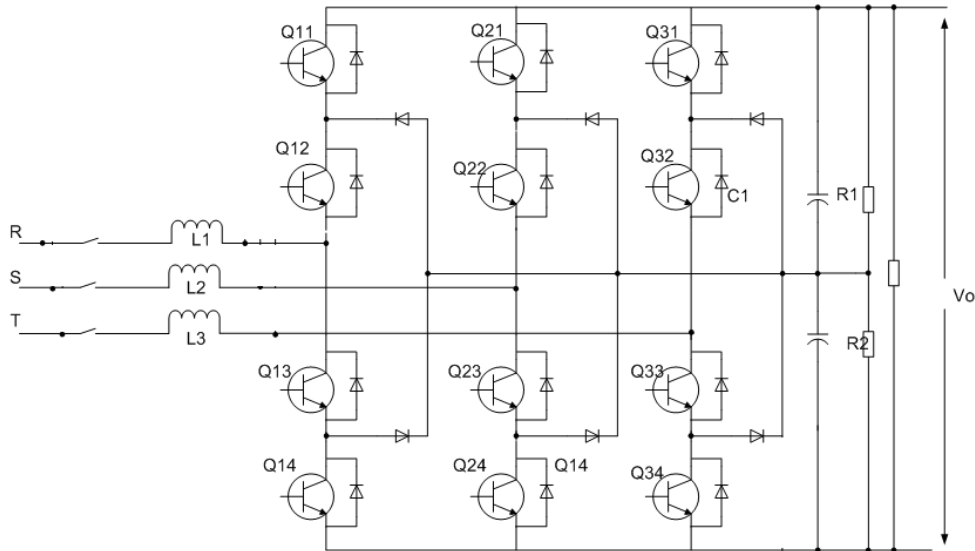


The 3-phase PWM rectifier topology is a controllable active power rectifier.

- Controllable output voltage.
- High PF and low THDi, controllable PF
- Can share the same board with 3 phase inverter
- High efficiency
- The controller is complicated
- Worse EMI than passive AC-DC

Introduction

- **Three Phase PFC Topology - 3 phase 3-level PWM rectifier**



The 3-level PWM rectifier topology is a controllable active power rectifier.

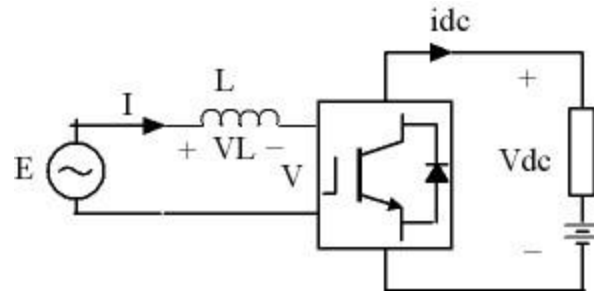
- **Controllable output voltage and bus balance**
- **High PF and low THDi, controllable PF**
- **Highest efficiency**
- **The controller is most complicated**
- **Worse EMI than passive AC-DC**

Introduction

- **Application field**
 - **UPS**
 - **Telecommunication**
 - **Motor driver**
 - **Motor Energy Feedback Unit**
 - **Active Power Filter**

Introduction

- 3-Phase 2-level PWM Rectifier principle



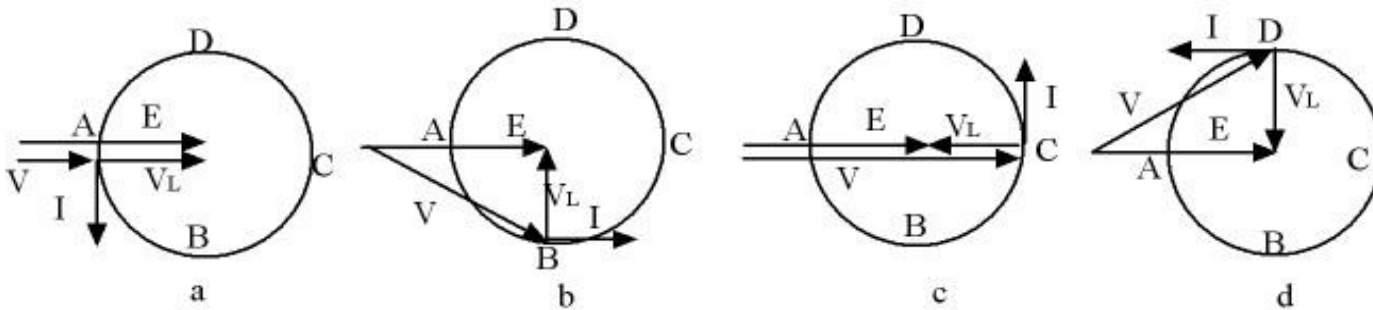
The PWM Rectifier can be equivalent to the figure above, then we can get the the equation:

$$E = V_L + V$$

$$i_{ac} V_{ac} = i_{dc} V_{dc}$$

Introduction

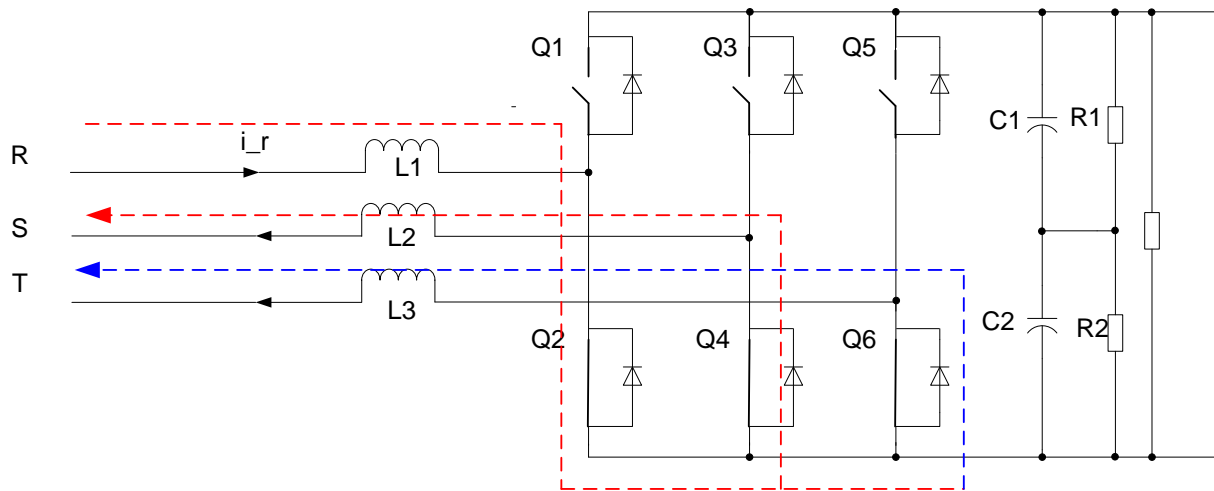
- **Three Phase PWM Rectifier principle**



When the V trace from the A to B in the above figure, the converter can work in rectifier mode, when the V at the B, then the we can get the highest power factor.

Introduction

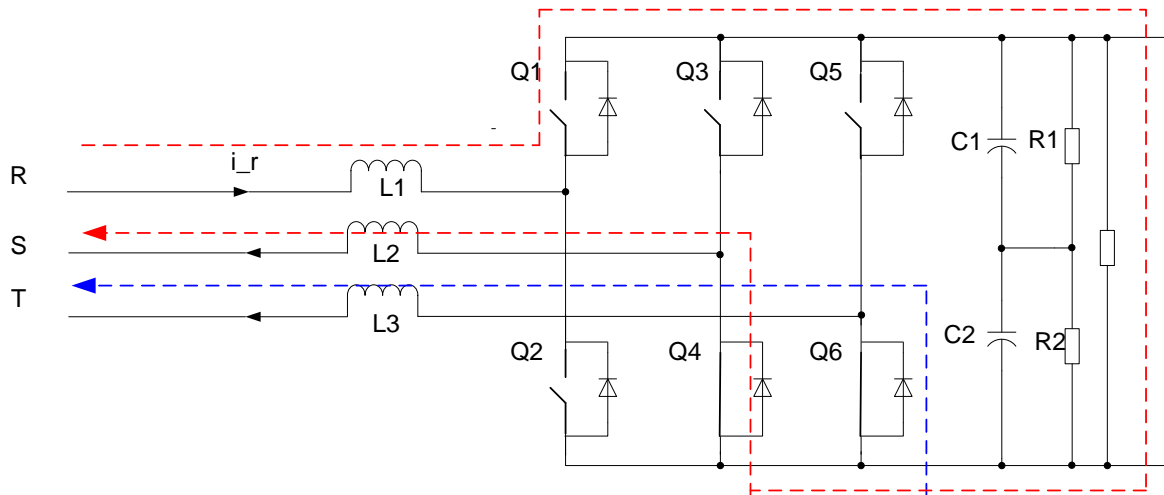
- The PWM on-off analysis



For R phase, when the Q2 is on, then the inductor current will rise, the current flow from R phase, then go through the Q4 or Q6 body diode, at last get into the S or T phase. Then the energy will store in the inductor.

Introduction

- The PWM on-off analysis



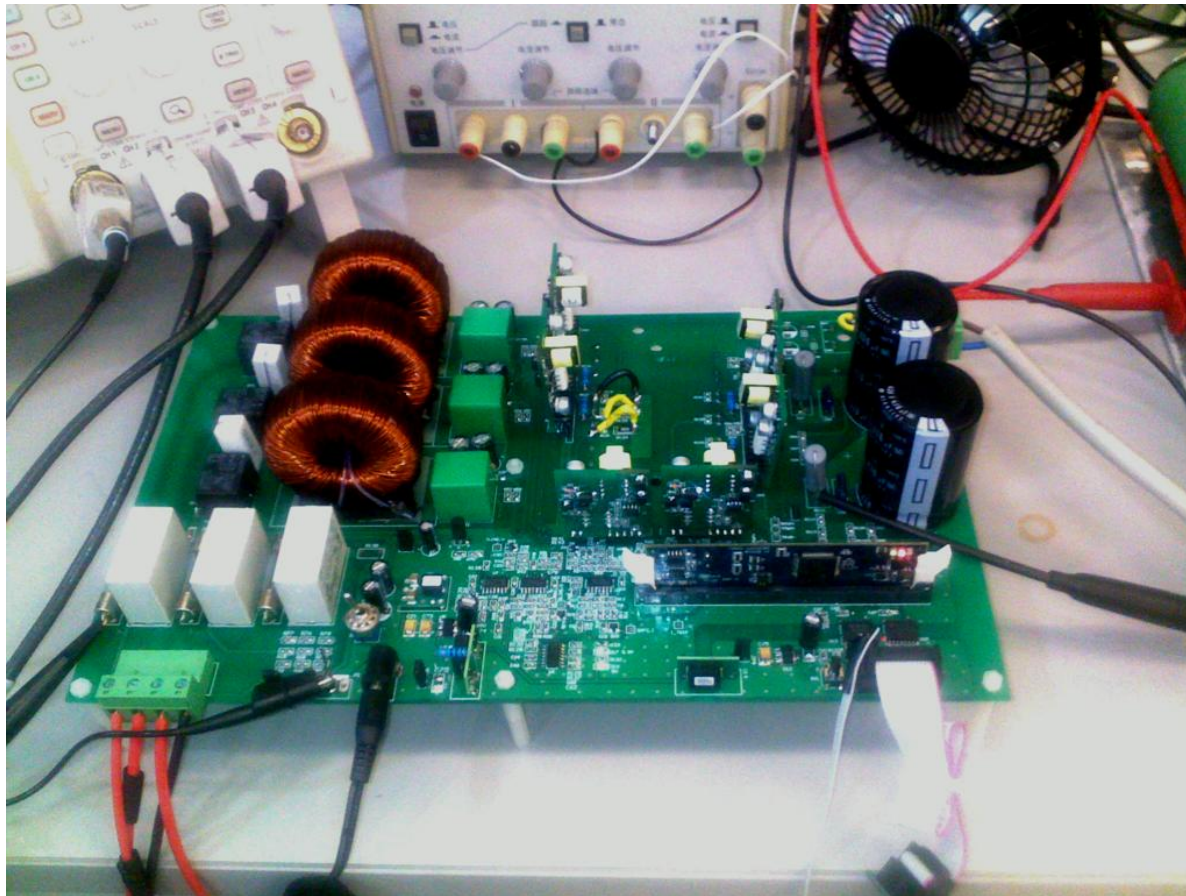
When the Q2 is off, the inductor current will fall, the current flow will go through the Capacitor, then get to the S or T phase, the energy stored in the inductor will be released.

Introduction

- **3-phase PFC EVM basic specification**
 - **3 phase 4 wire(or 3wire) input**
 - **1200W @ 380VAC/50Hz**
 - **Output Voltage: 700VDC**
 - **Efficiency: >95%**
 - **THDi<5% @ Full load**
 - **Current unbalance ratio: <3%**
 - **Power Factor > 0.99 @ >50% Load**
 - **Piccolo B**
 - **GUI support**

Introduction

- 3-phase PFC EVM Picture

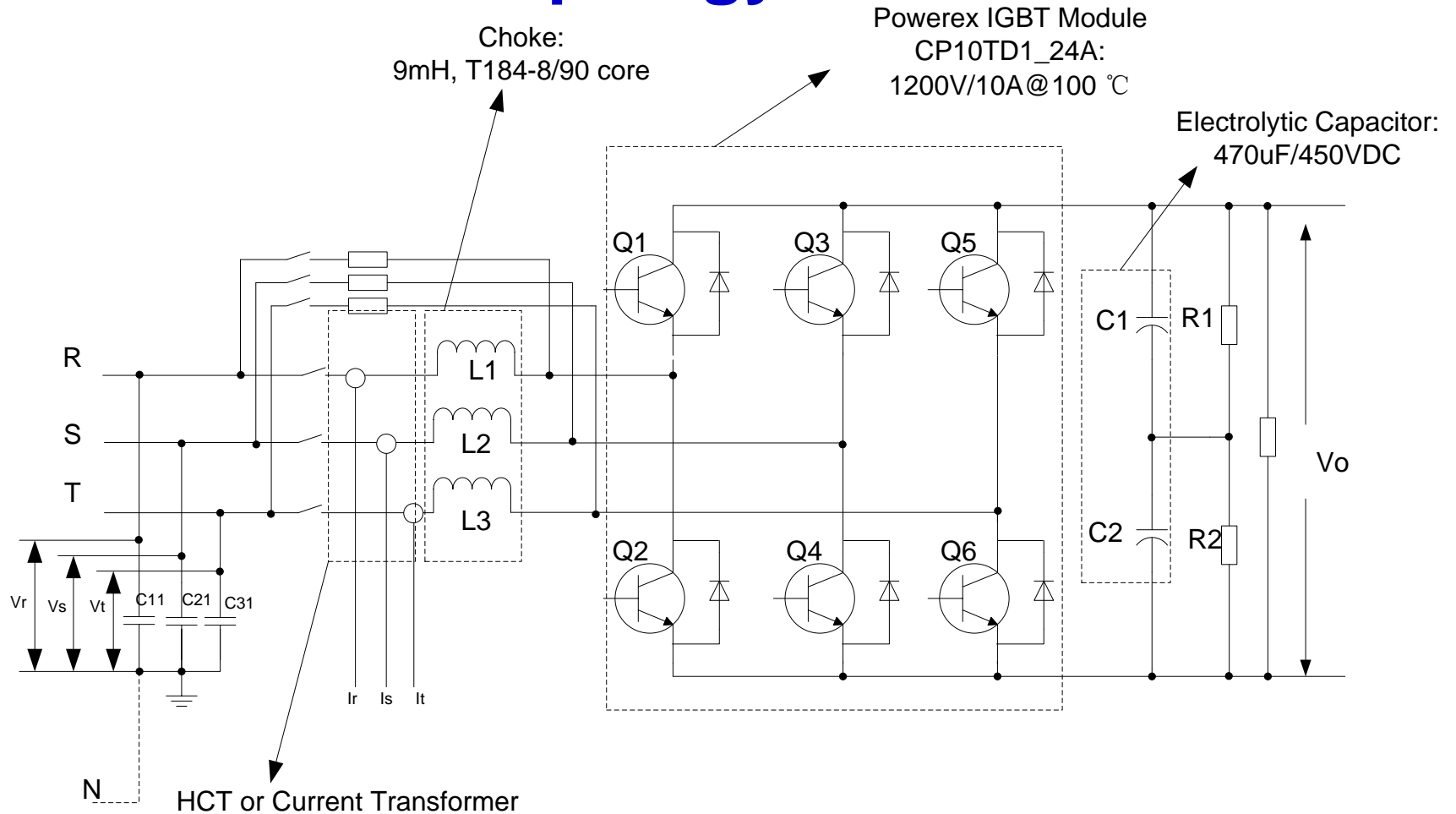


Content

- Introduction
- **Hardware Design Review**
- Software Design Review
- Close-Loop Controller Review

Hardware Design Review

- **Main circuit topology**



Hardware Design Review

- **Main circuit considerations**

1. **Switch Frequency ---- 20kHz.**

For motor control application, the F_s can be reduced to 10kHz, and the choke size will be bigger and the inductance is higher.

2. **IGBT**

1200V IGBT must be used in this topology, because the maximum voltage between the V_{ce} is over 700V in theory. Actually, the 30% margin need to be considered.

3. **Electrolytic Capacitor**

The output DC voltage is larger than 600VDC in 380VAC system, then we must use 2 electrolytic capacitors in series.

4. **Current sensing ---- HCT need to be used for current controller. 2 HCTs at least.**

5. **Line voltage sensing --- Line- Neutral voltage(or Line to Line) need to be sensed**

Hardware Design Review

• The inductor design

The inductor is determined by the following parameters:

- The DC output voltage and input voltage
- The switching frequency
- The current ripple needed

$$I_{\text{peak_1}} := \sqrt{2} \cdot \frac{\left[\frac{(S \cdot \text{PF})}{\eta_{\text{output}}} \right]}{3 \cdot V_{L\text{min}}} \quad \text{the maximum line current}$$

$$I_{\text{peak_rate}} := \sqrt{2} \cdot \frac{\left[\frac{(S \cdot \text{PF})}{\eta_{\text{output}}} \right]}{3 \cdot V_{\text{rate}}}$$

$$I_{\text{rp_1}} := I_{\text{rp}} \% I_{\text{peak_rate}} \quad \text{the maximum ripple current in the rated line voltage}$$

$$I_{\text{rp_1}} = 1.143 \cdot \text{A}$$

Calculate the inductor minimum value

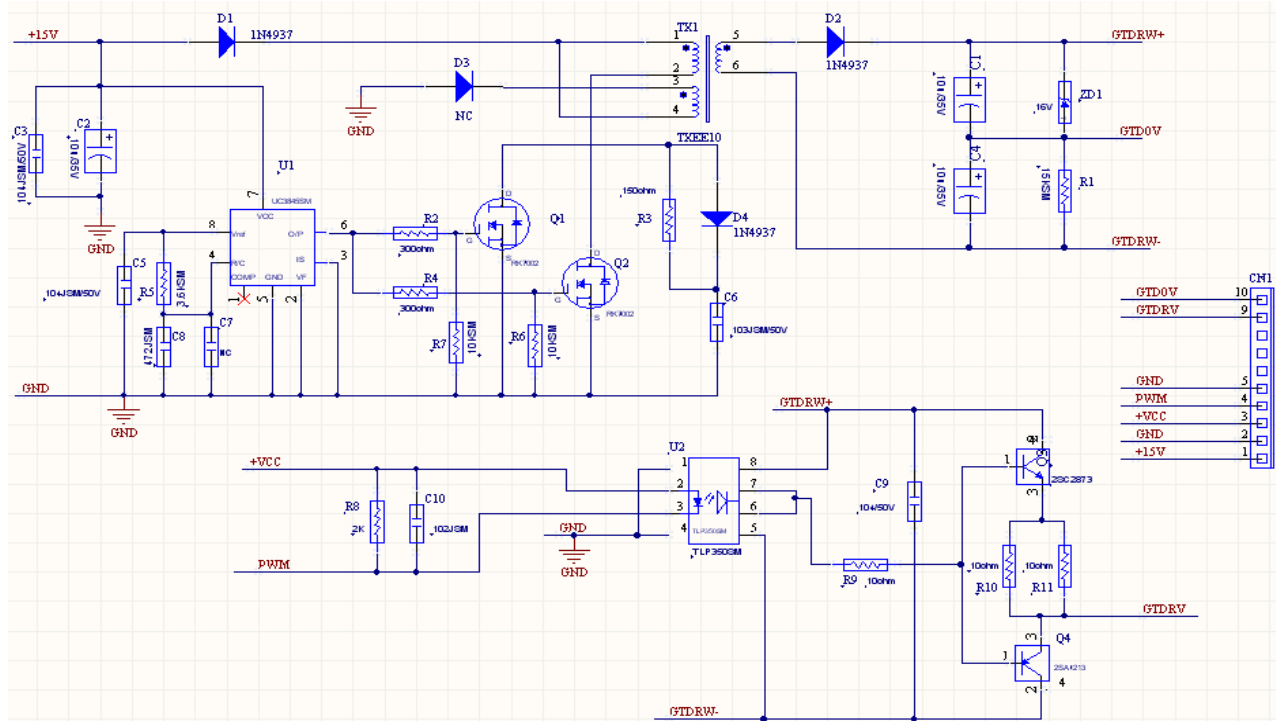
$$L_{\text{min_1}} := \frac{U_{\text{busdc}}}{2 \cdot f_{\text{sw}} \cdot I_{\text{rp_1}}} \quad \text{The max ripple at the line zero point, } d=0.5$$

$$L_{\text{min_1}} \text{ float, 4} \rightarrow 0.007976$$

So we select the Inductance value is $L := 9000 \mu\text{H}$

Hardware Design Review

- IGBT driver



The single 15V power input IGBT driver is used in this project. The driver was designed for IGBT application with the maximum F_s 40kHz.

Hardware Design Review

- **Auxiliary Power**

The project did not design a three phase input auxiliary power for the system, all the power is from the external +15V adapter.

- The +5V is generated by the PTH08080 with the +15V input
- The +3.3V is generated by the TLV1117-33, with the +5V input
- The -15V used by the HCT, is generated by the DCH010515S with +5V input.

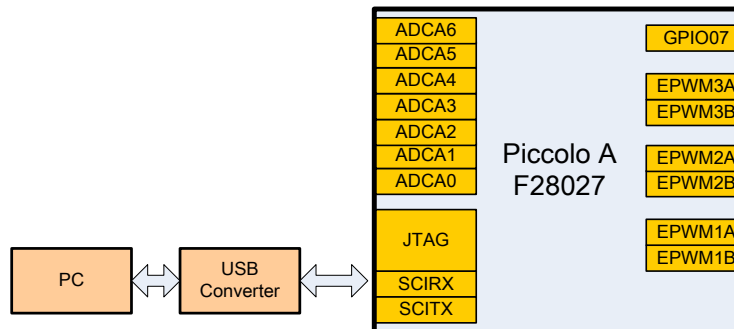
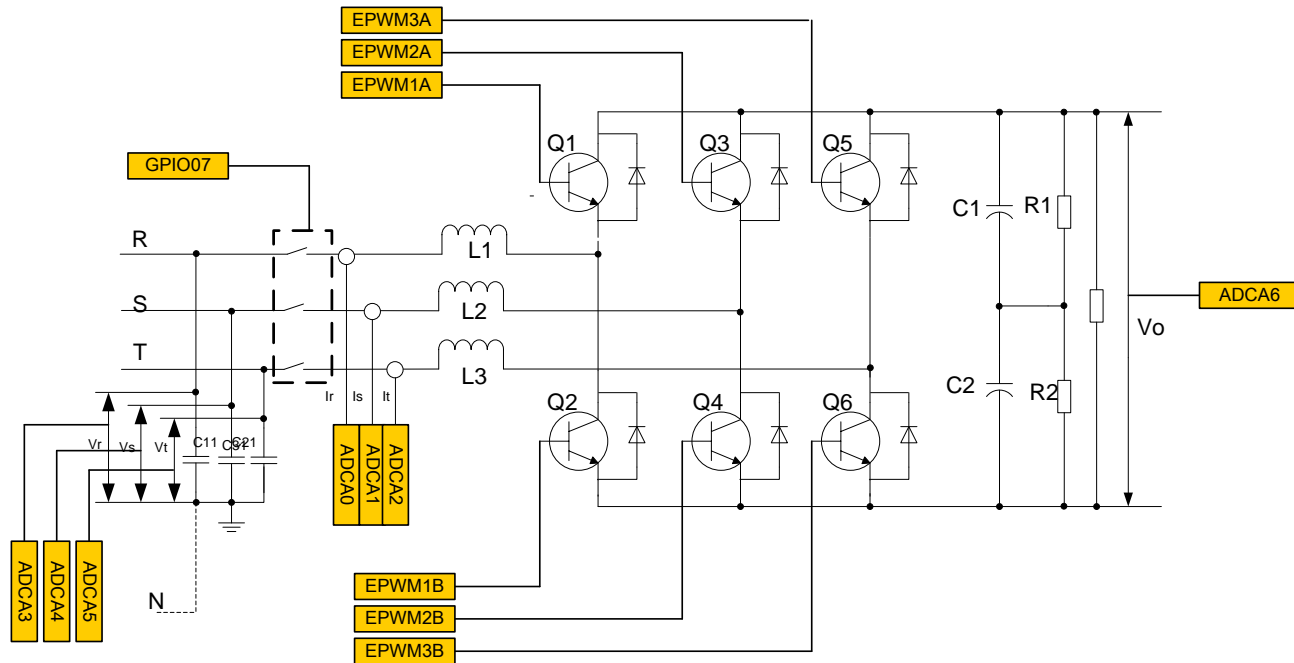
Hardware Design Review

- **Soft start circuit**

When the line voltage connect to the board, the bus capacitor will be charged by the soft start circuit, and the voltage will rise to about 300V. The soft start must be finished before the converter start to work. In order to charge the bus in a limited current, there is a 1k/5w resistor in each phase. Besides, 3 relays are used to connect the line input to softstart circuit.

Hardware Design Review

- MCU interface

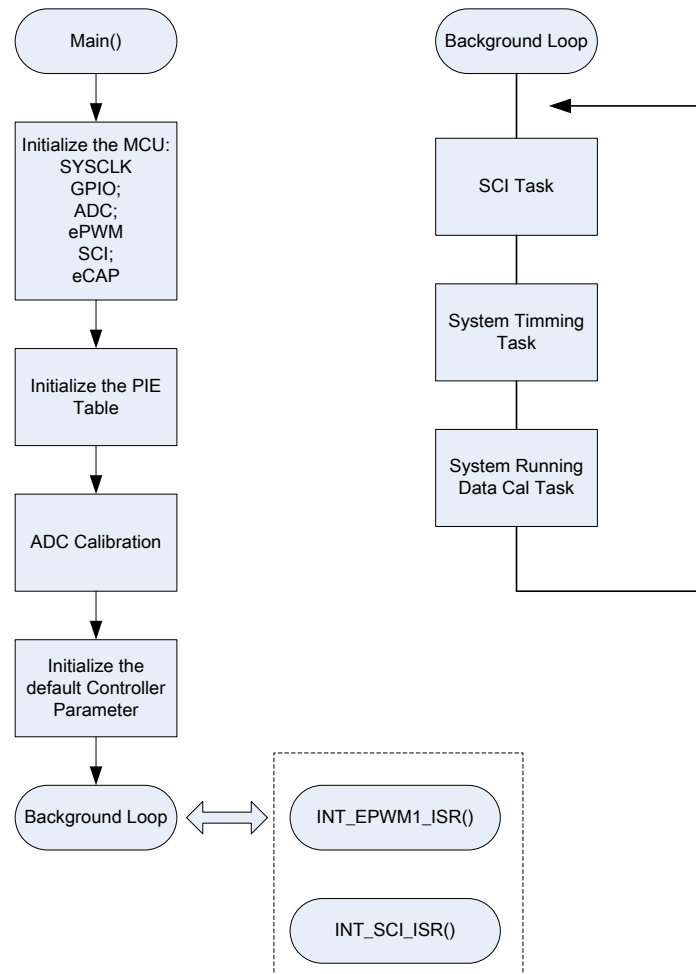


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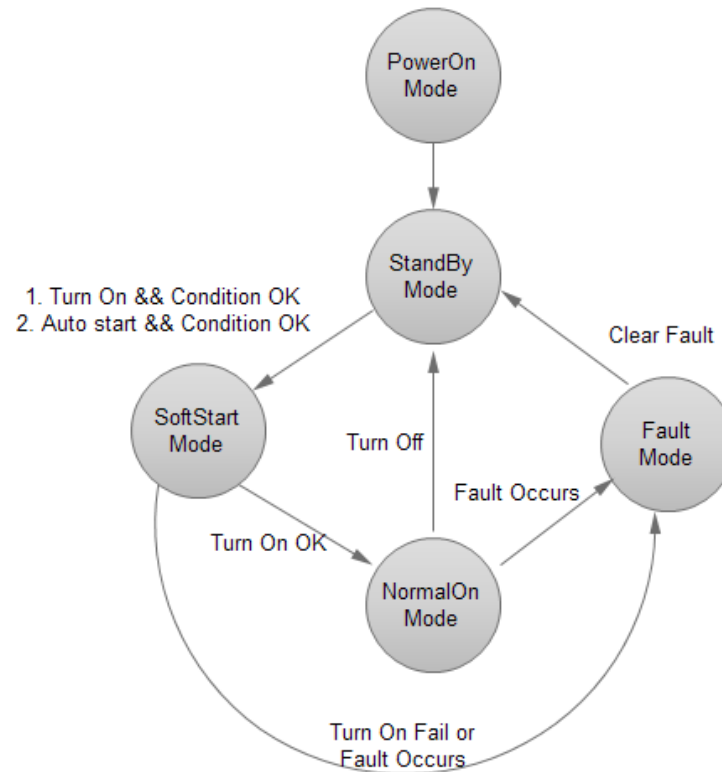
Software Design Review

- **Software Flow**



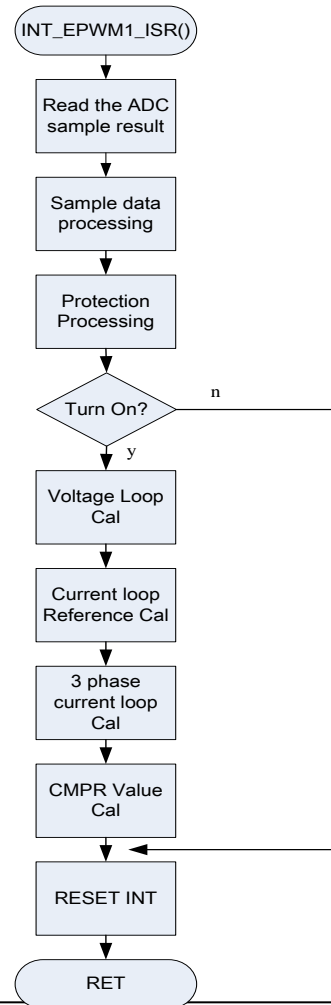
Software Design

•System Timing – Status machine



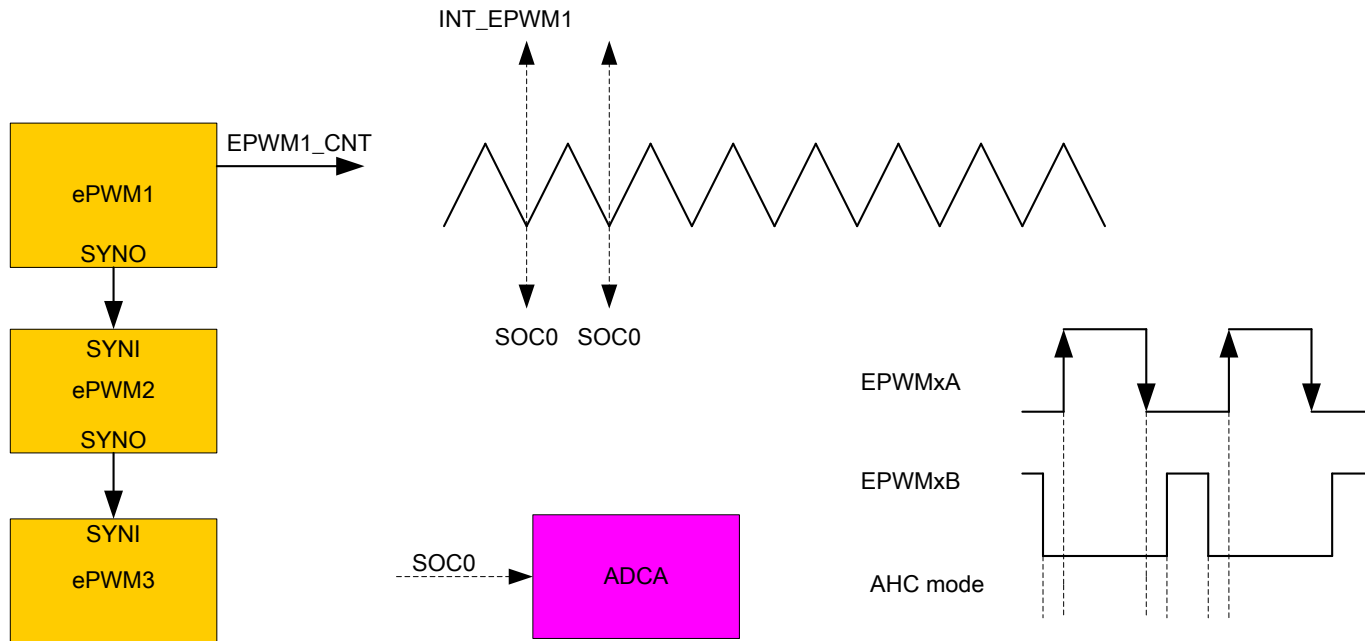
Software Design Review

- **Software Flow**



Software Design Review

- **ADC & ePWM**

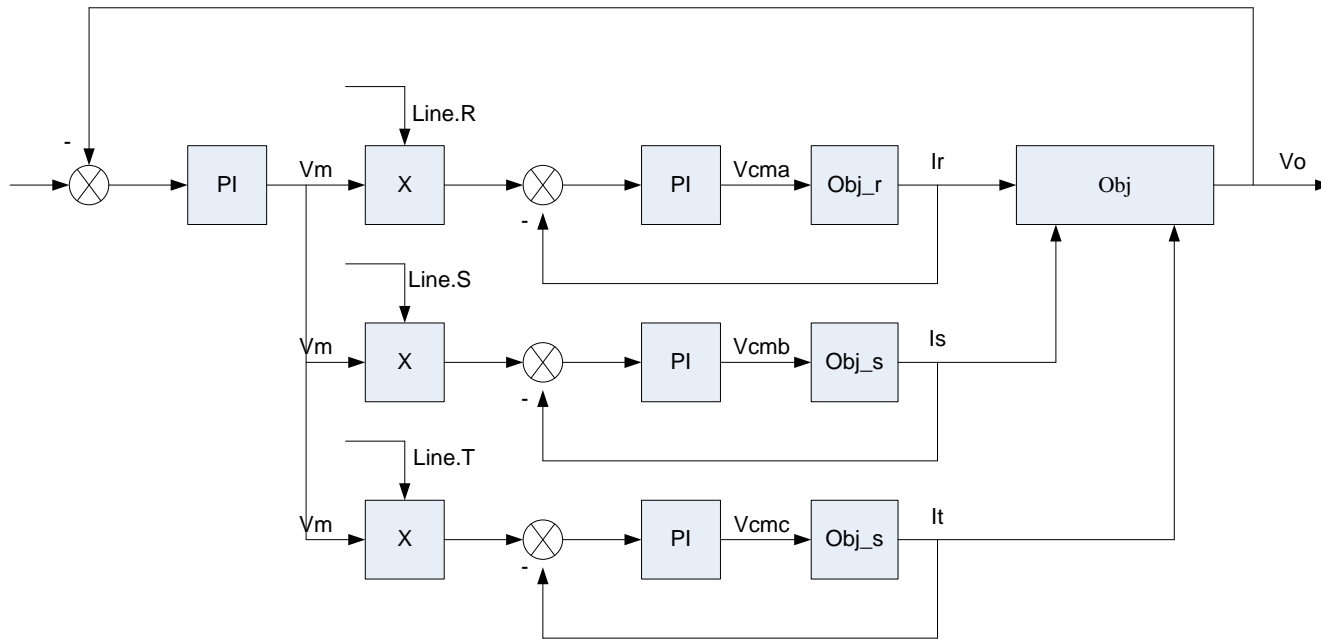


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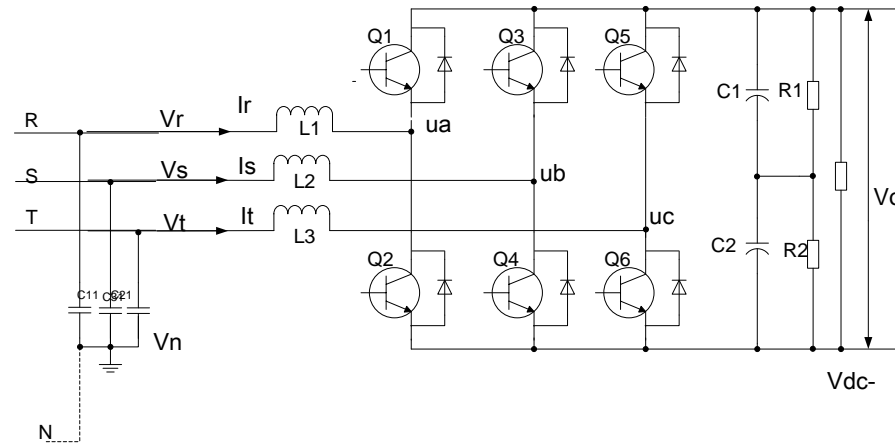
Close loop controller design

- The Direct Current close loop diagram



Close loop controller design

- The current loop object analysis



For phase R, the following equation is satisfied:

$$L \frac{dI_r}{dt} + rI_r = V_r - u_a$$

$$u_a = d_1 V_o + V_{dc-}$$



$$L \frac{dI_r}{dt} + rI_r = V_r - d_1 V_o - V_{dc-} \text{ -----(1)}$$

Close loop controller design

- **The current loop object analysis**

From the same method, we can get:

$$L \frac{dI_s}{dt} + rI_s = V_s - d_2 V_o - V_{dc-} \text{ -----(2)}$$

$$L \frac{dI_t}{dt} + rI_s = V_t - d_3 V_o - V_{dc-} \text{ -----(3)}$$

If the three phase system is balance, then add up (1) , (2) and(3) ,we can get:

If we ignore the high order harmonic wave

$$V_{dc-} = -\frac{1}{3}(d_1 + d_2 + d_3)V_{dc}$$

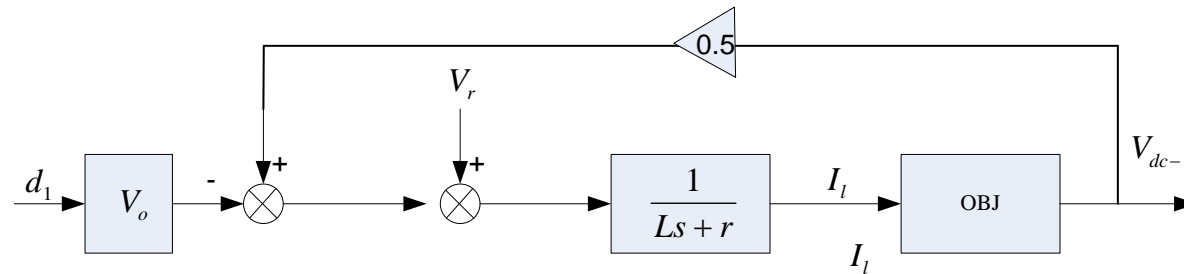


$$V_{dc-} = -\frac{1}{2}V_{dc}$$

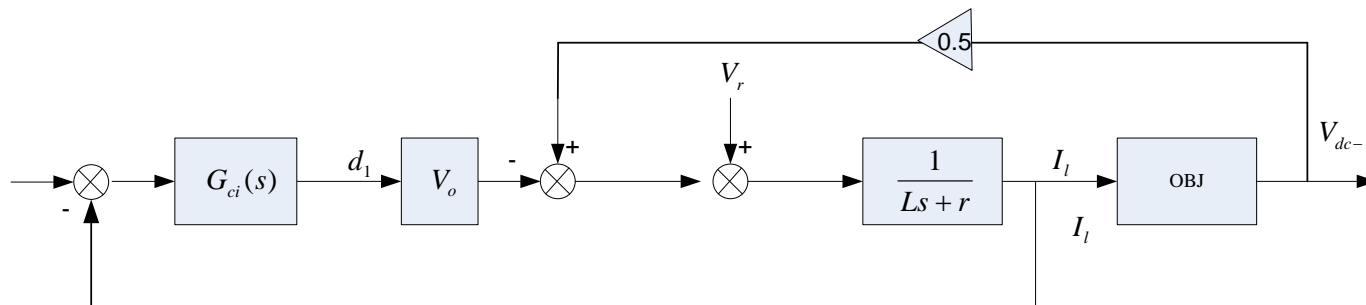
Close loop controller design

- **The current loop object analysis**

From the Lap conversion, we can get:



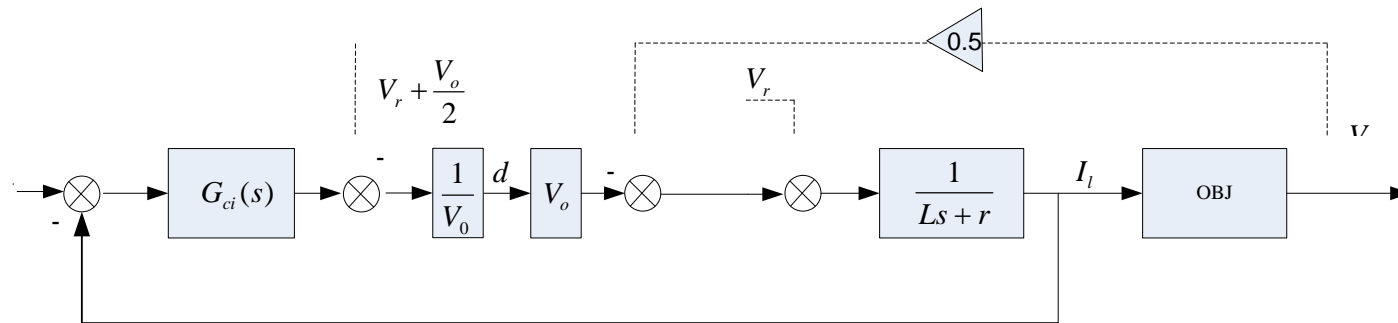
So, the current close-loop diagram is below



Close loop controller design

- **The current loop object analysis**

From the last diagram, we can see the G_s is enclosed by the current loop, so the open-loop transfer function is difficult to deal with. But we can use the feedback linearization to simplify the control loop.



Close loop controller design

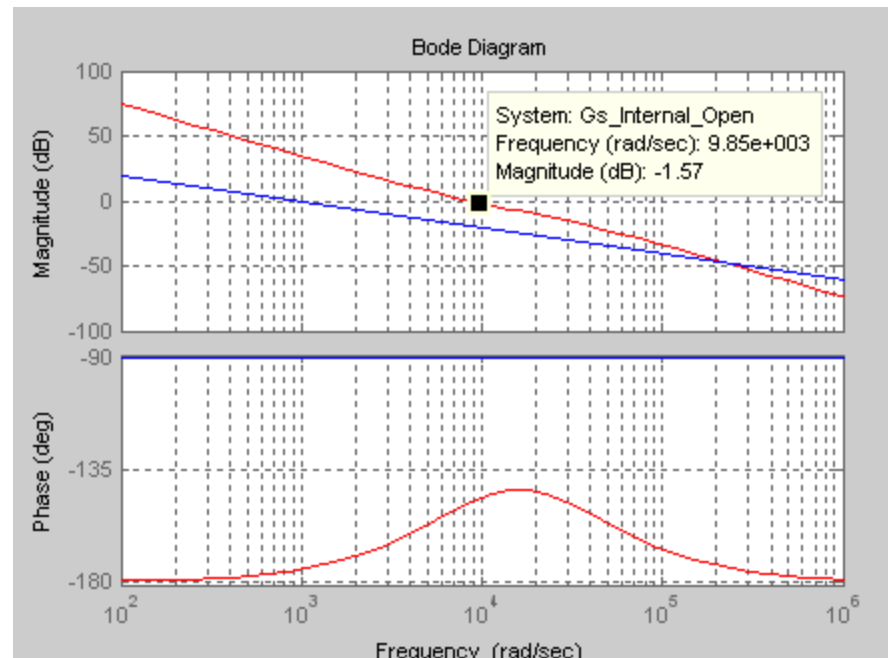
- **The current loop controller**

From the analysis above, we can select the close loop controller and the plot the bode figure for the internal loop.

$$G_{ci}(s) = \frac{K(s+a)}{s(s+b)}$$



$$G_{ci}(z) = \frac{a_{c_0} + a_{c_1}z^{-1} + a_{c_2}z^{-2}}{1 + b_{c_0}z^{-1} + b_{c_1}z^{-2}}$$



Close loop controller design

- **The voltage loop controller**

For the system with a large storage capacitor, we can easily choose the voltage controller by experience. In this system, we choose the following controller:

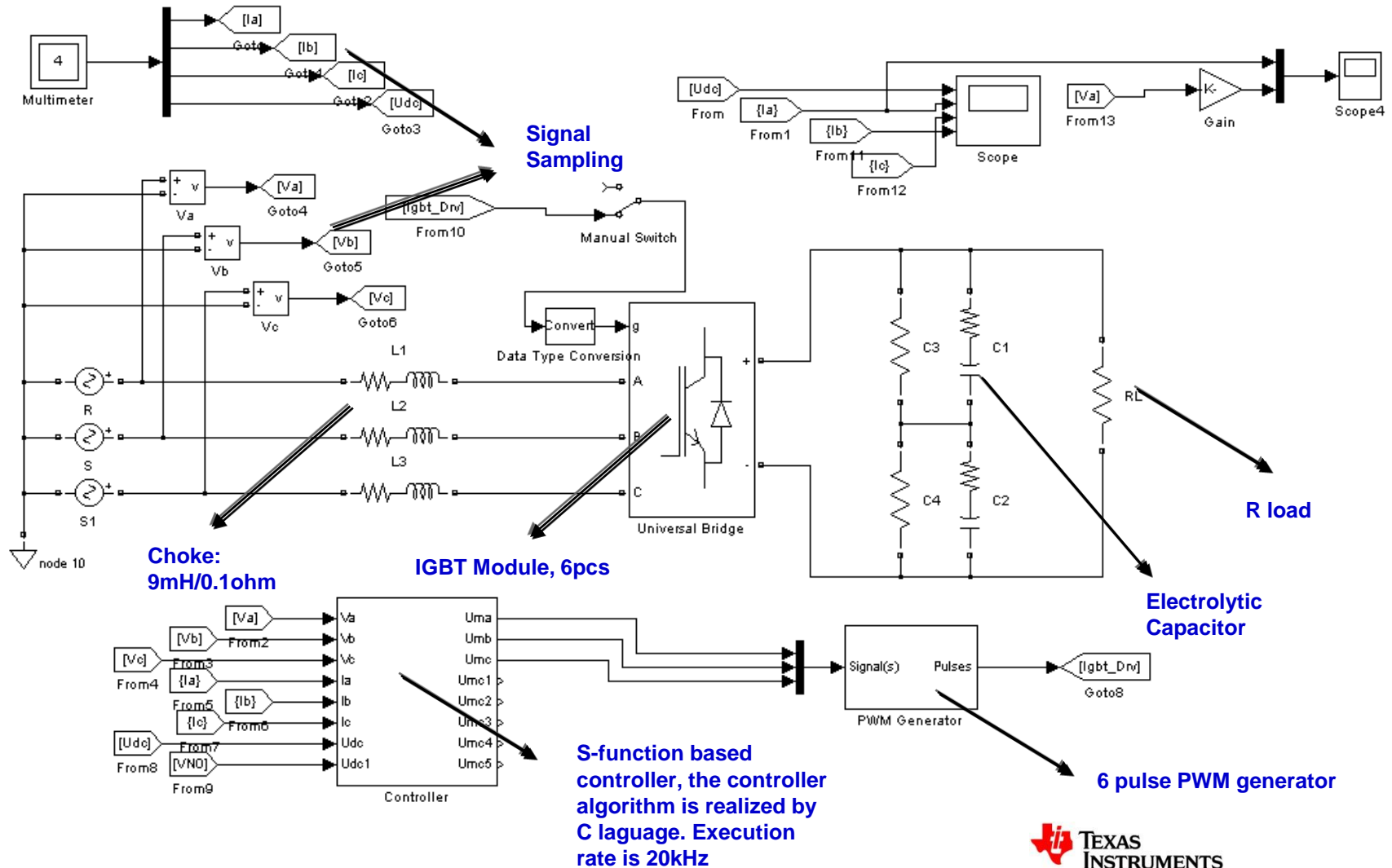
$$G_{cv}(s) = \frac{K(s+a)}{s(s+b)}$$

Use the parameter above, we can build a simulation system by using the Matlab. The following tools are used:

- m-file editor
- s-function by C language
- Simulink
- SimPowerSys

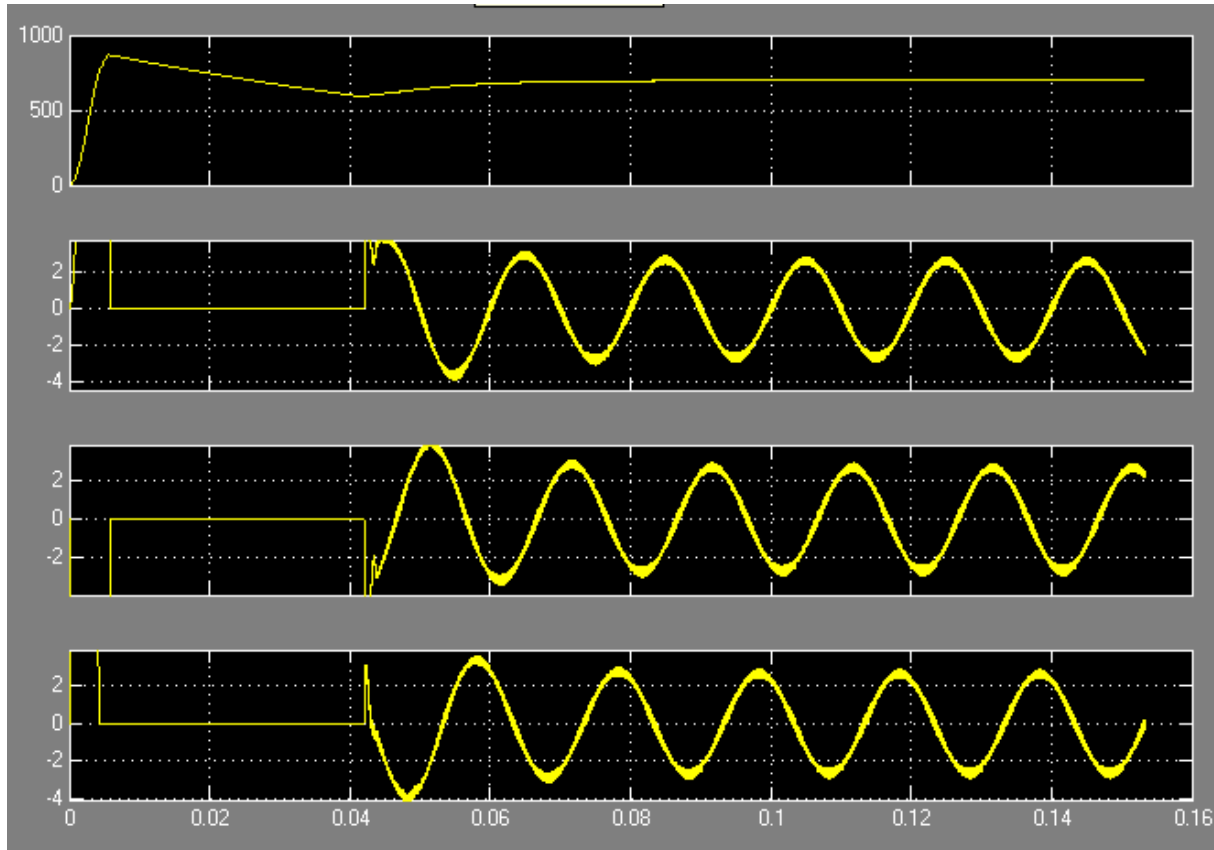
Close loop Controller Design

- The simulation diagram



Close loop Controller Design

- **The simulation result**



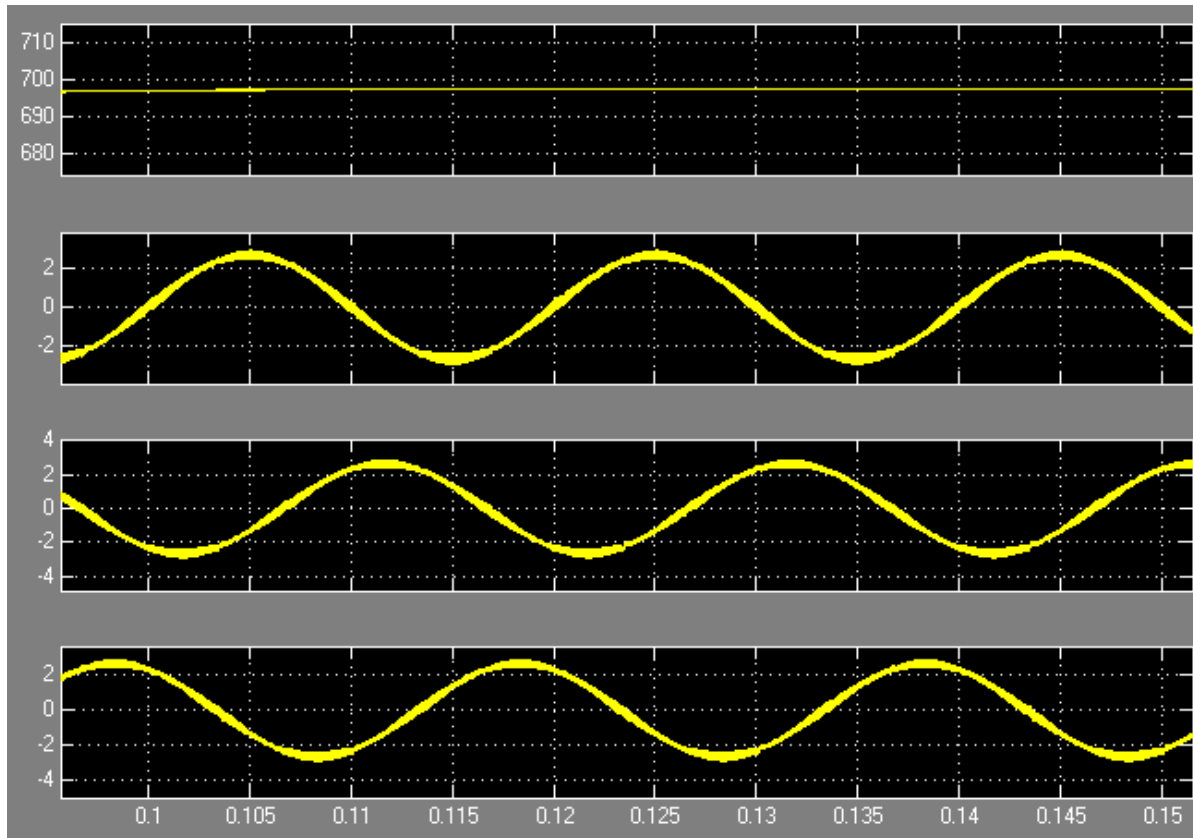
CH1: V_{dc}
CH2: R phase current
CH3: S phase current
CH4: T phase current

Conditions:

1. Directly input the line voltage to the converter from 0~0.04s;
2. At 0.04s, step to 700V_{dc} reference;
3. Full load.

Close loop Controller Design

- **The simulation result --- Stable state**



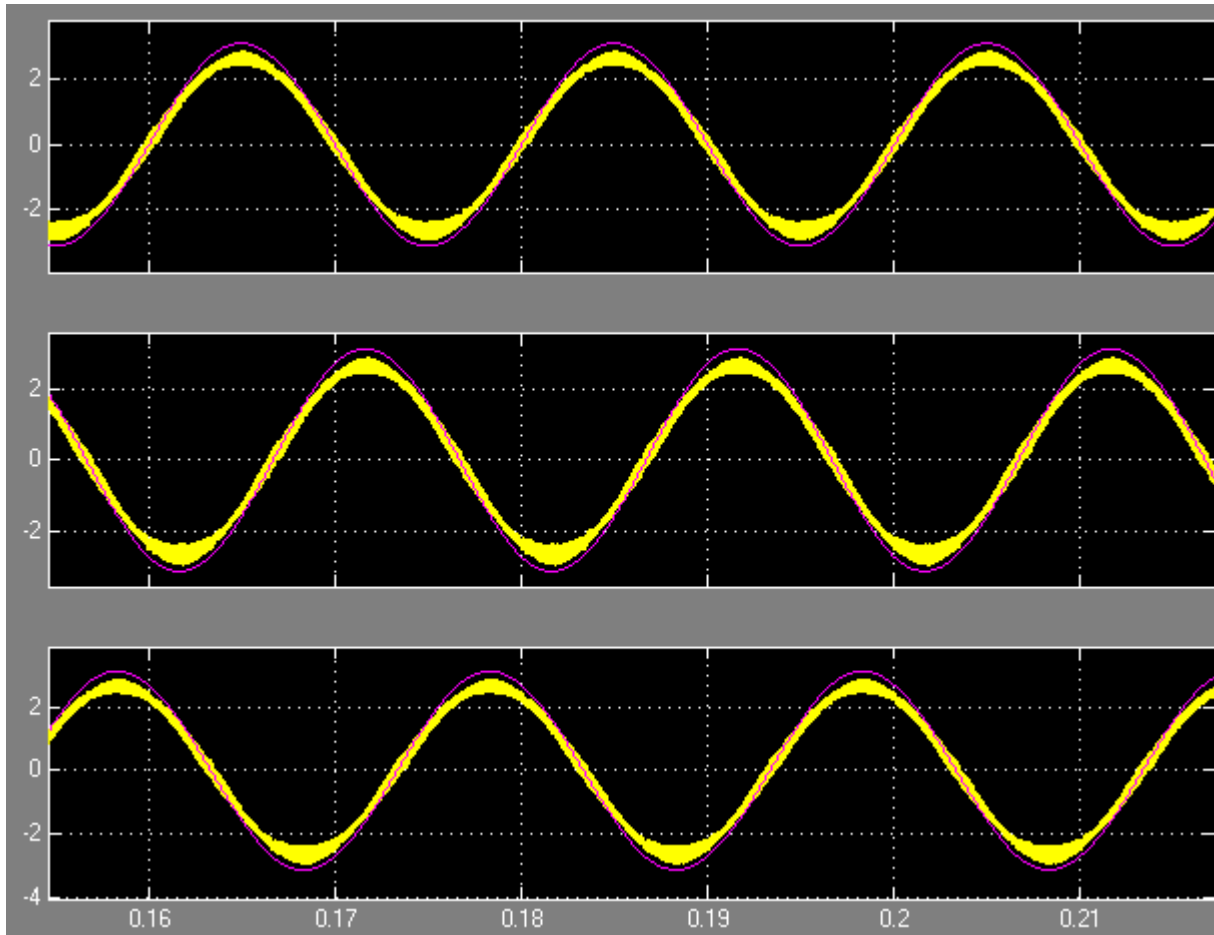
CH1: V_{dc}
CH2: R phase current
CH3: S phase current
CH4: T phase current

Conditions:

Full load at stable state.

Close loop Controller Design

- **The simulation result --- Stable state**

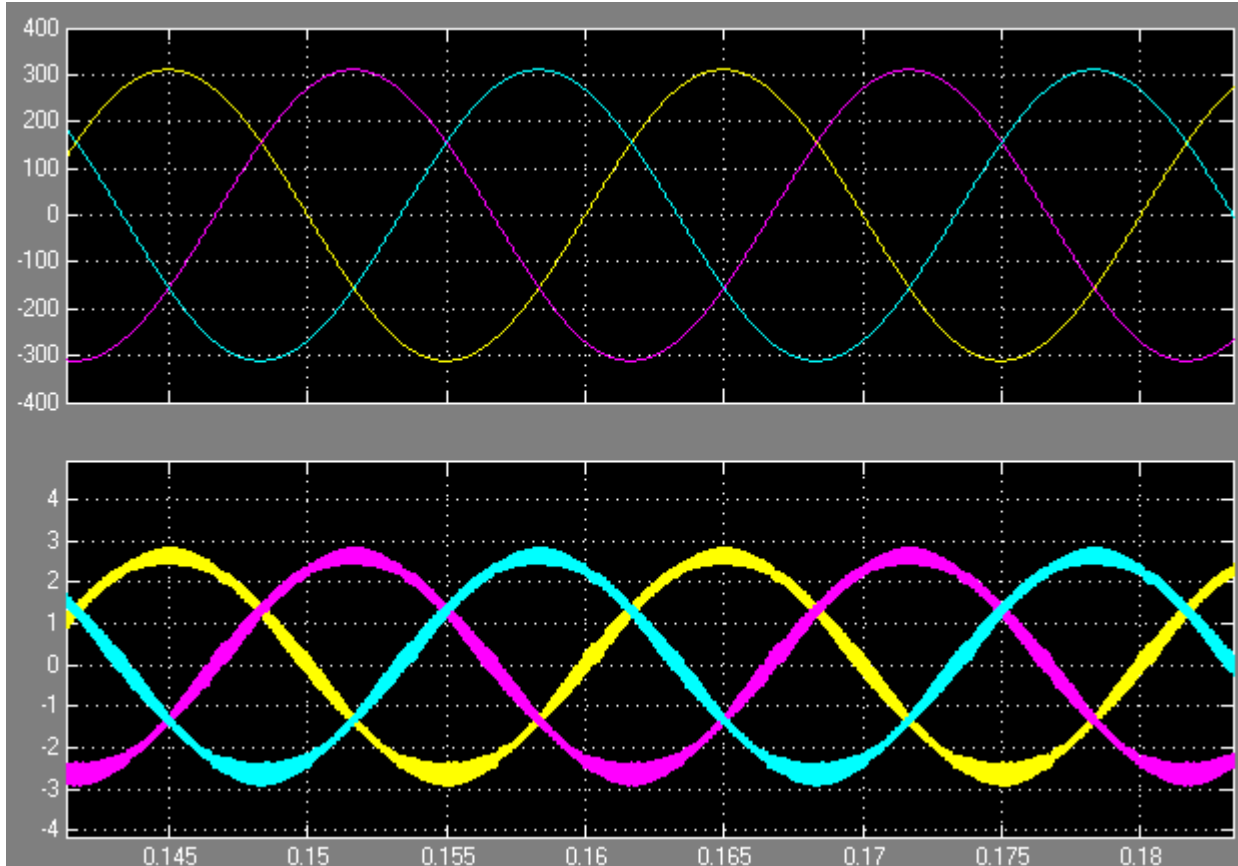


Yellow : phase current

Red: Line Voltage(1/100)

Close Loop Controller Design

- **The simulation result --- Stable state**

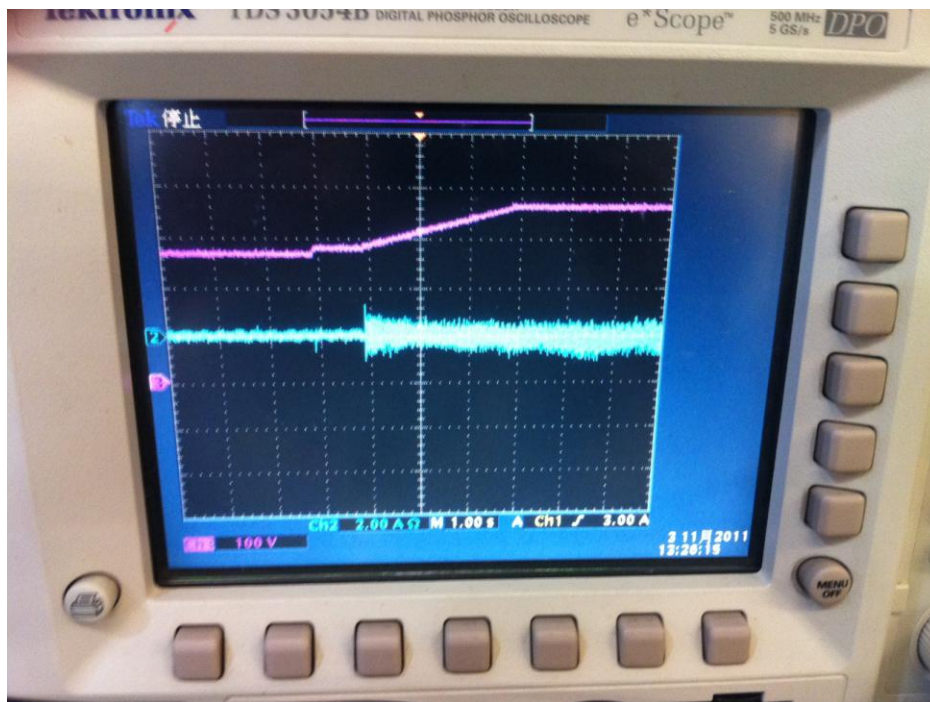


CH2 : phase current

CH1: Line Voltage(1/100)

Close Loop Controller Design

- **Runing Result – Bus Softstart**

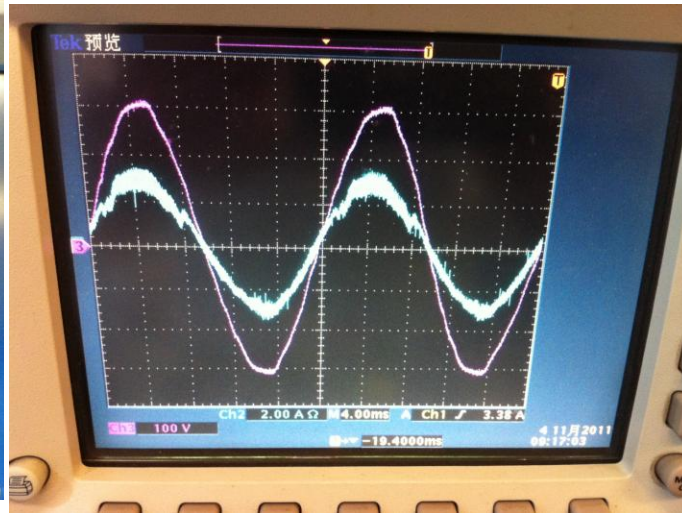
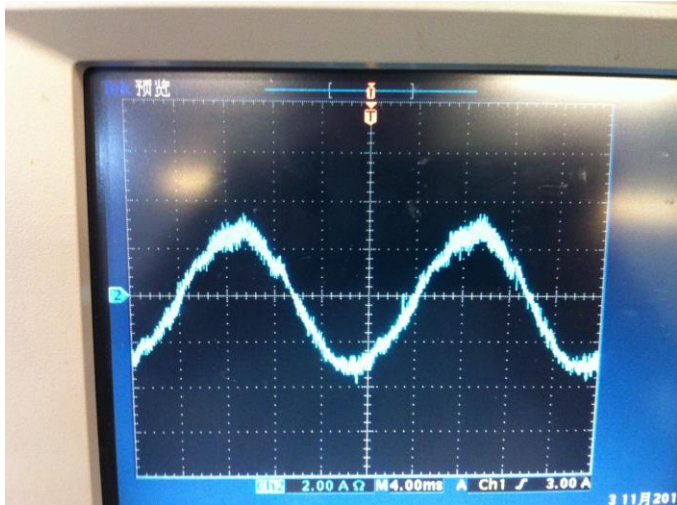


CH3 : Bus Voltage
(200V/div)

CH2: R Phase Input
Current

Close Loop Controller Design

- **Runing Result – Current & Voltage**

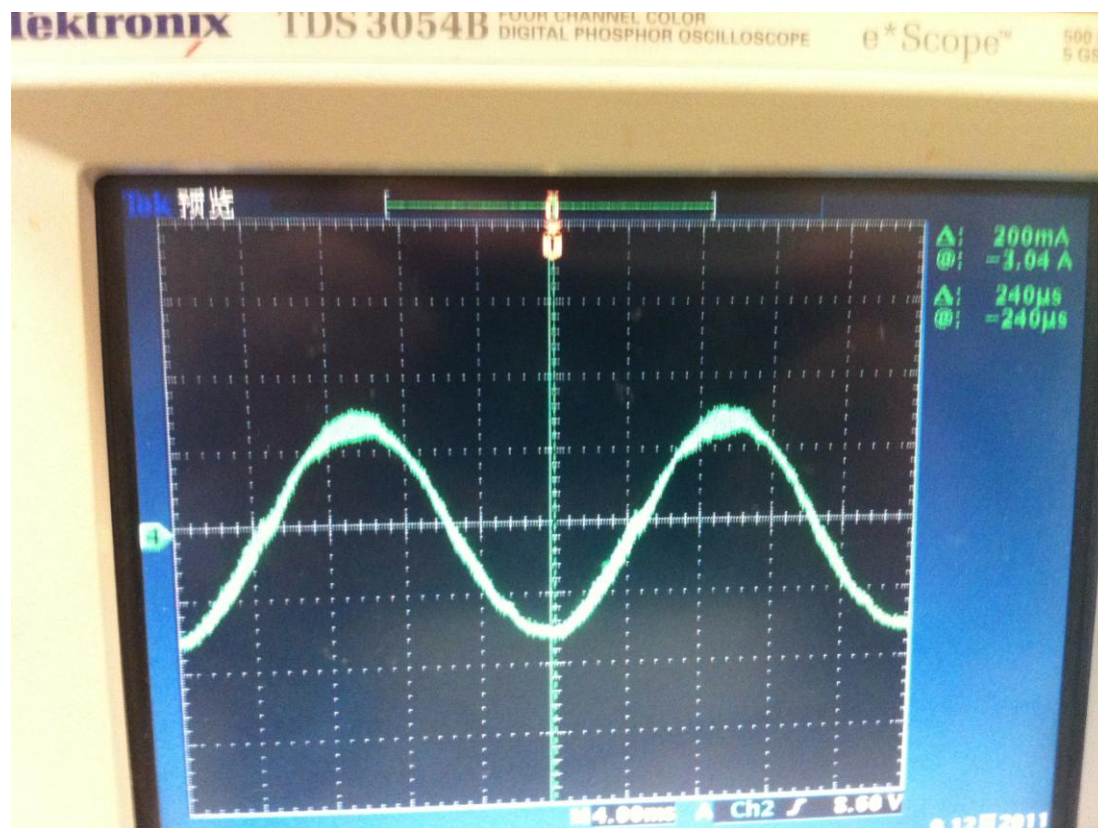


H3 : Line Voltage
(200V/div)

H2: R Phase Input
Current

Close Loop Controller Design

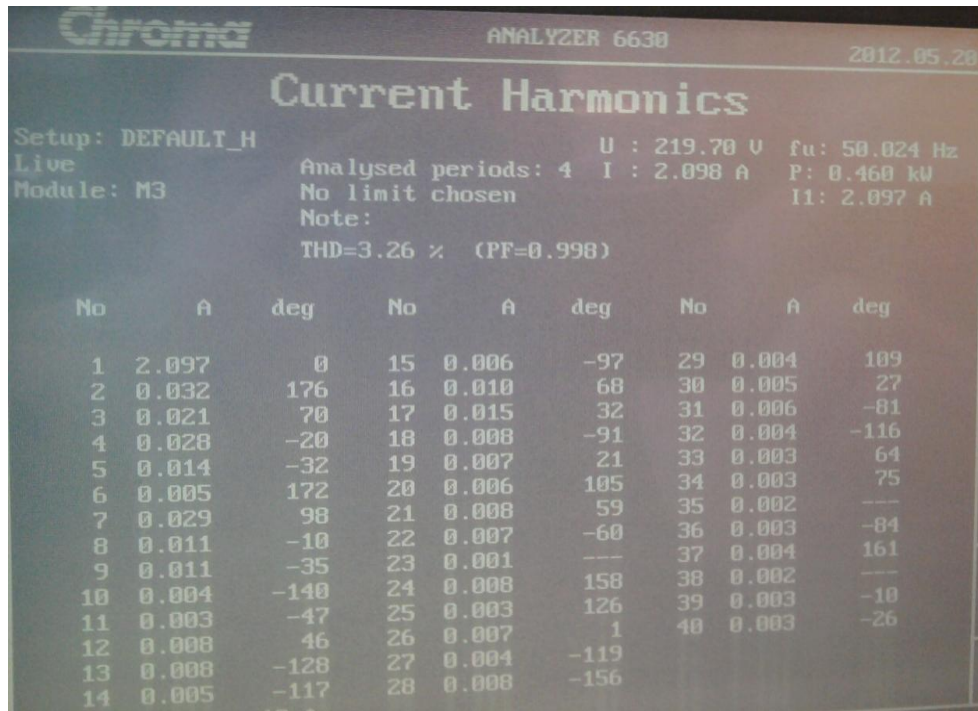
- **Runing Result – The Optimized Current**



CH2: R Phase Input
Current

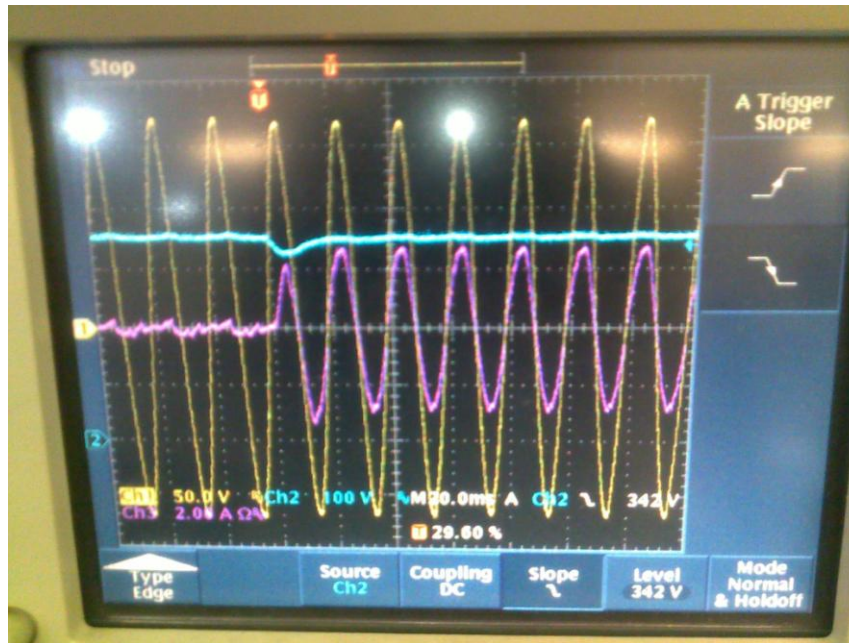
Close Loop Controller Design

- **Runing Result – The THD & PF**



Close Loop Controller Design

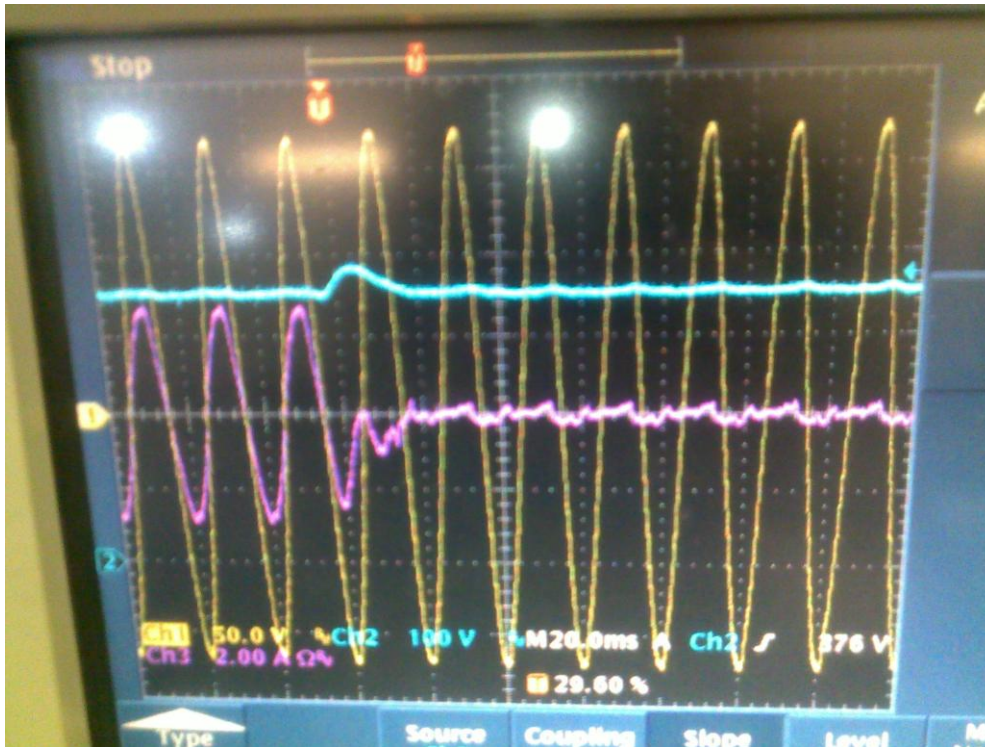
- **Runing Result – The Dynamic Response**



CH1 : Line Voltage
(100V/div)
CH2: Bus Voltage
CH3: Phase Current

Close Loop Controller Design

- **Runing Result – The Dynamic Response**



CH1 : Line Voltage
(100V/div)
CH2: Bus Voltage
CH3: Phase Current

Q&A

Thanks!