3 phase PFC and APF application with TI C2000 MCU

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Texas Instruments

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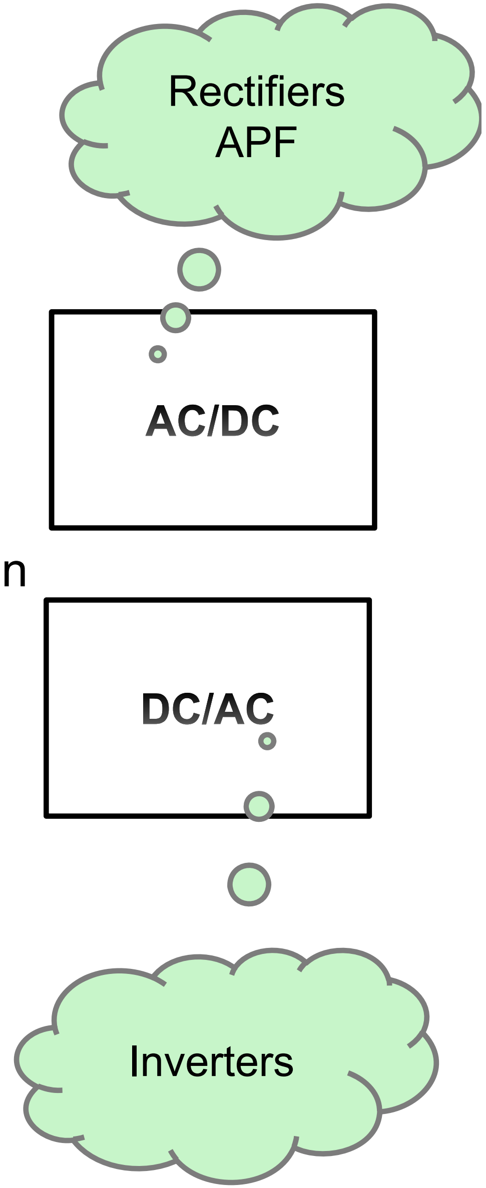
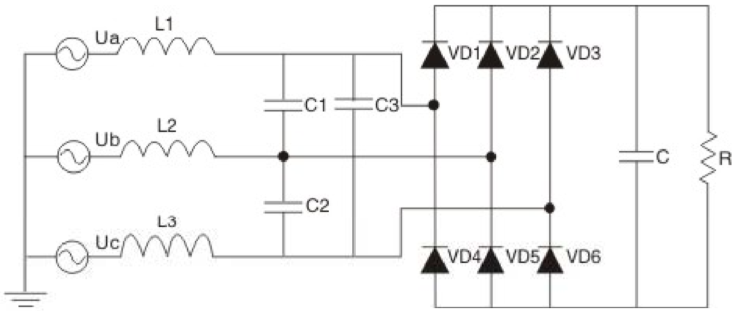
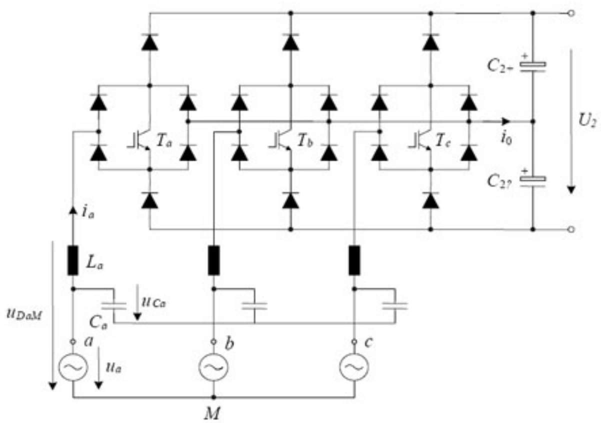
- Introduction
- PFC Application
  - Software Design
  - Close-Loop Controller
- APF Application
  - Software Design
  - Close-Loop Controller
- *Unbalanced grid voltage treatment
- TI EVM Implementation

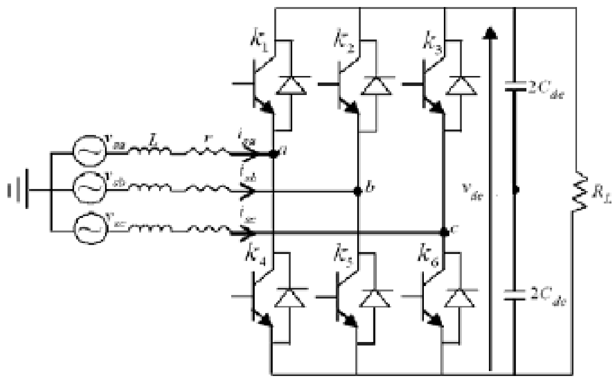
Introduction

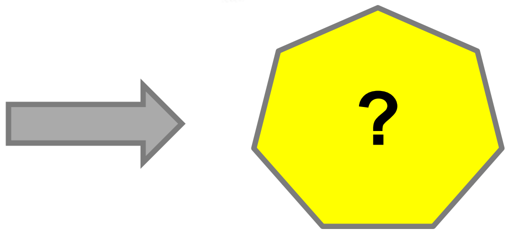
- 3 phase Power electronics rectifier device
  - Objectives
    - AC to Dc , get constant Dc Voltage
    - Harmonic regulation/compensation
    - Active power/reactive power regulation/compensation





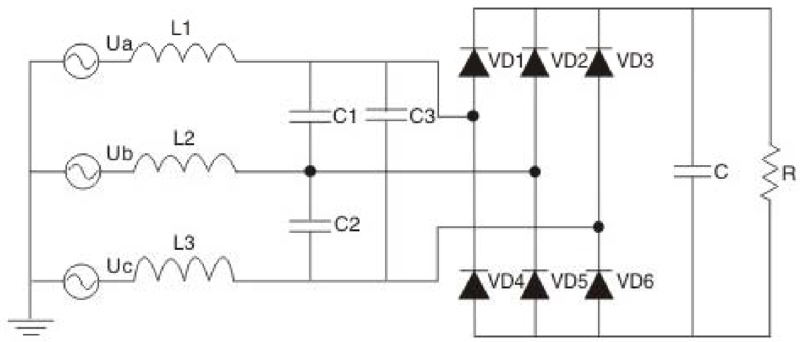


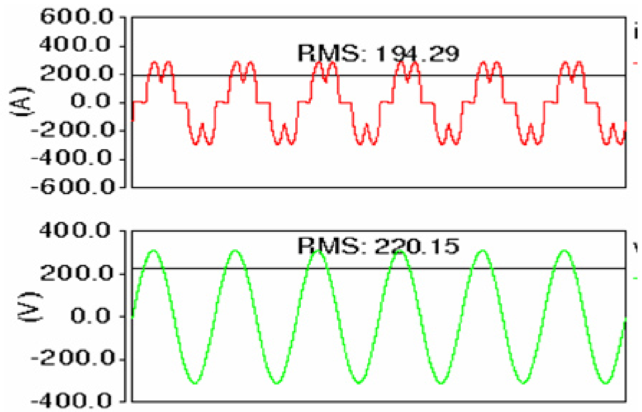




Introduction

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



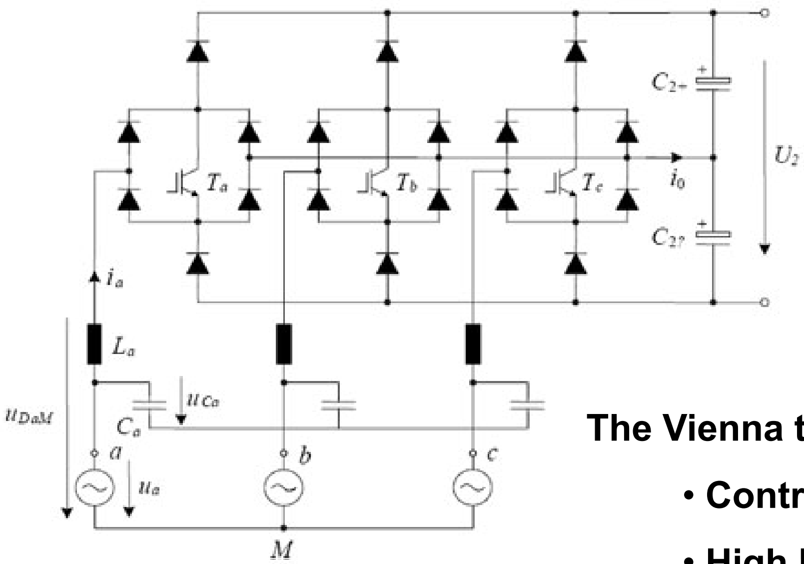


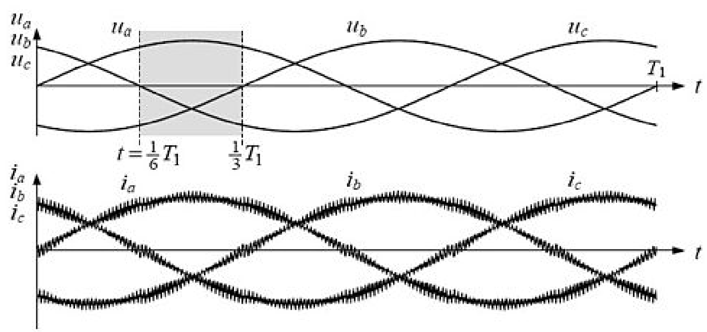
It is a non-controllable rectifier, the input current contains many harmonic waves. (ie, 5,7,11,13….)

So the PF and the THDi performance is bad.

Introduction

- **Three Phase PFC Topology - Vienna topology**



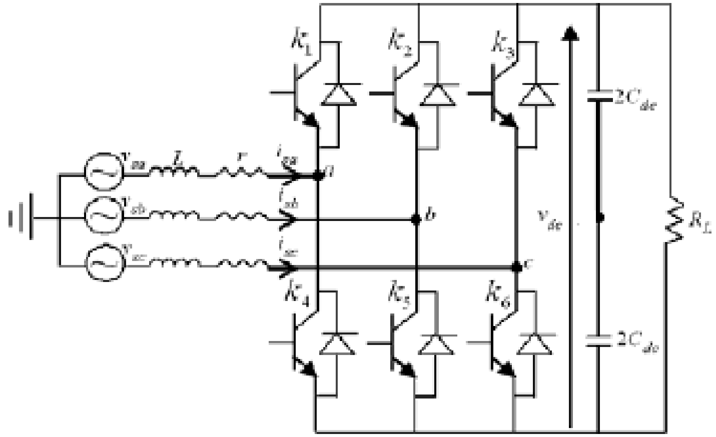


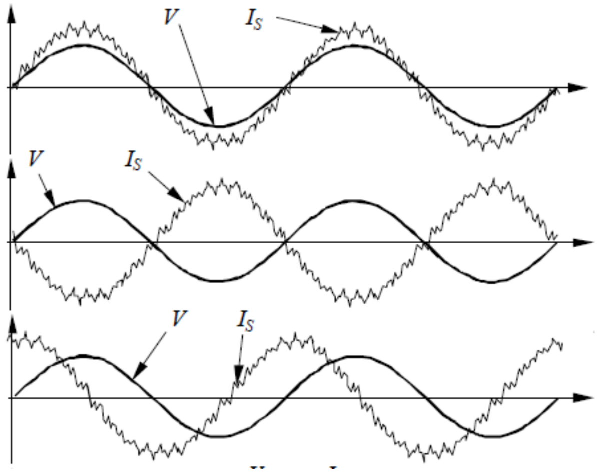
The Vienna topology is a controllable active power rectifier.

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

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**
- **Reversible bi-direction current**

Harmonic related Standards

- IEEE-std-519-1992 Total THDI < 5%
- IEC_61000-3-2-2009
- GB-T_14549-1993

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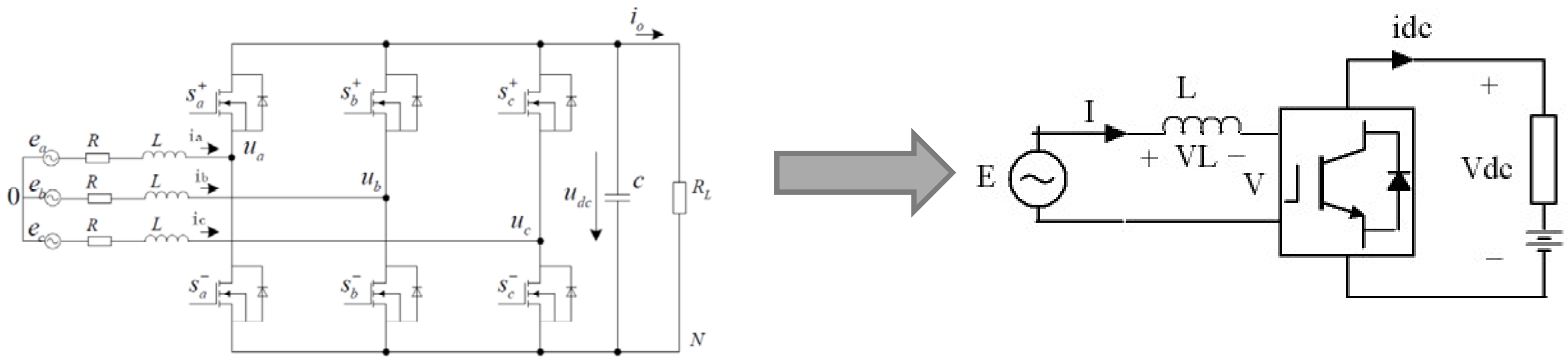
PFC Application

- **3-Phase 2-level PWM Rectifier principle**



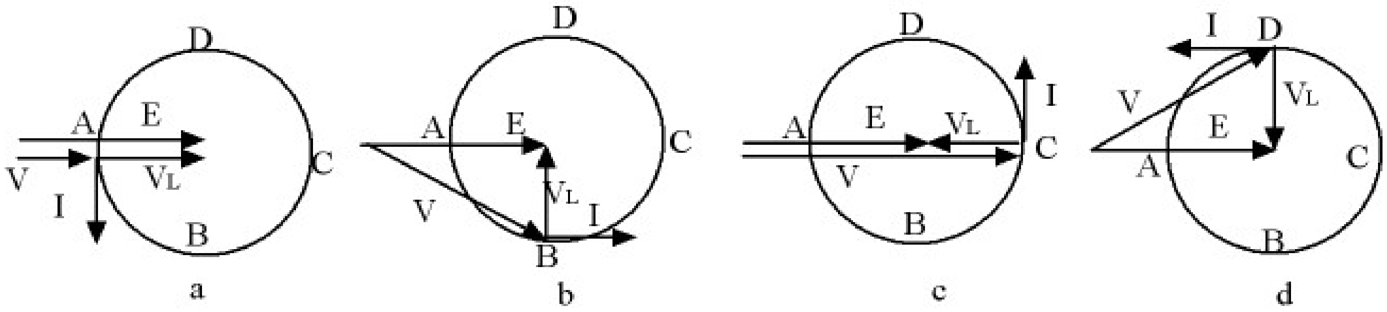
The PWM Rectifier can be equivalent to the figure above, then we can get the the equation:

$$E = V_L + V$$

$$i_{ac} v_{ac} = i_{dc} v_{dc}$$

PFC Application

- **Three Phase PWM Rectifier principle**



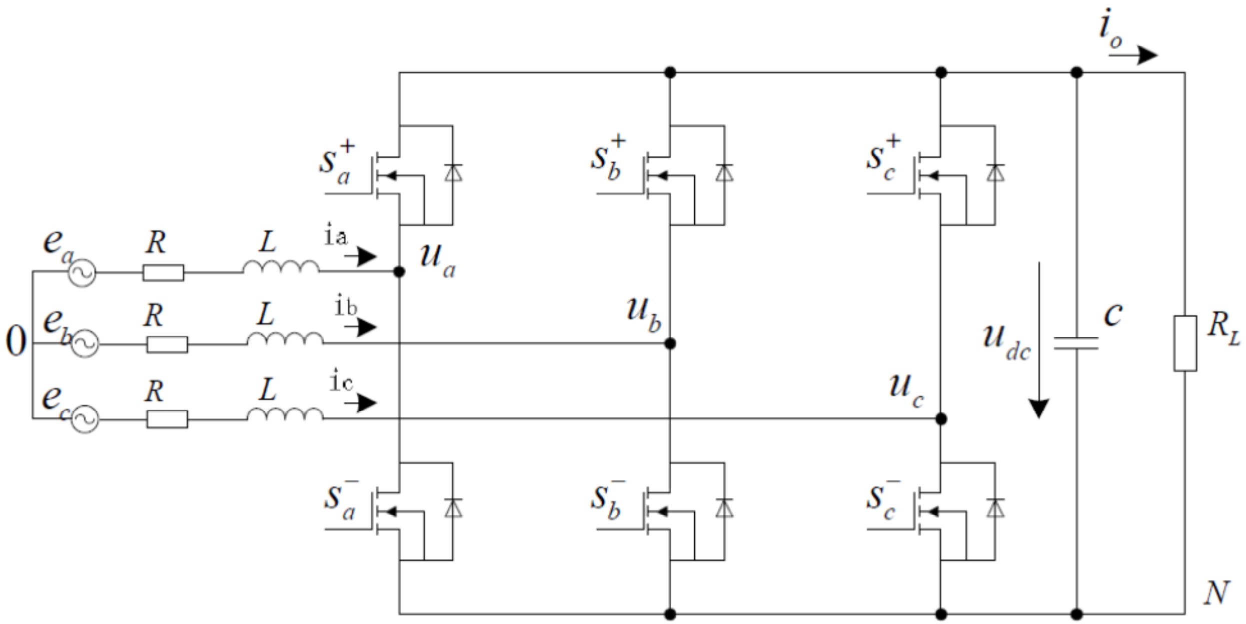
When the *V* trace from the A to B in the above figure, the converter can work in rectifier mode, when the V at the B, then the we can get the highest power factor.

Control Objective:

-Constant Bus Voltage

-Sinusoidal current wave, PF= 1

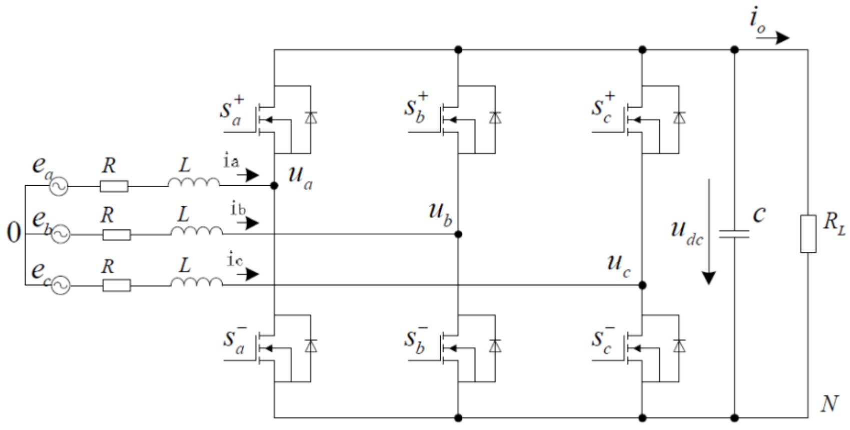
Modeling



- e_a , e_b, e_c → source voltages;
- i_a, i_b, i_c → line currents;
- u_a , u_b, u_c → rectifier input voltages;
- u_{dc} → bus voltage;
- R → resistance of the line reactor;
- L → inductance of the line reactor;
- C → smoothing capacitor;
- i_o → load current;
- R_L → resistance;

Modeling

$$\begin{cases} L\dfrac{di_a}{dt} + Ri_a = e_a - (u_a + u_{N0}) \\ L\dfrac{di_b}{dt} + Ri_b = e_b - (u_b + u_{N0}) \\ L\dfrac{di_c}{dt} + Ri_c = e_c - (u_c + u_{N0}) \\ C\dfrac{du_{dc}}{dt} = i_a * s_a + i_b * s_b + i_c * s_c - i_0 \end{cases}$$



$$s_k = \begin{cases} 1, & \text{up switch closed, down switch opened} \\ 0, & \text{up switch opened, down switch closed} \end{cases}$$

$$\begin{cases} u_k = u_{dc} * s_k, (k = a, b, c) \\ u_{N0} = -\dfrac{u_{dc}}{3}(s_a + s_b + s_c) \end{cases}$$

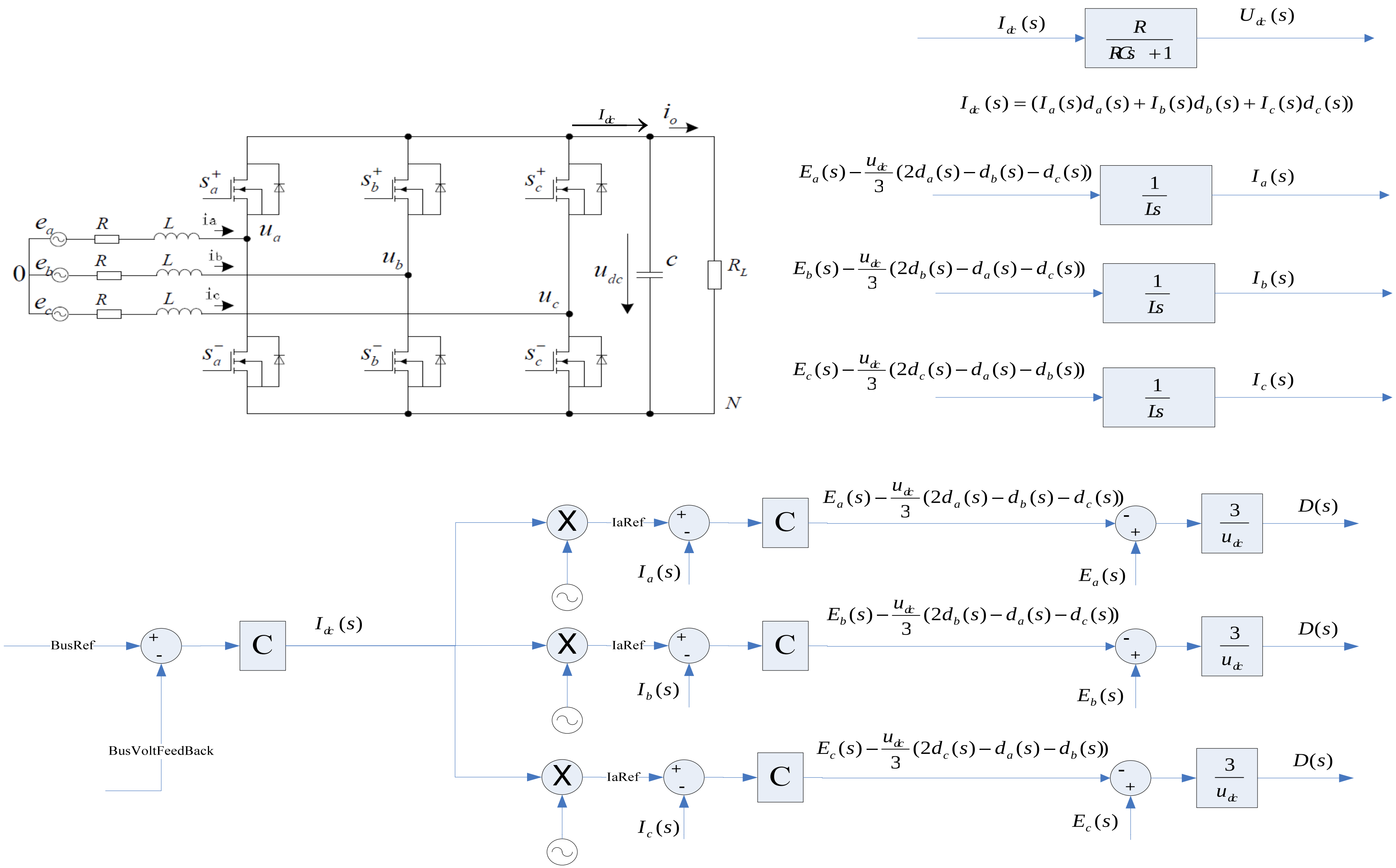
$$\begin{cases} L\dfrac{di_a}{dt} = e_a - \dfrac{u_{dc}}{3}(2d_a - d_b - d_c) \\ L\dfrac{di_b}{dt} = e_b - \dfrac{u_{dc}}{3}(2d_b - d_a - d_c) \\ L\dfrac{di_c}{dt} = e_c - \dfrac{u_{dc}}{3}(2d_c - d_a - d_b) \\ C\dfrac{du_{dc}}{dt} = (i_a d_a + i_b d_b + i_c d_c) - \dfrac{u_{dc}}{R} \end{cases}$$

Frequency domain model

$$
\begin{cases}
L\dfrac{di_a}{dt} = e_a - \dfrac{u_{dc}}{3}(2d_a - d_b - d_c) \\
L\dfrac{di_b}{dt} = e_b - \dfrac{u_{dc}}{3}(2d_b - d_a - d_c) \\
L\dfrac{di_c}{dt} = e_c - \dfrac{u_{dc}}{3}(2d_c - d_a - d_b) \\
C\dfrac{du_{dc}}{dt} = (i_a d_a + i_b d_b + i_c d_c) - \dfrac{u_{dc}}{R}
\end{cases}
$$

$$
\begin{cases}
LsI_a(s) = E_a(s) - \dfrac{u_{dc}}{3}(2d_a(s) - d_b(s) - d_c(s)) \\
LsI_b(s) = E_b(s) - \dfrac{u_{dc}}{3}(2d_b(s) - d_a(s) - d_c(s)) \\
LsI_c(s) = E_c(s) - \dfrac{u_{dc}}{3}(2d_c(s) - d_a(s) - d_b(s)) \\
CU_{dc}(s) = (I_a(s)d_a(s) + I_b(s)d_b(s) + I_c(s)d_c(s)) - \dfrac{U_{dc}(s)}{R}
\end{cases}
$$

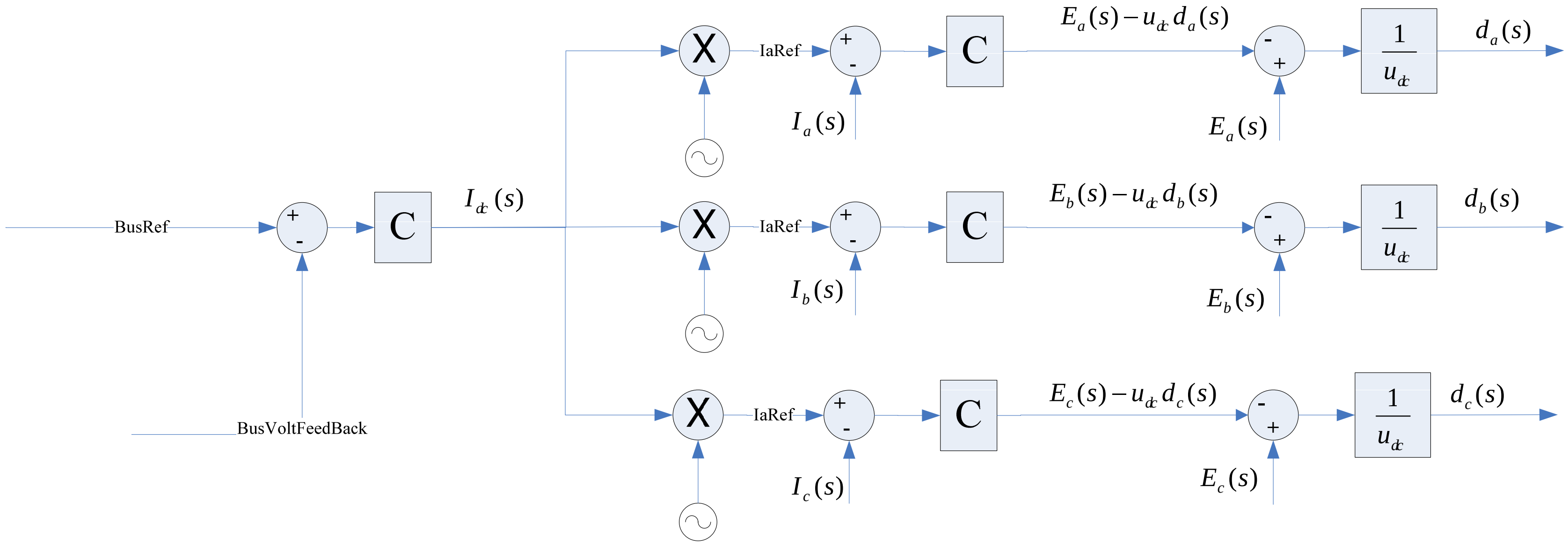
abc ordinate model & Direct Current Control



abc ordinate model & Direct Current Control

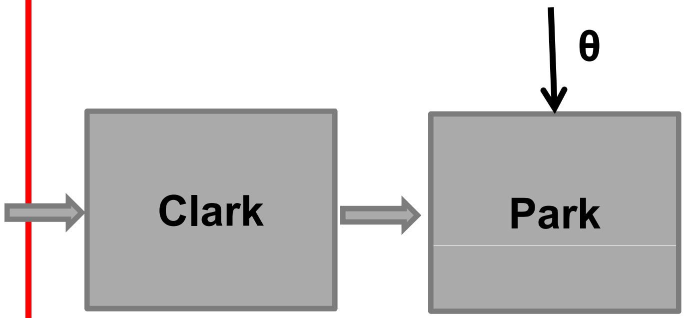
- In steady state, and with the balanced input voltage Ua + Ub + Uc = 0, Ia + Ib + Ic = 0 ,
- so the hypotheses could be made:

$$d_a(s) + d_b(s) + d_c(s) = 0$$



dq ordinate modeling

$$\begin{cases} L\dfrac{di_a}{dt} = e_a - \dfrac{u_{dc}}{3}(2d_a - d_b - d_c) \\ L\dfrac{di_b}{dt} = e_b - \dfrac{u_{dc}}{3}(2d_b - d_a - d_c) \\ L\dfrac{di_c}{dt} = e_c - \dfrac{u_{dc}}{3}(2d_c - d_a - d_b) \\ C\dfrac{du_{dc}}{dt} = (i_a d_a + i_b d_b + i_c d_c) - \dfrac{u_{dc}}{R} \end{cases}$$



$$V_a(t) + V_b(t) + V_c(t) = 0$$

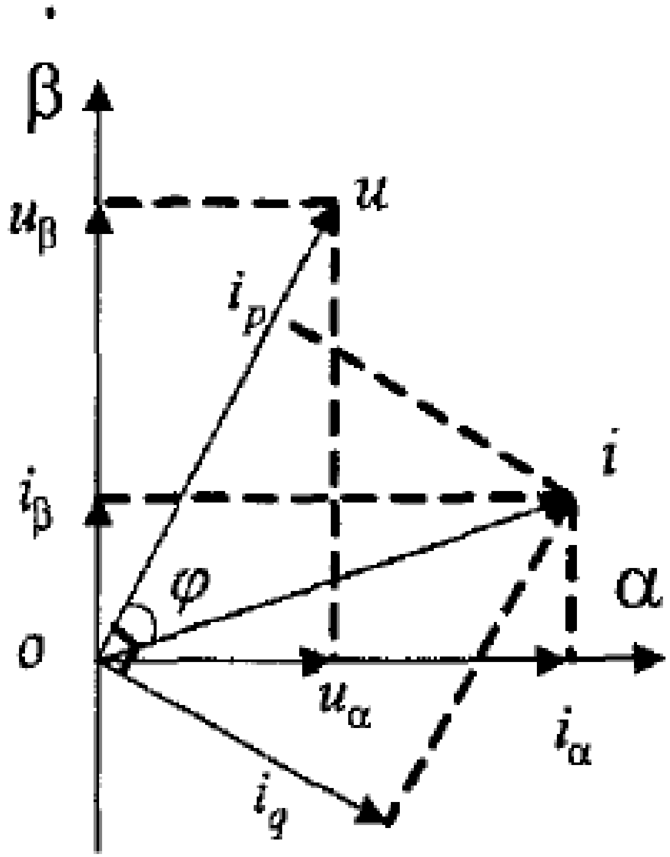
$$I_a(t) + I_b(t) + I_c(t) = 0$$

$$\begin{cases} L\dfrac{di_d}{dt} = e_d - u_{dc}d_d + L\omega i_q \\ L\dfrac{di_q}{dt} = e_q - u_{dc}d_q - L\omega i_d \\ C\dfrac{du_{dc}}{dt} = \dfrac{3}{2}(i_d d_d + i_q d_q) - \dfrac{u_{dc}}{R} \end{cases}$$

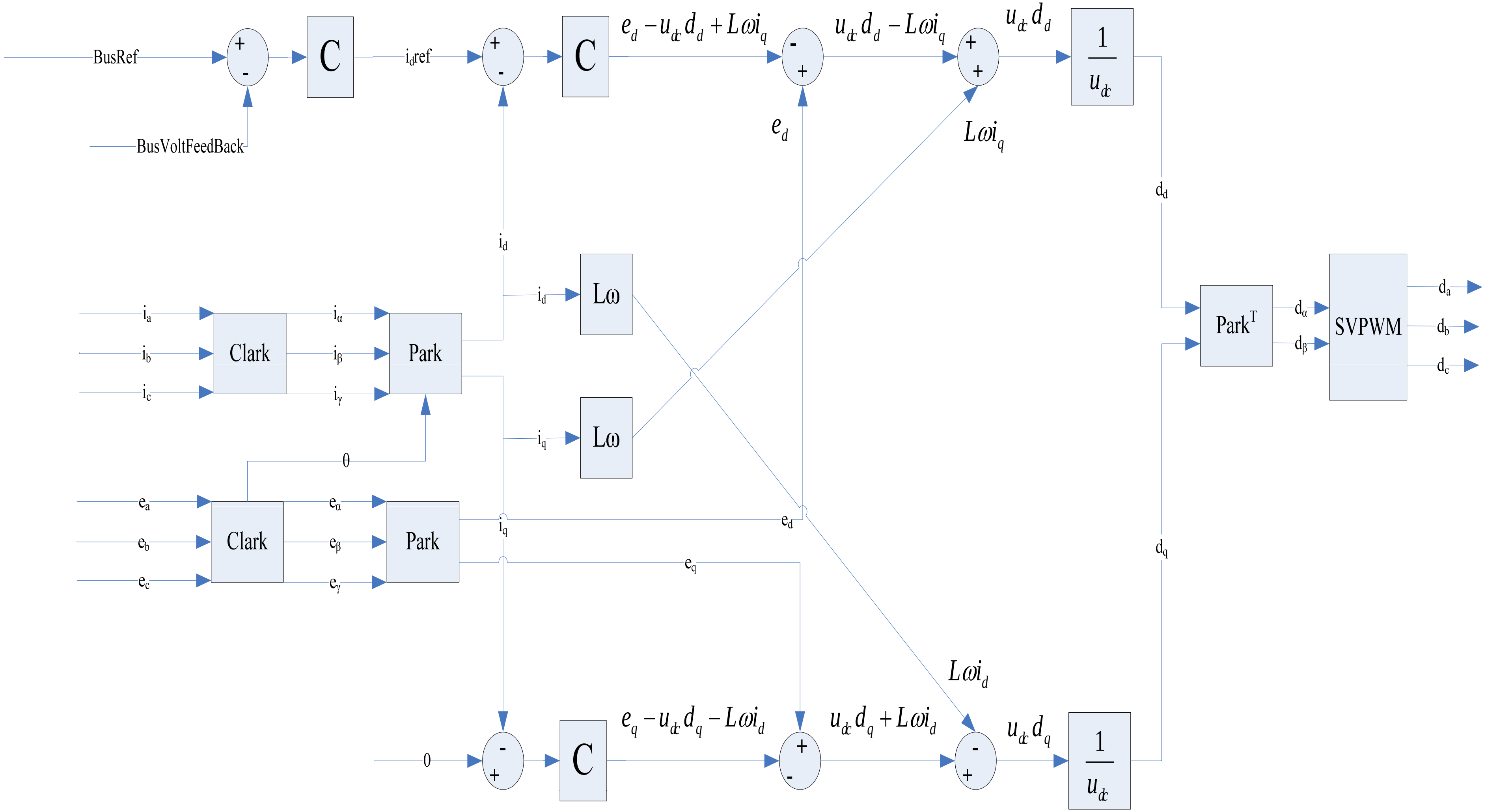
Clark and Park Transfer

$$\begin{cases} V_a(t) = V_m \cos(\omega t + \alpha) \\ V_b(t) = V_m \cos(\omega t - 120^\circ + \alpha) \\ V_c(t) = V_m \cos(\omega t + 120^\circ + \alpha) \end{cases}$$

$$\begin{cases} I_a(t) = I_m \cos(\omega t + \alpha) \\ I_b(t) = I_m \cos(\omega t - 120^\circ + \alpha) \\ I_c(t) = I_m \cos(\omega t + 120^\circ + \alpha) \end{cases}$$



dq ordinate modeling



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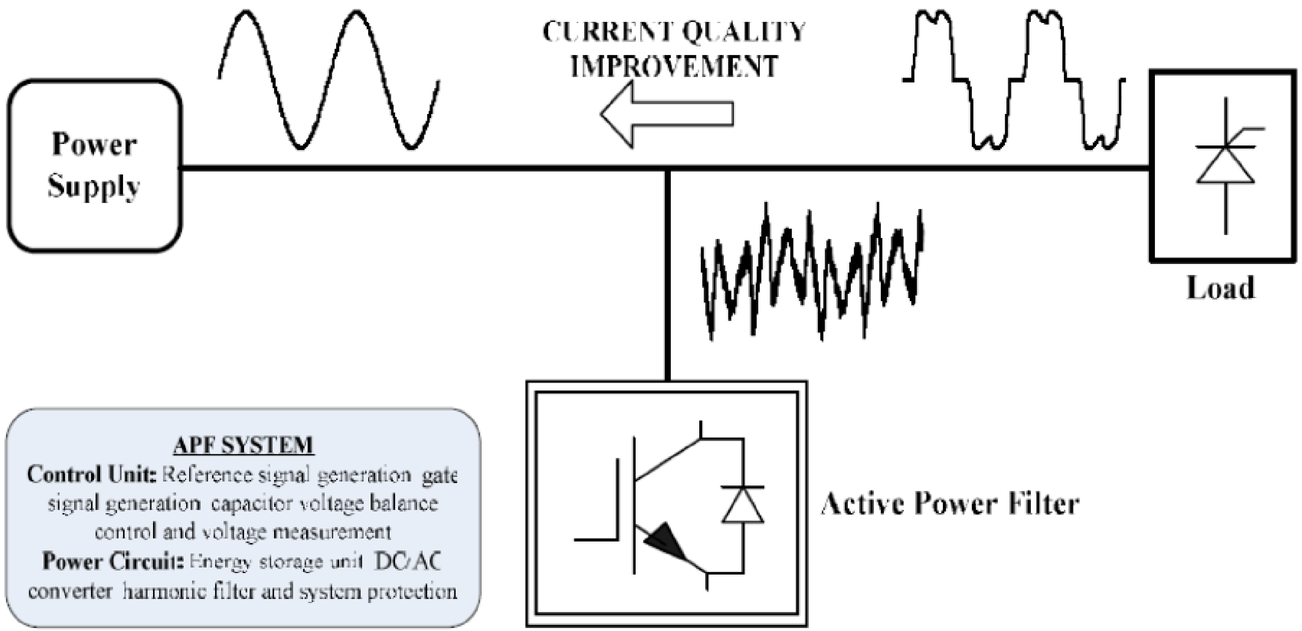
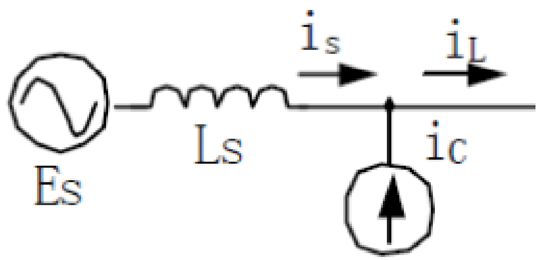
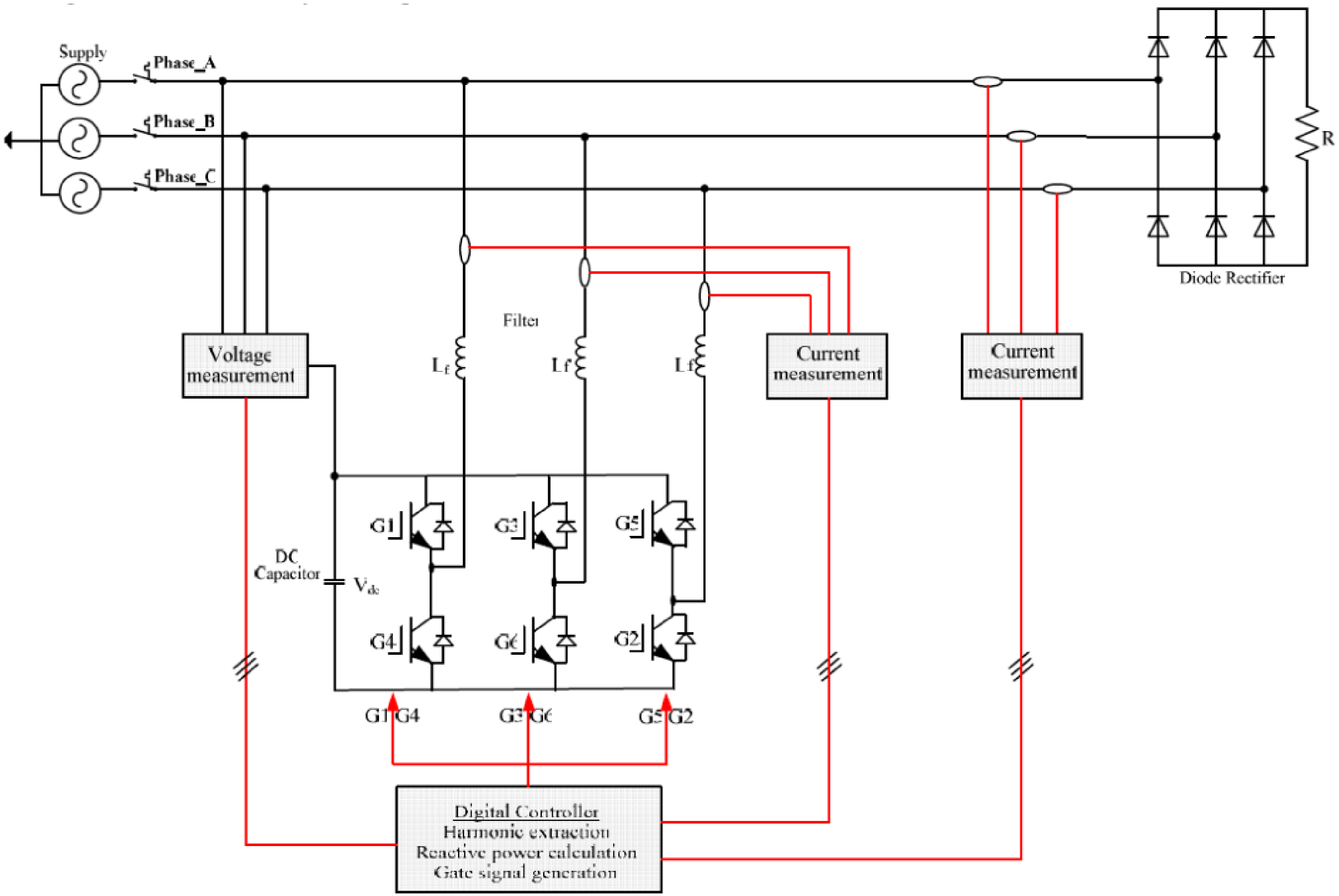
What's APF


Power Supply
CURRENT QUALITY IMPROVEMENT
Load
Active Power Filter
APF SYSTEM
Control Unit: Reference signal generation gate signal generation capacitor voltage balance control and voltage measurement
Power Circuit: Energy storage unit DC/AC converter harmonic filter and system protection


i_s
i_L
i_C
L_S
E_S

APF



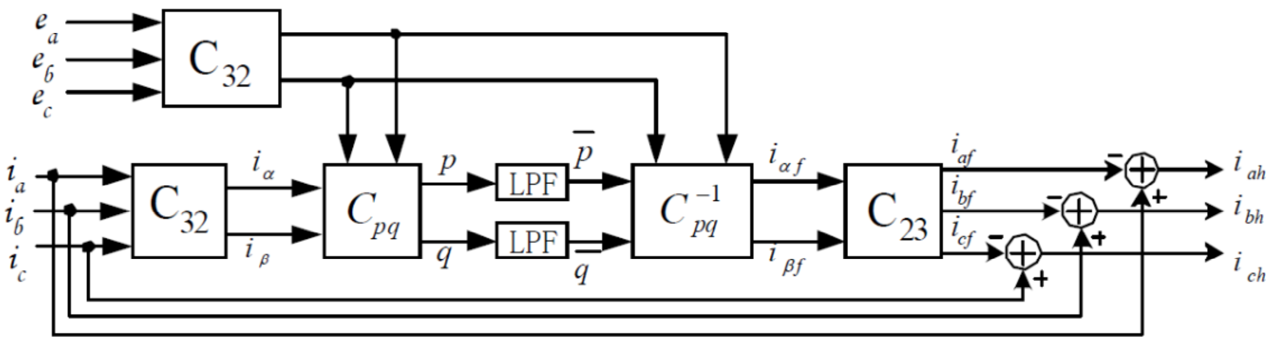
Supply
Phase_A
Phase_B
Phase_C
Diode Rectifier
R
Filter
Lf
Lf
Lf
Voltage measurement
Current measurement
Current measurement
DC Capacitor
Vdc
G1
G3
G5
G4
G6
G2
G1 G4
G3 G6
G5 G2
Digital Controller
Harmonic extraction
Reactive power calculation
Gate signal generation

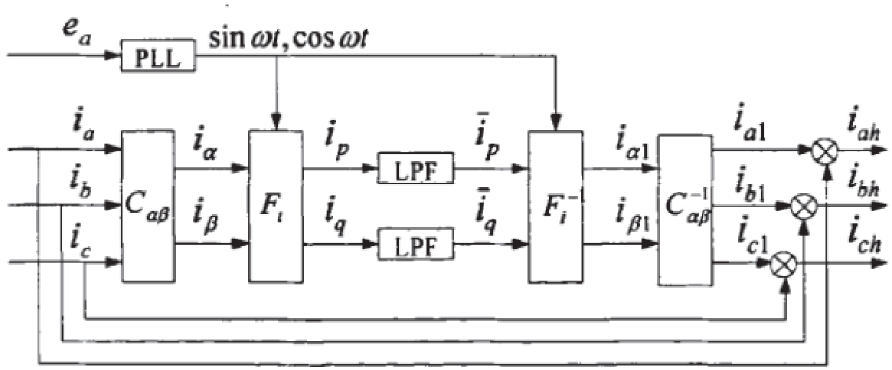
Key Techniques

- Harmonic detection technique
  - Detection algorithm
  - Response time (The best product 10ms response time)
- Decrease the volume of APF
  - Only consider harmonic compensation
    Volume ≈ 25% of load power
  - Reactive power considered
    Volume ≈ 100% of load power
- Duplicated functionality of APF
  - Solar inverter + APF
- Paralleled APF
  - Different APF in charge of different range of Harmonic compensation

Harmonic detection

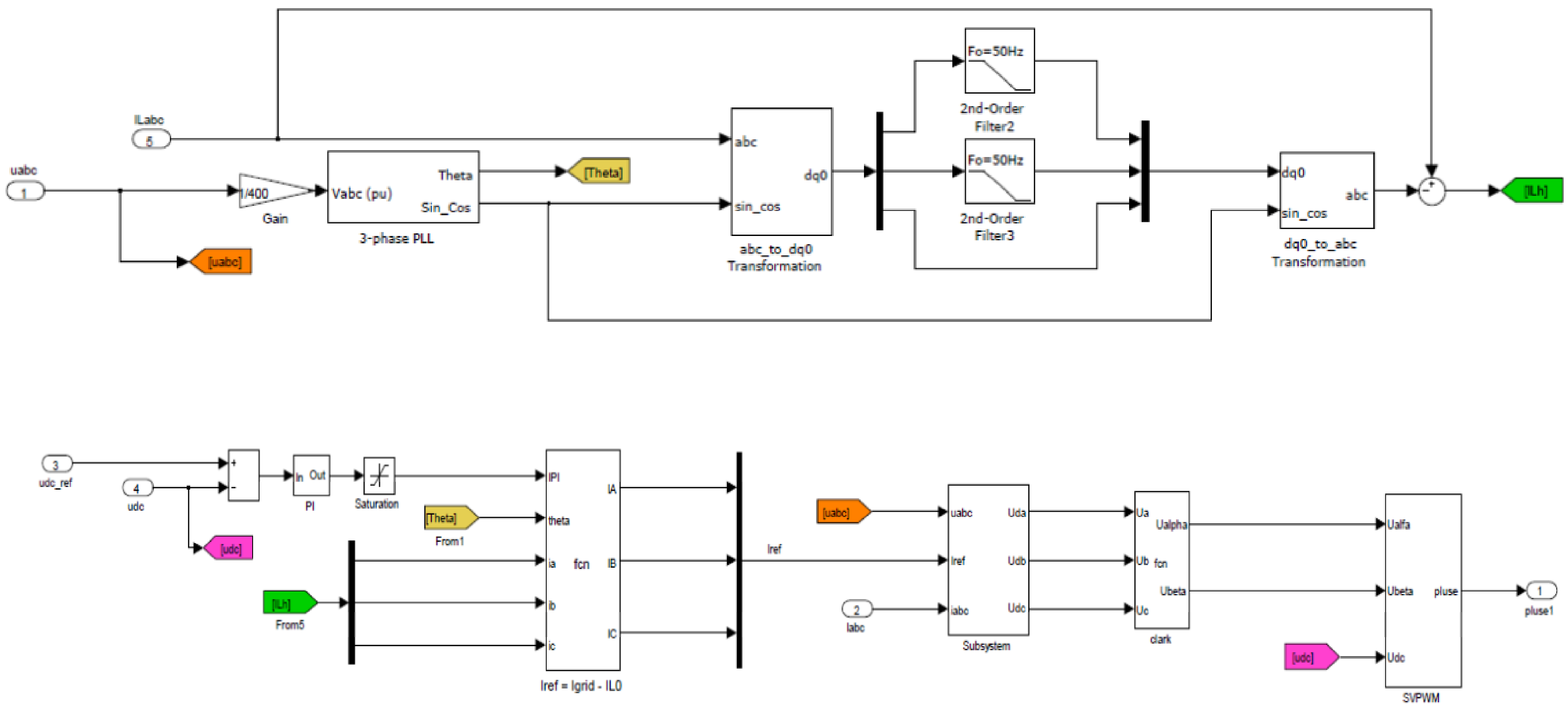
- Instantaneous reactive power theory*
- FFT



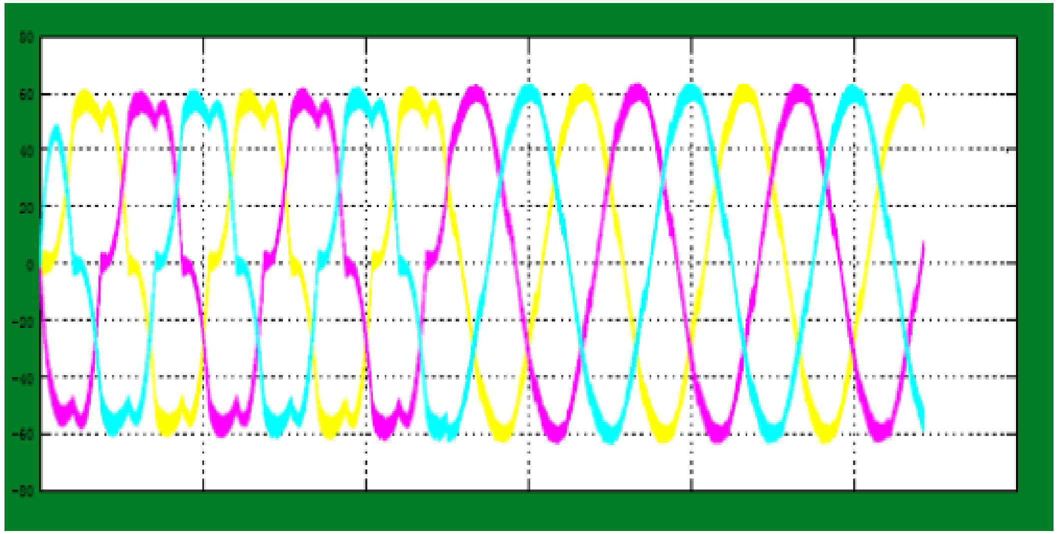


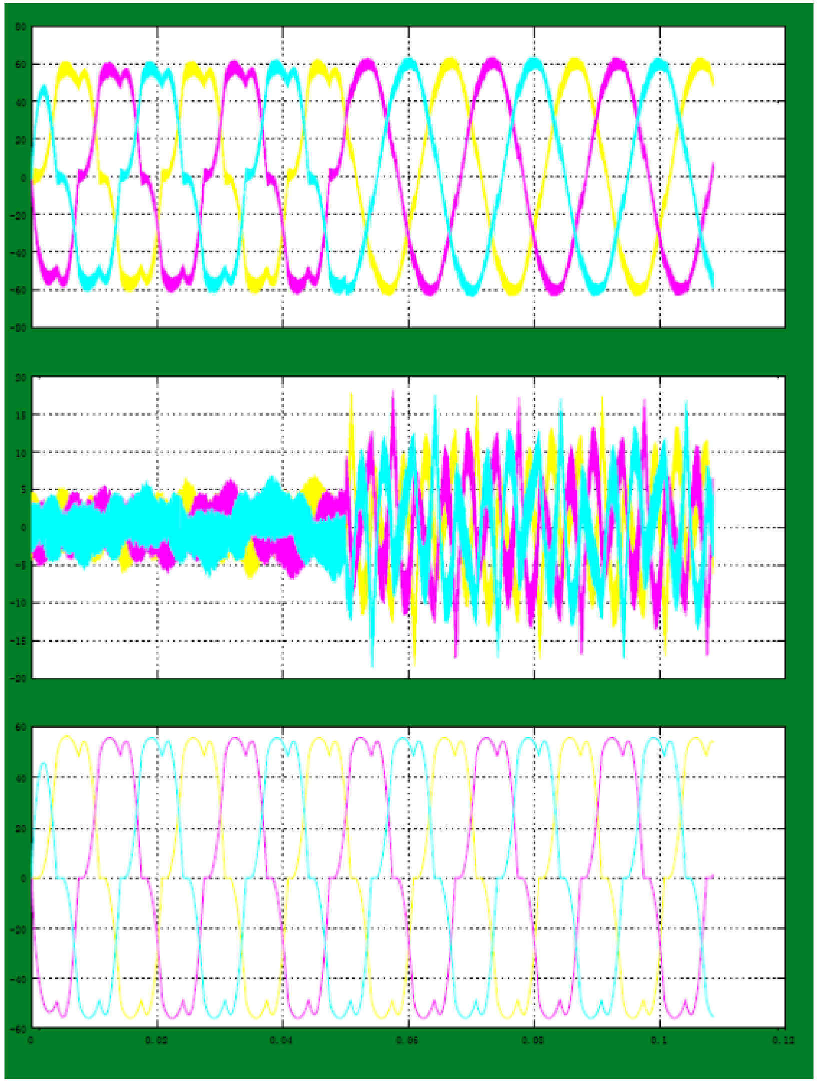
Control loop Schema

- Control Loop of APF



Simulation Result





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Unbalanced grid voltage

All the above control loop are build based on hypotheses : balanced three voltage!

But the reality is not so accurate.

* Positive and Negative sequence decomposition and control

Respect to Dr C.L.FORTESCUE

,

- Dr C.L.FORTESCUE's research in 1918,

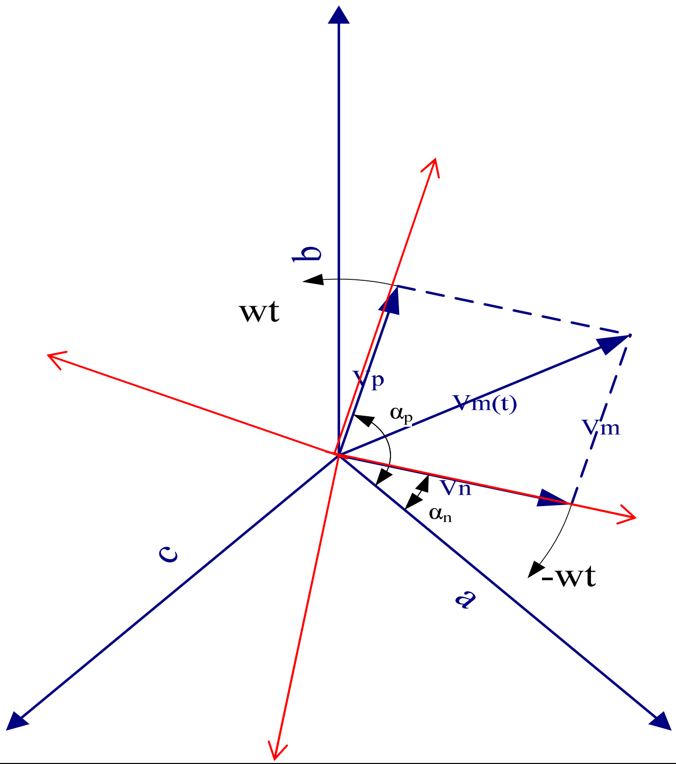
  any unbalanced three vectors could be decomposed into a balanced positive sequence, a balanced negative sequence and a zero sequence.

- Positive Sequence PARK:

$$Park^{p} = \begin{bmatrix} \cos\omega t & \sin\omega t \\ -\sin\omega t & \cos\omega t \end{bmatrix}$$

- Negative Sequence PARK:

$$Park^{n} = \begin{bmatrix} \cos\omega t & -\sin\omega t \\ \sin\omega t & \cos\omega t \end{bmatrix}$$



Positive & Negative sequence decomposition

$$\begin{cases} V_{di}^{p}(t) = V_p \cos(\alpha_p) + V_n \cos(2\omega t + \alpha_n) \\ V_{qi}^{p}(t) = V_p \sin(\alpha_p) - V_n \sin(2\omega t + \alpha_n) \\ V_{di}^{n}(t) = V_p \cos(2\omega t + \alpha_p) + V_n \cos(\alpha_n) \\ V_{qi}^{n}(t) = V_p \sin(2\omega t + \alpha_p) - V_n \sin(\alpha_n) \end{cases} \quad \begin{bmatrix} V_{di}^{p}(t) \\ V_{qi}^{p}(t) \\ V_{di}^{n}(t) \\ V_{qi}^{n}(t) \end{bmatrix} * \left[NotchFilter\right] = \begin{cases} V_{d}^{p}(t) = V_p \cos(\alpha_p) \\ V_{q}^{p}(t) = V_p \sin(\alpha_p) \\ V_{d}^{n}(t) = V_n \cos(\alpha_n) \\ V_{q}^{n}(t) = -V_n \sin(\alpha_n) \end{cases}$$

$$\begin{cases} I_{di}^{p}(t) = I_p \cos(\alpha'_p) + I_n \cos(2\omega t + \alpha'_n) \\ I_{qi}^{p}(t) = I_p \sin(\alpha'_p) - I_n \sin(2\omega t + \alpha'_n) \\ I_{di}^{n}(t) = I_p \cos(2\omega t + \alpha'_p) + I_n \cos(\alpha'_n) \\ I_{qi}^{n}(t) = I_p \sin(2\omega t + \alpha'_p) - I_n \sin(\alpha'_n) \end{cases} \quad \begin{bmatrix} I_{di}^{p}(t) \\ I_{qi}^{p}(t) \\ I_{di}^{n}(t) \\ I_{qi}^{n}(t) \end{bmatrix} * \left[NotchFilter\right] = \begin{cases} I_{d}^{p}(t) = I_p \cos(\alpha'_p) \\ I_{q}^{p}(t) = I_p \sin(\alpha'_p) \\ I_{d}^{n}(t) = I_n \cos(\alpha'_n) \\ I_{q}^{n}(t) = -I_n \sin(\alpha'_n) \end{cases}$$

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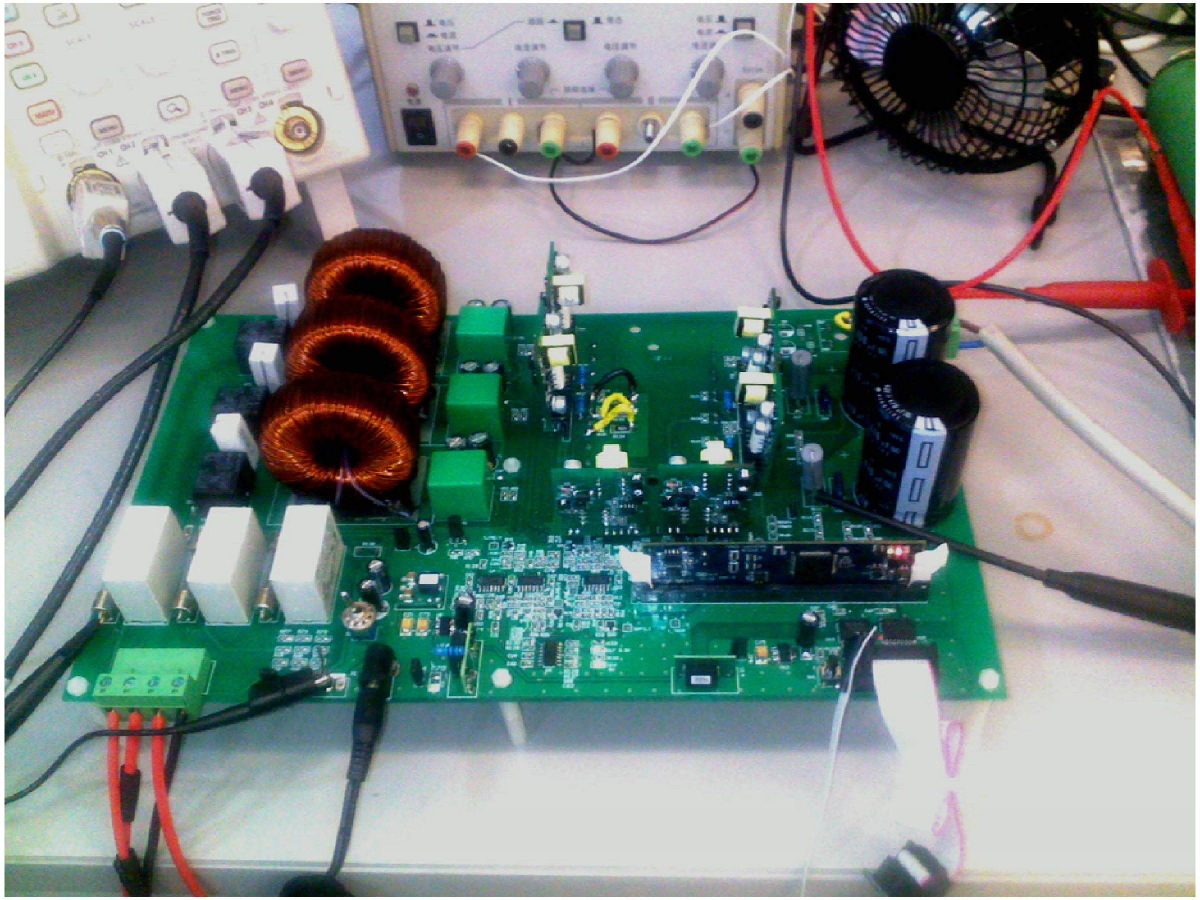
Specifications

- **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

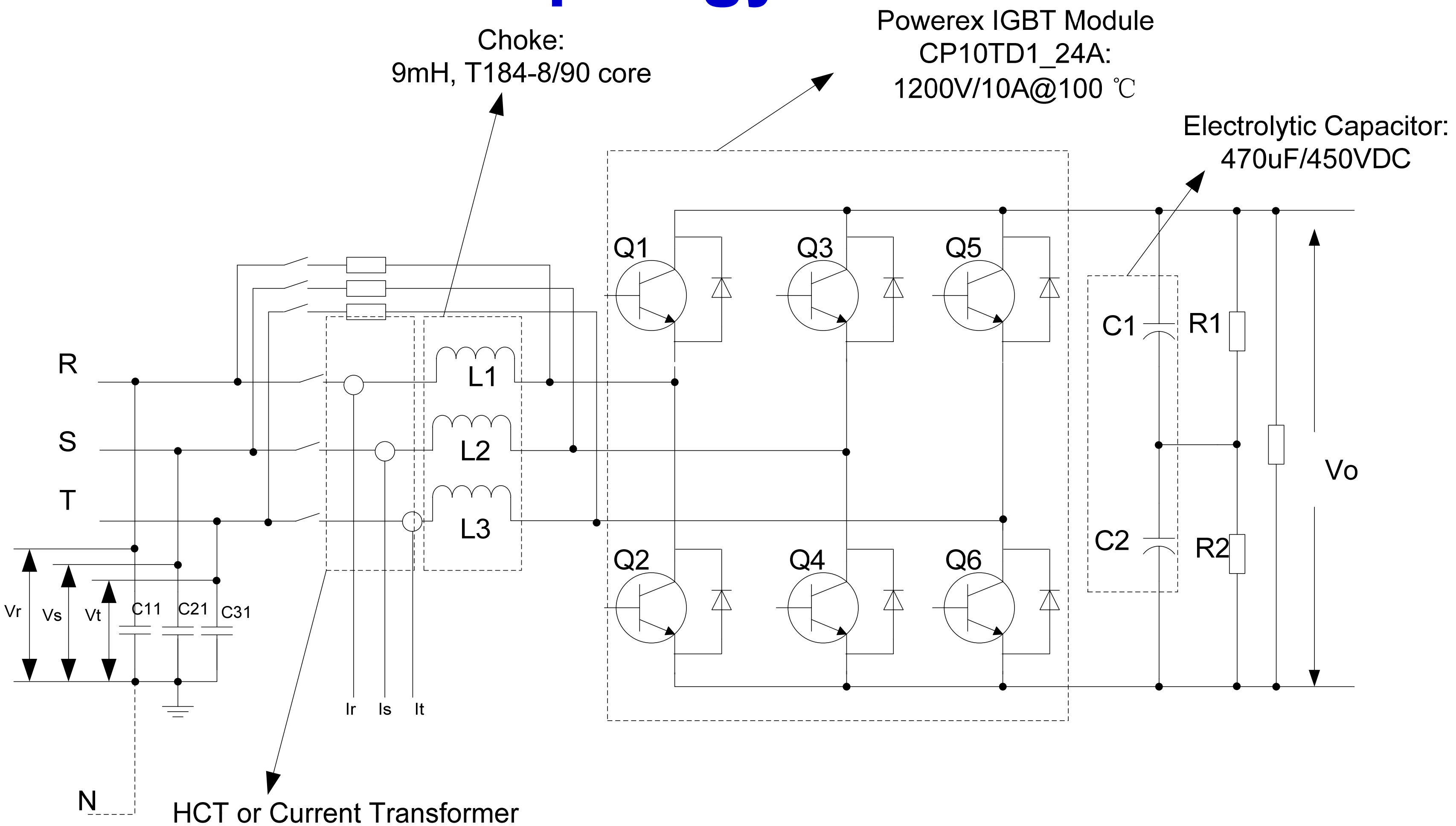
3-phase PFC EVM

- 3-phase PFC EVM Picture



Hardware Description

- **Main circuit topology**



Hardware Description

- ## Main circuit considerations

1.Switch Frequency ---- 20kHz.
For motor control application, the Fs 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 Vce 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 Description

- ## 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.**

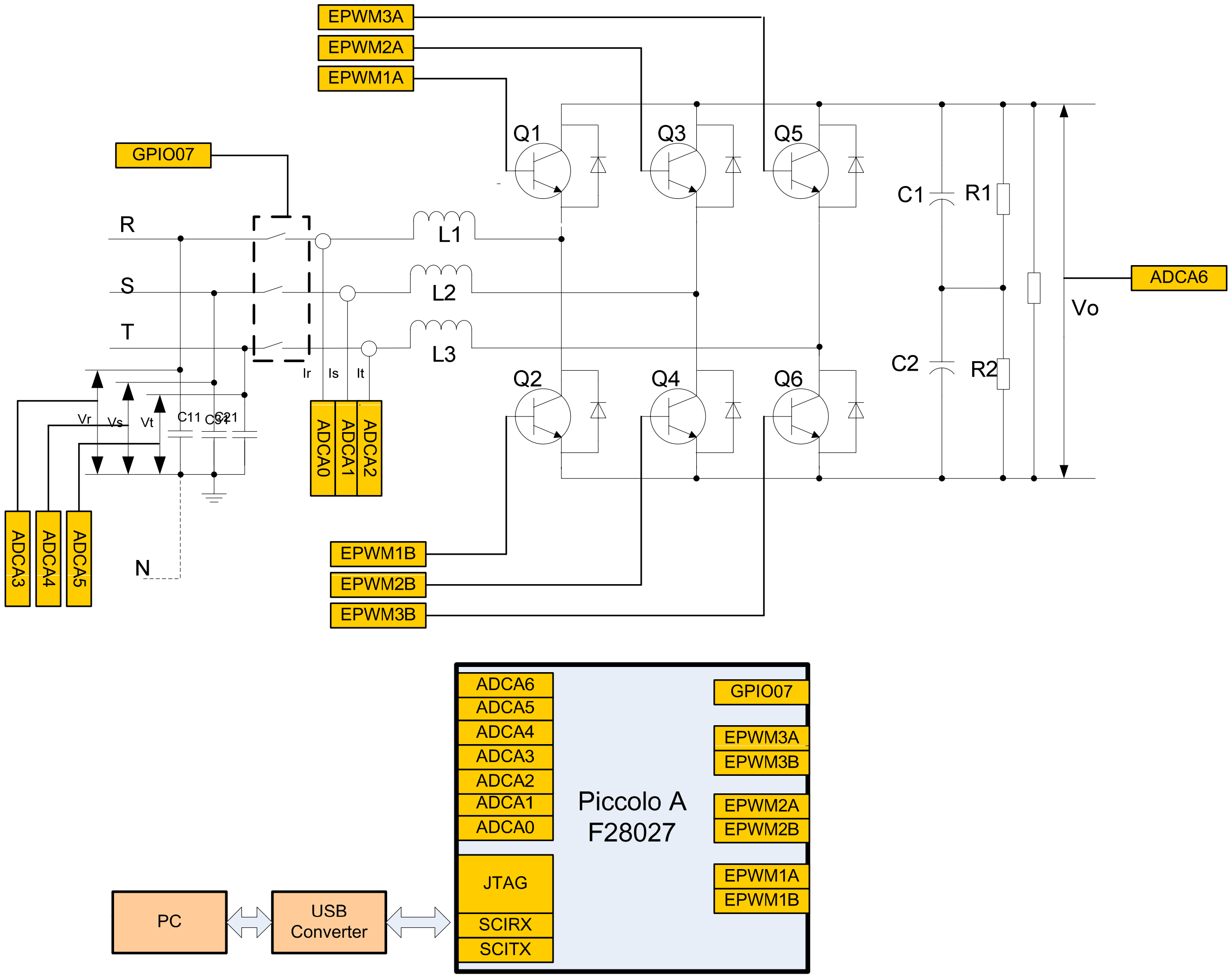
Hardware Description

- ## 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.

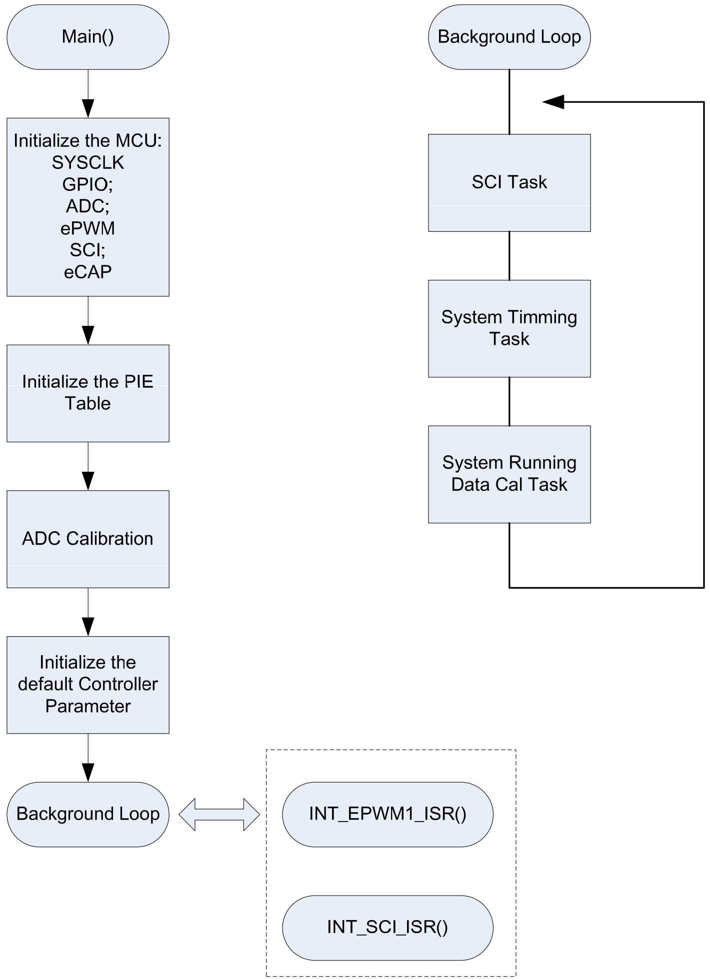
Hardware Description

- **MCU interface**



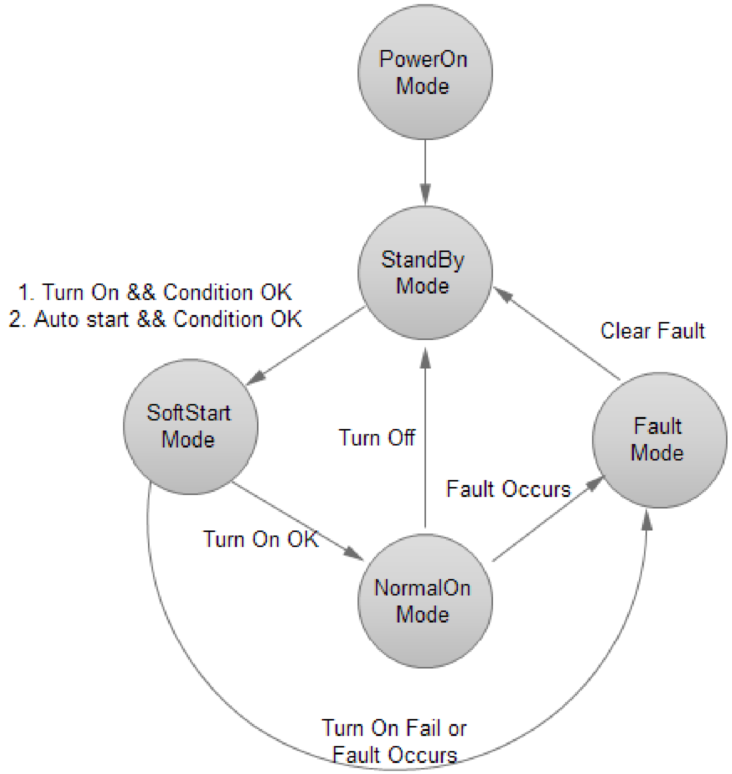
Software Description

- **Software Flow**



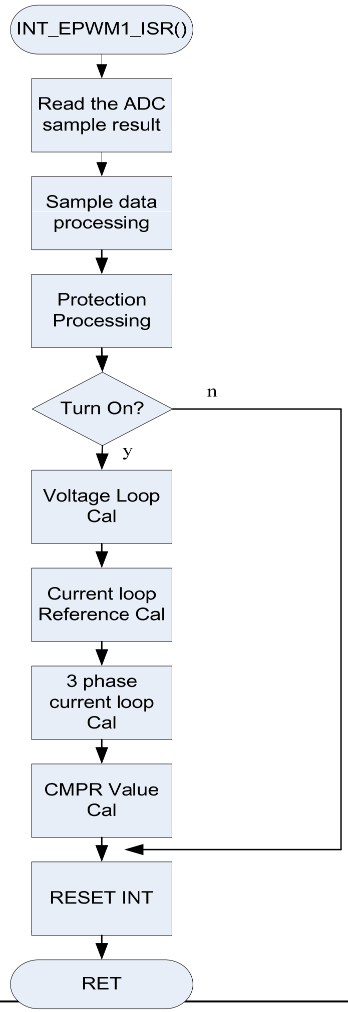
Software Description

•System Timing – Status machine



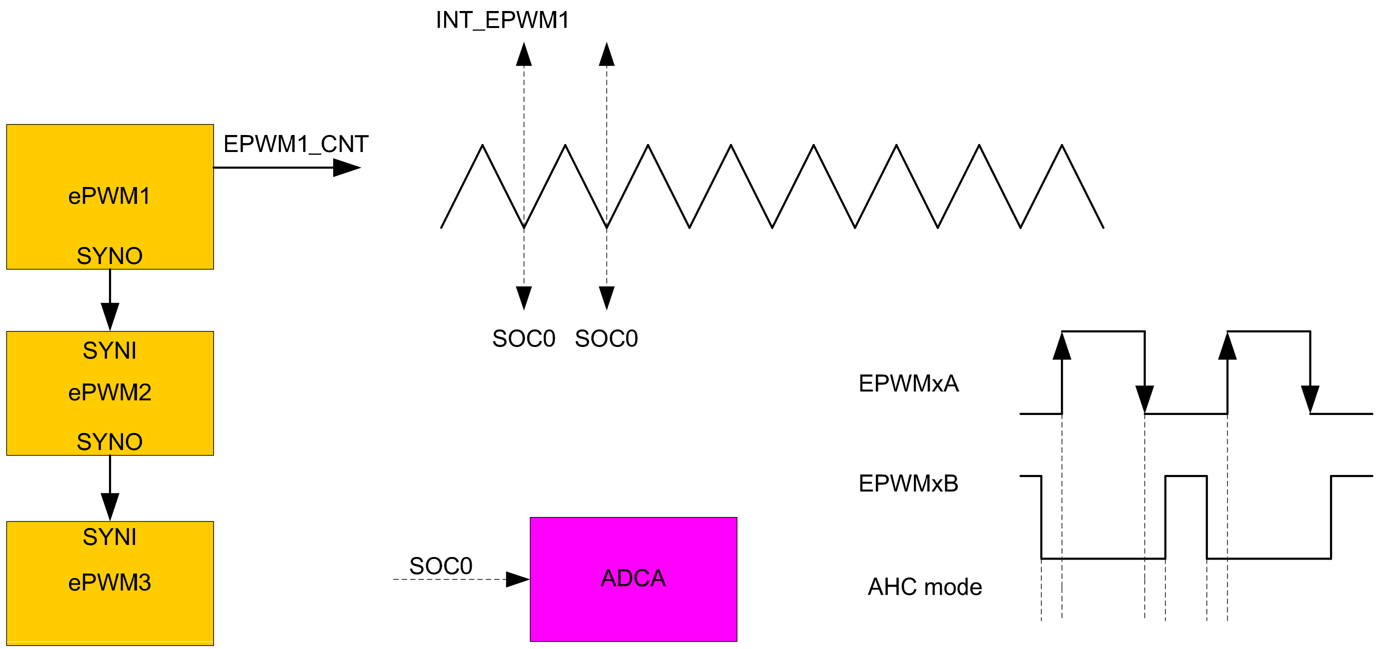
Software Description

- **Software Flow**



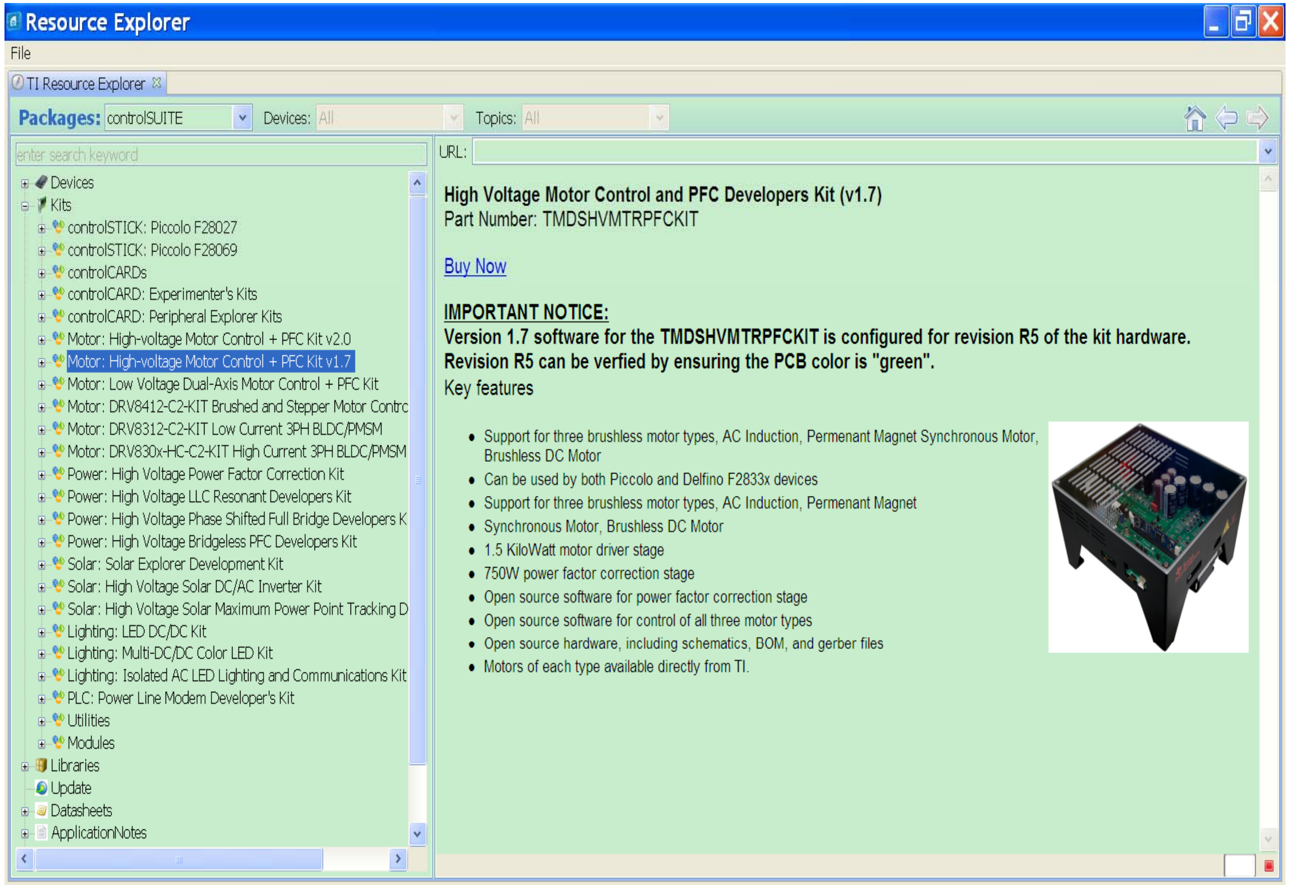
Software Description

- **ADC & ePWM**



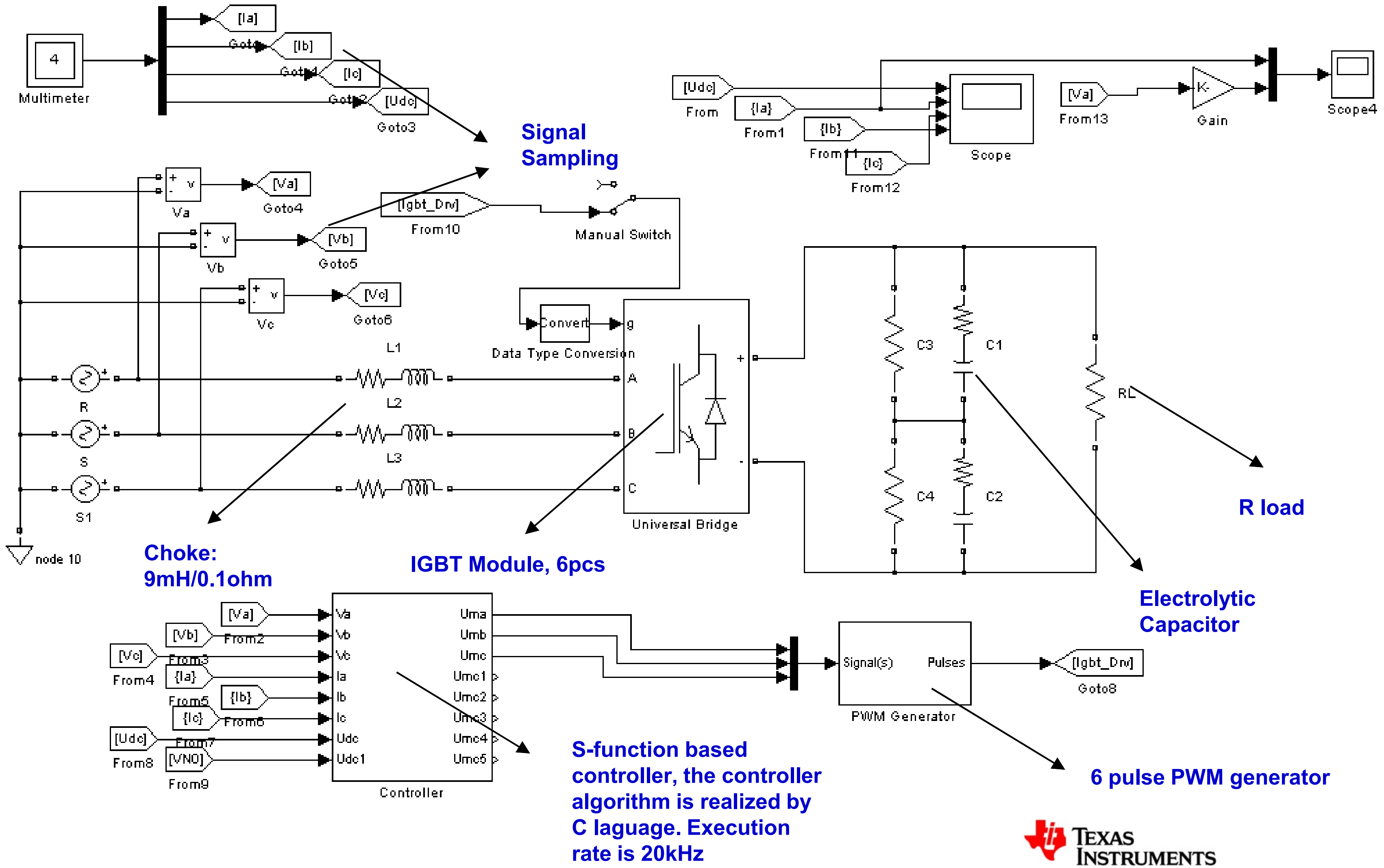
Control SUITE

- http://www.ti.com/mcu/docs/mcuproductcontentnp.tsp?sectionId=95&familyId=916&tabId=2656



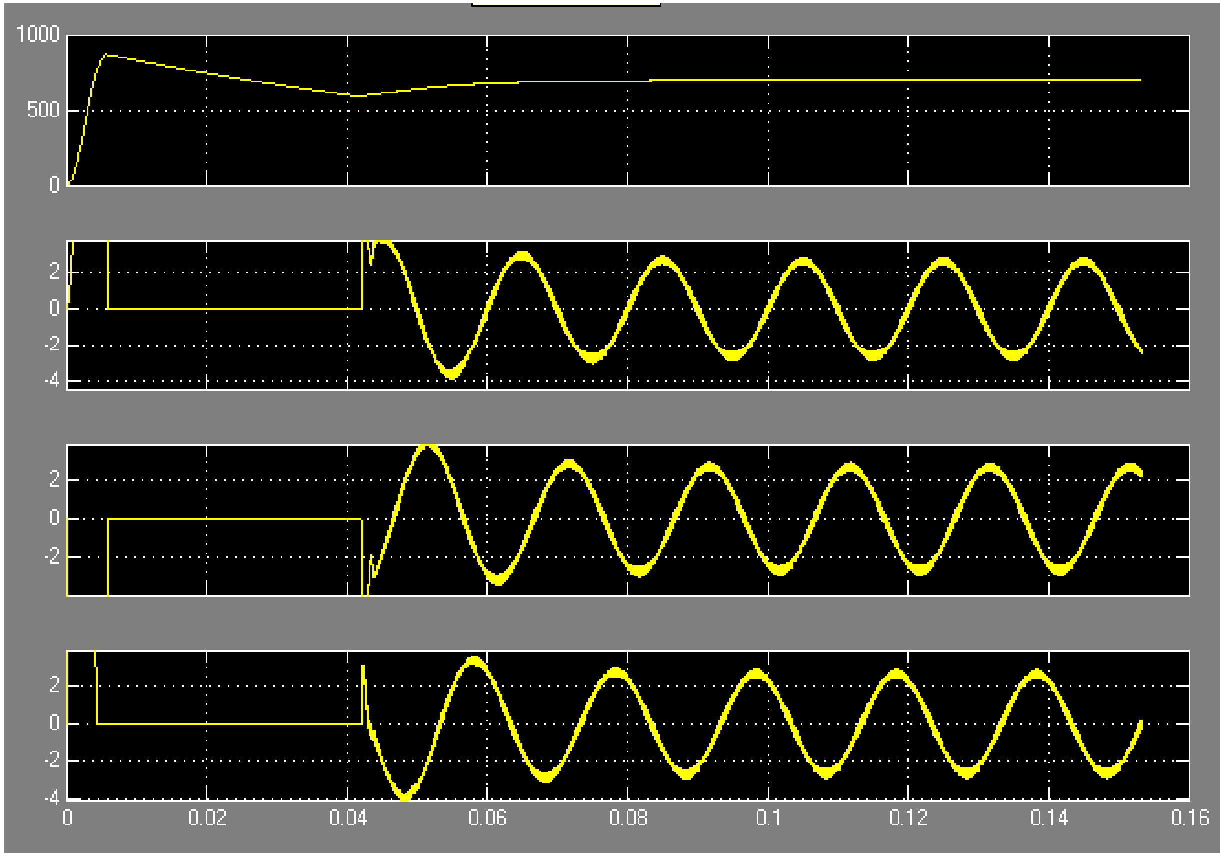
Simulation

- **The simulation diagram**



Simulation Result

- **The simulation result**



CH1: Vdc
CH2: R phase current
CH3: S phase current
CH4: T phase current

Conditions:

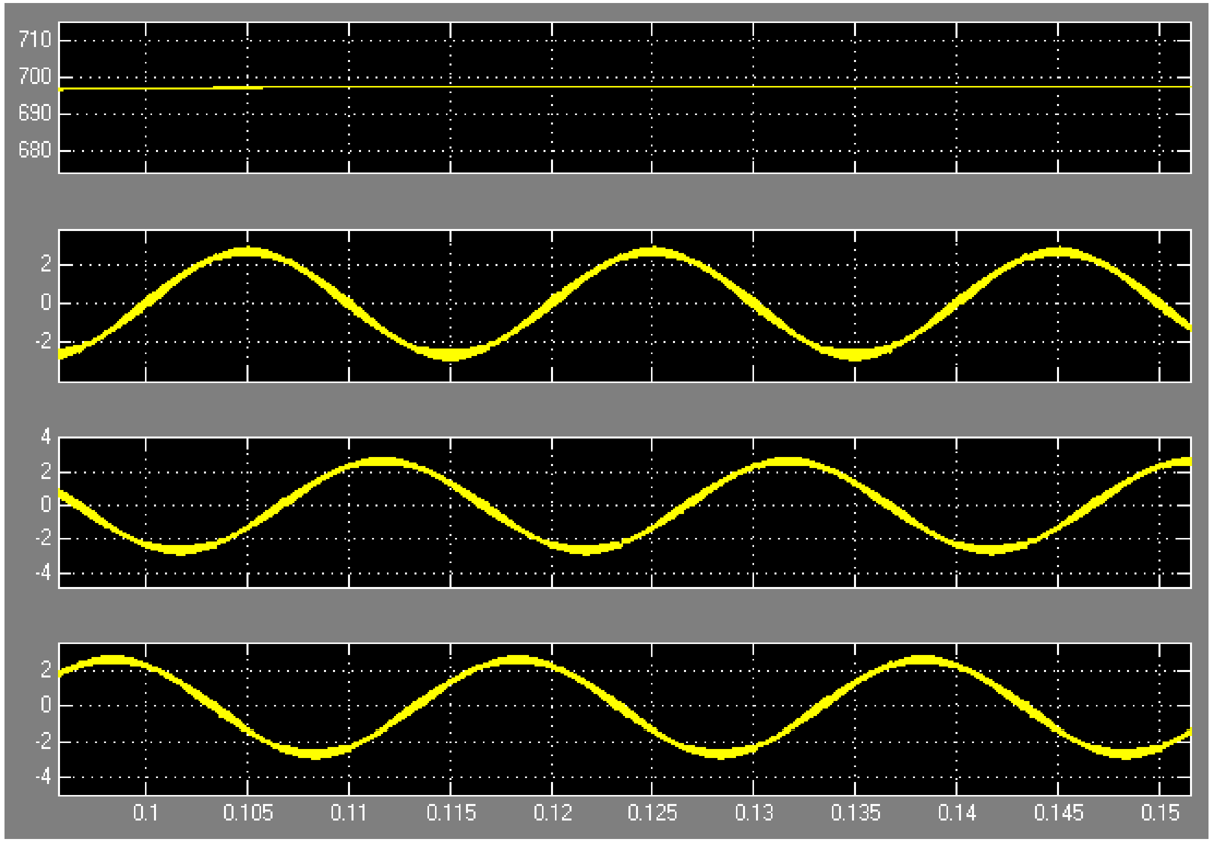
1. Directly input the line voltage to the converter from 0~0.04s;

2. At 0.04s, step to 700Vdc reference;

3. Full load.

Close loop Controller Design

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



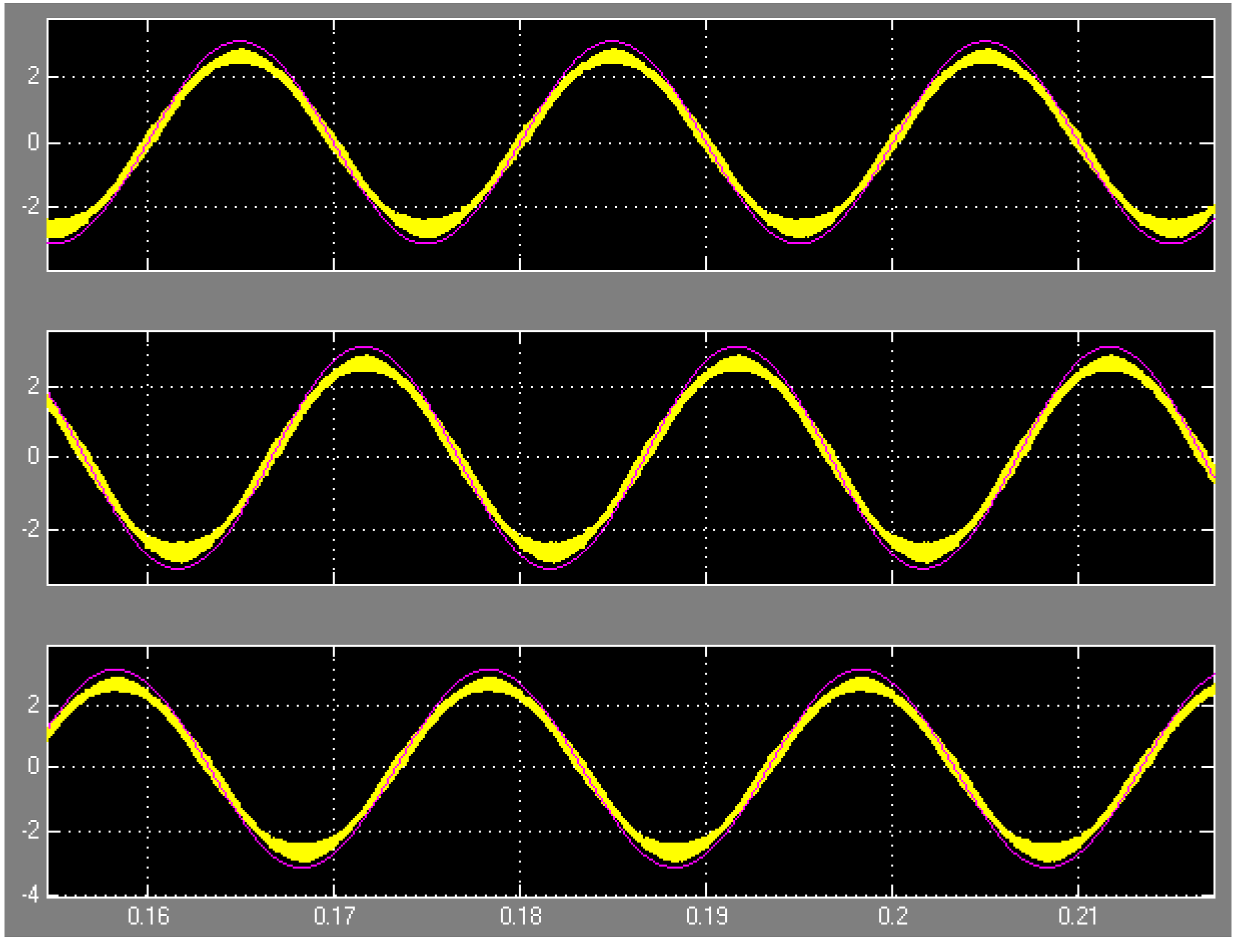
CH1: Vdc
CH2: R phase current
CH3: S phase current
CH4: T phase current

Conditions:

Full load at stable state.

Close loop Controller Design

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

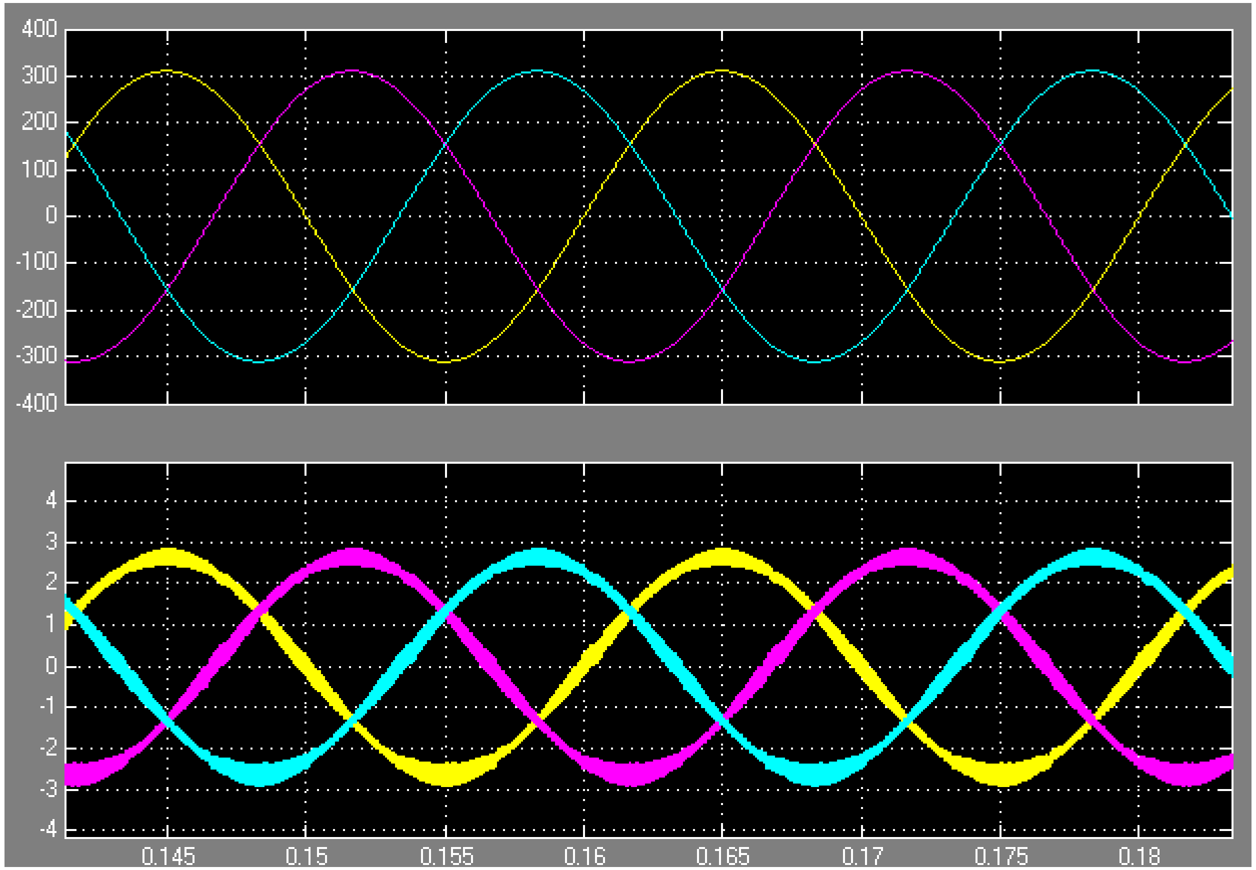


Yellow : phase current

Red: Line Voltage(1/100)

Close Loop Controller Design

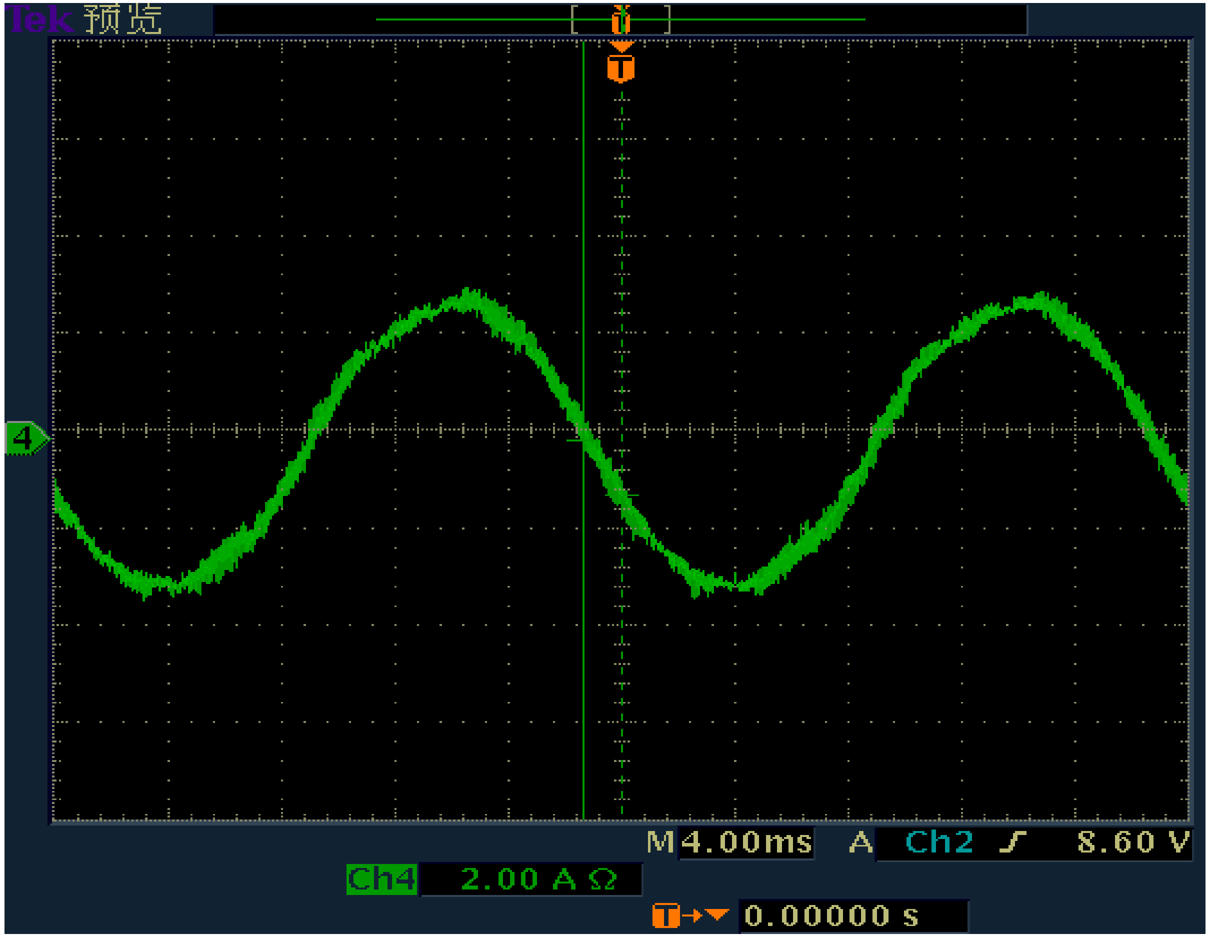
- **The simulation result --- Stable state**



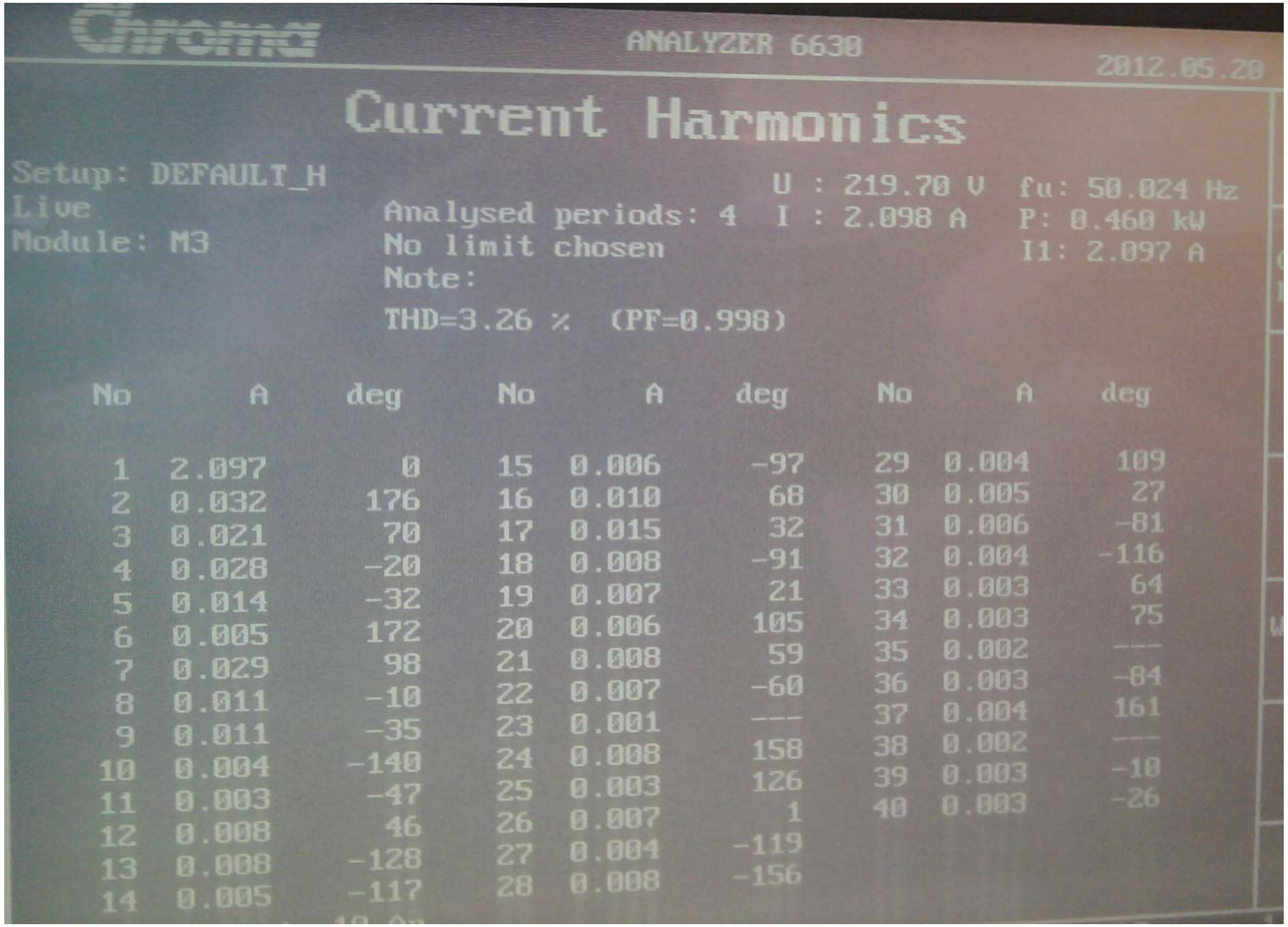
CH2 : phase current

CH1: Line Voltage(1/100)

EVM Performance



EVM Performance



Q&A

Thanks!