12脈波三相不連續導流模式切換式整流器之開發
(Development of 12-pulse Three-phase DCM Switch-mode Rectifier）

組別：A220. 組員：周芳毅、楊松諭　指導老師：廖聰明 教授

Abstract- This special topic develops a 12-pulse AC/DC converter using two three-phase discontinuous current mode (DCM) switch-mode rectifiers (SMRs). The serially connected two SMRs are powered by two three-phase balanced voltages with 30-degree phase shift generated from the grid AC source via $Y-Y$ and $Y-\Delta$ transformer banks. First, the power circuit is properly designed to let the SMR cell be operated under DCM with inherent power factor corrected (PFC) function without current control. Then the practical design approach for voltage feedback controller is proposed to preserve well-regulated DC output voltage. Second, the 12-pulse AC/DC converter with two DCM SMR cells in healthy condition is established and evaluated. The satisfactory steady-state and dynamic operation characteristics are achieved thanks to the properly designed schematic and control scheme.

Finally, the fault-tolerant operations and controls are conducted. The studied scenarios include: (i) One cell is faulted and becomes a three-phase diode rectifier. Even only one cell possesses the switching control ability, the DC-link voltage of the 12-pulse AC/DC converter can still be successfully regulated; and (ii) The power switches of the constituted two SMR cells are all disabled. The 12-pulse SMR is naturally changed to a 12-pulse rectifier. Although the DC-link voltage can still be established, the voltage regulation control capability is lost. The operating characteristics under all cases are comparatively evaluated experimentally.

Key words: AC/DC converter, switch-mode rectifier, power factor correction, multi-phase converter, control, design, realization, SiC device.

摘要- 本專題旨在開發以兩組三相不連續導流模式切換式整流器串接建構之十二脈波交流/直流轉換器。兩切換式整流器分別由 $Y-Y$ 接及 $Y-\Delta$ 接變壓器以三十度相位差之三相電壓供電。首先，適當地設計電力電路使切換式整流器在不連續導流模式下，無需電流控制具有功率因數校正功能。接著，以所提電壓迴授控制器設計方法，獲得調節良好之直流輸出電壓。第二，建立及評估具兩組健全 SMR 之十二脈波交流/直流轉換器。由於妥善設計之電力電路以及控制機構，具良好之穩態及動態操控特性。

最後，從事所建系統之容錯操作及控制。探討之狀況包括：(i) 一組 SMR 故障成為整流器：即使只有一組切換式整流器具有切控能力，十二脈波交流/直流轉換器仍具輸出電壓調節能力；(ii) 兩組 SMR 故障：十二脈波之切換式整流器變成一般十二脈波整流器。直流鏈電壓仍可建立，但已失去電壓調控能力。所有情況之操運特性均以實測評估。

關鍵詞: 交流/直流轉換器、切換式整流器、功因矯正、多相轉換器、控制、設計、電路實現、碳化矽元件

Contents

1. Introduction

1.1 Literature Survey

The survey for the the related technologies concerning this special topic project can be referred to the detailed report, including AC-DC converters, single-phase and three-phase SMRs, three-phase single-switch (3P1SW) DCM SMRs, multi-pulse converters, transformer rectifier units (TRUs) for aircraft power system, and PI feedback controller design, etc.

1.2. System Configuration and Contributions

The schematic of the developed 12-pulse three-phase DCM SMR is shown in Fig. 1.1. It is formed with two serially connected 3P DCM SMRs. The two SMRs are powered by two three-phase balanced voltages with 30° phase shift generated by $\text{Y}-\text{Y}$ and $\text{Y}-\Delta$ transformer banks. The major works includes: (i) Establishment and control of 3P DCM SMR cell; (ii) Development and control of the proposed 12-pulse DCM SMR in healthy condition; and (iii) Fault-tolerant operation and control of the developed system under one-cell and two-cell faults.

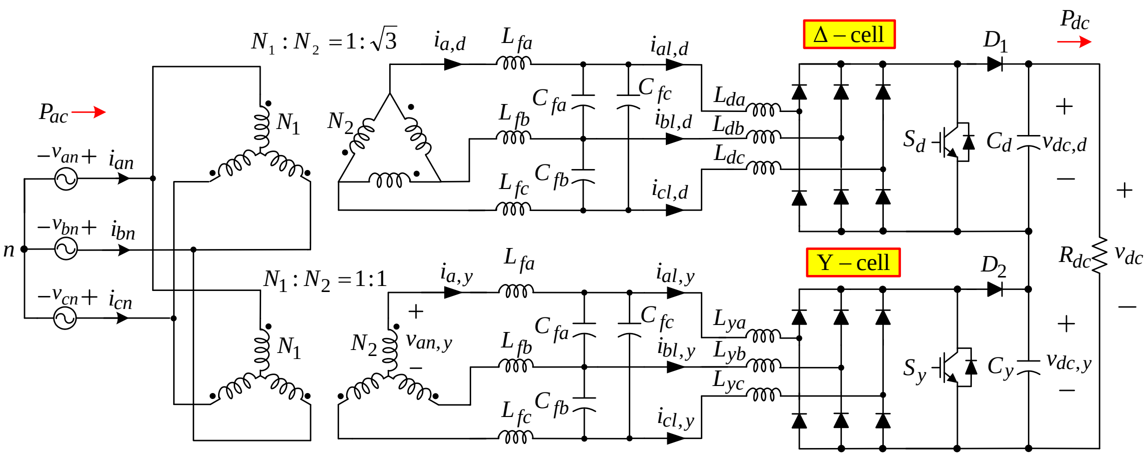


Fig. 1.1 The developed 12-pulse three-phase DCM switch-mode rectifier.

2. Three-phase Transformers and Operation of Converter

2.1 12-pulse AC-DC Converter by $\text{Y}-\text{Y}$ and $\text{Y}-\Delta$ transformers

2.2 DCM and CCM Operations of Converter

The detailed contents are presented in the final report.

3. Development of 3P1SW DCM SMR Cell

3.1 Power Circuit

The system variables and specifications are listed below:

- AC input: three-phase line-to-line voltage $V_{ab} = 220\text{V}/60\text{Hz}$ ($\omega = 120\pi$).
- DC output: $V_{dc} = 400\text{V}$, $P_{dc} = 1\text{kW}$.
- Switching frequency: $f_s = 15\text{kHz}$.
- Three-phase input LC filter: $L_f = L_{fa} = L_{fb} = L_{fc} = 186\mu\text{H}$ and $C_f = C_{fa} = C_{fb} = C_{fc} = 2\mu\text{F}$, which can obtain the corresponding corner frequency is $1/(2\pi\sqrt{L_f C_f}) = 8.252\text{kHz}$.
- Power switch: SiC MOSFET H1M065F050 ($V_{DS,\max} = 650\text{V}$, $I_{D,\max} = 52\text{A}$).
- Output capacitor: $C_{dc} = 1120\mu\text{F}, 450\text{V}$.
- Diodes: H3D065E040 ($V_{RRM} = 600\text{V}$, $I_{FAV} = 15\text{A}$).

In order to make sure that the power circuit is operated in DCM under all load condition, we derive the maximum inductance of energy storage inductor under boundary condition at the peak of input phase voltage $V_m(\omega t = 90^\circ)$. The maximum value of line current can be written as:

$$i_{b1,\max} = \frac{V_m}{L_b} DT_s \tag{3.1}$$

where D is the duty cycle, T_s is the switching period, V_m is the peak value of v_{an}, and L_b is the inductance of energy storage inductor. From (3.1) one can find the limited inductance for DCM operation:

$$L_b < L_{b,\max} = \frac{V_m}{i_{b1,\max}} DT_s \tag{3.2}$$

Under boundary condition, we can use the following voltage transfer equation:

$$\frac{V_{dc}}{V_m} = \frac{\sqrt{3}}{1-D} \tag{3.3}$$

From the known data, the duty cycle can be determined as $D = 0.2222$. Then from (3.2), the constraint is found as:

$$L_b < L_{b,\max} = \frac{3V_m^2}{4P_{dc}} DT_s = 358.453(\mu\text{H}) \tag{3.4}$$

Accordingly, the energy storage inductor is chosen to be $L_b = 60\,\mu\text{H}$.

3.2 Control Scheme

The control scheme of the 3P1SW DCM SMR is shown in Fig. 3.1(a) and its analog circuit realization is shown in Fig. 3.1(b). Because of the inherent PFC function, the current sensing is not necessary. In the voltage feedback control scheme, the voltage feedback signal is obtained using the LV25-P, and the sensing factor is set as:

$$K_v = 0.02375\,\text{V/V} \tag{3.5}$$

<u>PI feedback controller:</u> The PI voltage controller is chosen as:

$$G_{cv}(s) = K_{Pv} + \frac{K_{Iv}}{s} \tag{3.6}$$

The single OP amplifier-based realization circuit is emphasized on Fig. 3.1(a). The K_{Pv} and K_{Iv} gains can be expressed as:

$$K_{Pv} = \frac{R_2}{R_1}, \quad K_{Iv} = \frac{1}{R_1 C} \tag{3.7}$$

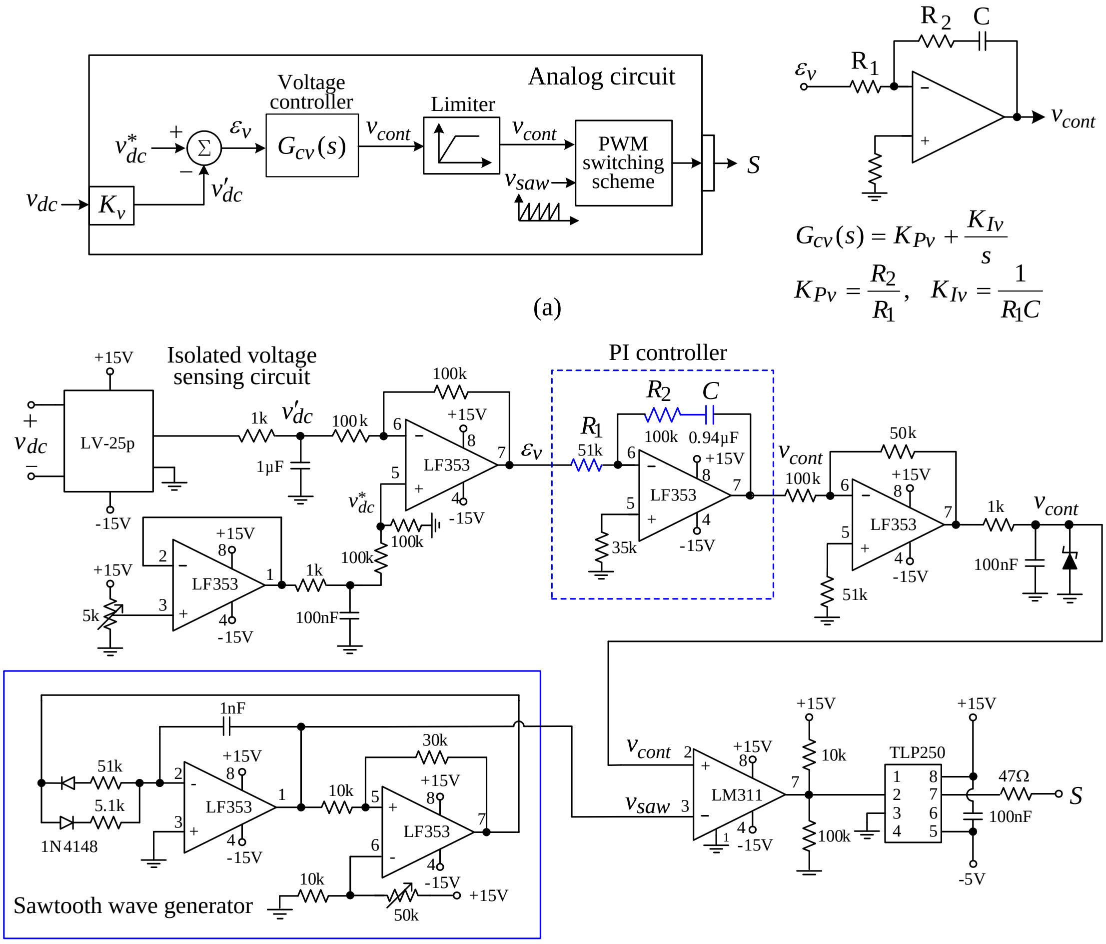
Through trial-and-error based on experimental experience, the parameters are set as:

$$K_{Pv} = 1.9608,\ K_{Iv} = 20.8594,\ R_1 = 51k\Omega,\ R_2 = 100k\Omega,\ C = 0.94\mu\text{F} \tag{3.8}$$

3.3. Measured Results

A. Steady-state Characteristics

The measured steady-state characteristics of the single 3P1SW DCM SMR cell under ($V_{ab} = 220\text{V}/60\text{Hz}, V_{dc} = 400\text{V}$) at $R_{dc} = 150\Omega$ ($P_{dc} = 1066\text{W}$) are plotted in Fig. 3.2(a) to Fig. 3.2(d). Normal operations can be observed from the results. More specifically, the magnified waveform depicted in Figs. 3.2(d). The steady-state characteristics corresponding to Figs. 3.2 measured by HIOKI 3390 power meter are listed in Table 3.1. From Table 3.1, one can find that the efficiency is higher, the THDi in input current will be reduced when the SMR operates under higher power.



(b)

Fig. 3.1. Control scheme of 3P1SW DCM SMR: (a) block diagram; (b) analog realization circuit.

B. Dynamic Response

The measured (v_{dc}, v_{cont}) of the developed 3P1SW boost SMR due to a step load change of ($R_{dc} = 300 \rightarrow 150\Omega$) are shown in Fig. 3.2(e) and Fig. 3.2(f). (Curves①). It can be seen that the dynamic response is satisfactory.

Enhanced PI controller:

From (3.7) one can find the following facts: (i) Varying R_1 can change the K_{Pv} and K_{Iv} gains in equal weighting; (ii) Hence similar to the robust control presented in [19], by letting $G_{cv}(s)$ to K_e (equivalent to $(1/(1-W_v))$ in [19]), the tracking error ε_v can be reduced to $\varepsilon'_v = \varepsilon_v / K_e$. However, the rate of v_{cont} will be magnified, i.e., $|dv'_{cont} / dt| = K_e |dv_{cont} / dt|$. And the feedback contaminated noise (for example, the voltage ripple) will also be magnified by a factor of K_e.

To verify the above facts, the measured (v_{dc}, v_{cont}) due to same step load change by $K_e G_{cv}$, $K_e = 1, 2, 4, 8$ are compared in Fig. 3.2(e) and Fig. 3.2(f).

Table 3.1: Measured steady-state characteristics of 3P1SW DCM SMR under two loads

$V_{ac} = 220\text{V/60Hz},\ V_{dc} = 400\text{V}, R_{dc} = 300\Omega$						
	i_{an}	i_{bn}	i_{cn}	P_{ac}(W)	P_{dc}(W)	η(%)
rms value (A)	1.716	1.728	1.650	609	487.8	80.06
THD_i(%)	25.56	21.42	22.46			
PF	0.9452	0.9484	0.9137			
$V_{ac} = 220\text{V/60Hz},\ V_{dc} = 400\text{V}, R_{dc} = 150\Omega$						
	i_{an}	i_{bn}	i_{cn}	P_{ac}(W)	P_{dc}(W)	η(%)
rms value (A)	3.399	3.435	3.294	1239	1055.9	85.25
THD_i(%)	21.65	24.13	26.76			
PF	0.9664	0.9681	0.9484			

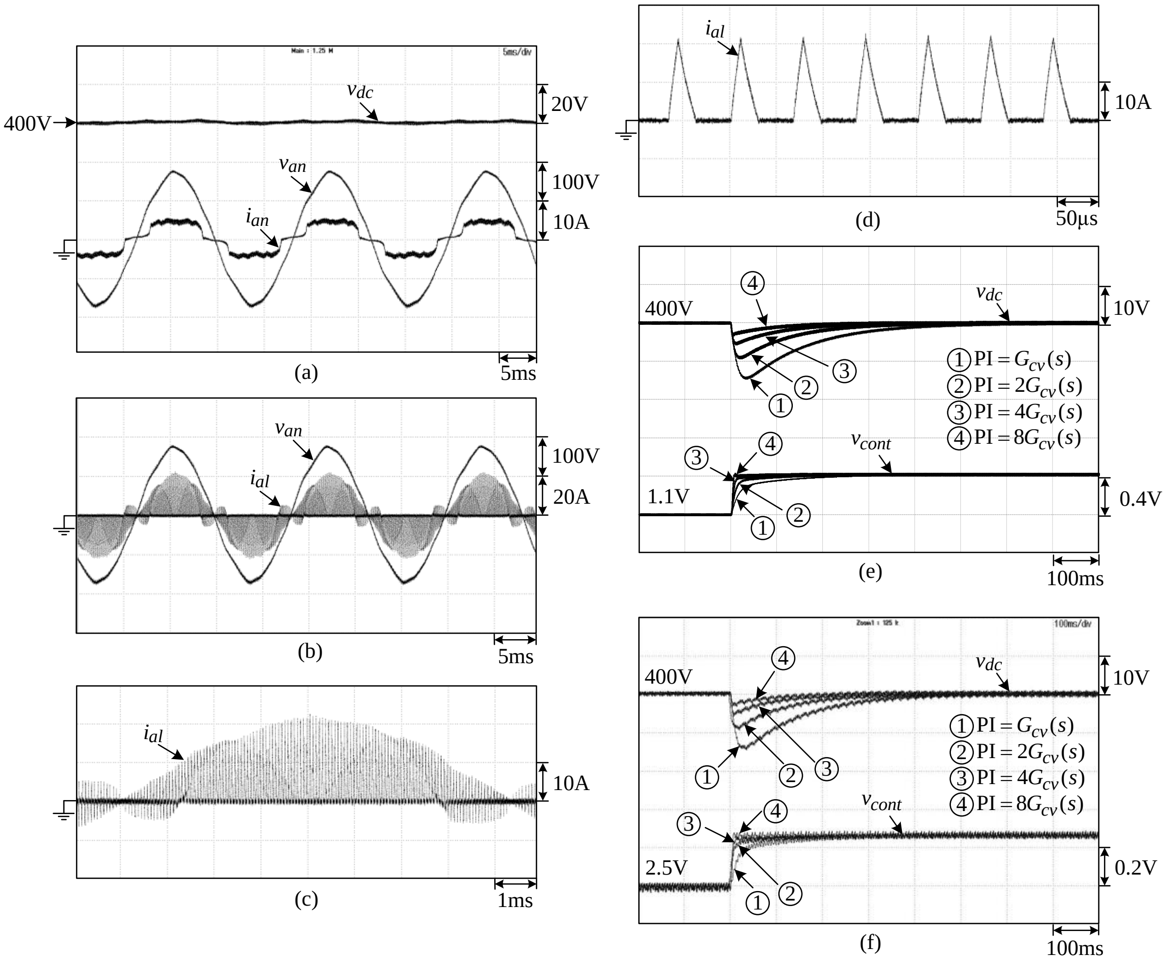


Fig. 3.2. Measured results of the single 3P1SW boost SMR cell at $V_{ab} = 220\text{V/60Hz}$, $v_{dc}^{*} = 400\text{V}$ and $R_{dc} = 150\Omega$ ($P_{dc} = 1066\text{W}$): (a) (v_{dc}, v_{an}, i_{an}); (b) (v_{an}, i_{al}); (c) i_{al} with time scale being 1ms; (d) i_{al} with time scale being $50\mu\text{s}$. Measured (v_{dc}, v_{cont}) of the developed 3P1SW boost SMR due to a step load change ($R_{dc} = 300 \rightarrow 150\Omega$) under different gains of PI controller: (e) Simulated result; (f) measured result.

4. Development of 12-pulse Three-phase DCM Switch-mode Rectifier

4.1 Power Circuit

The specifications and components of the developed 12-pulses DCM SMR shown in Fig. 1.1 are given below:

- AC input: three-phase, $V_{ab} = 220\text{V/60Hz}$.
- DC output: $V_{dc} = 700\text{V}$, $P_{dc} = 2\text{kW}$ $(R_{dc} = 245\Omega)$.
- Switching frequency: $f_s = 15\text{kHz}$.
- Energy storage inductance: $L_b = 60\mu\text{H}$
- Filtering capacitors: $C_d = C_y = 560\mu\text{F}, 450\text{V}$.

4.2. Control Scheme

The control scheme of the 12-pulse DCM SMR and its analog circuit realization is neglected here. The voltage controller is same as those designed in Sec. 3. The voltage sensing factor is set as:

$$K_v = 0.01\text{V/V} \tag{4.1}$$

4.3. Measured Results under Healthy Condition

The established 12-pulse DCM SMR with healthy two SMR cells is first evaluated.

A. Steady-state Characteristics

Figs. 4.1(a) to 4.1(c) show the measured $(v_{dc}, (v_{an}, i_{an}))$, $((v_{an,d}, i_{an,d}), (v_{an,y}, i_{an,y}))$ and $((v_{an,d}, i_{al,d}), (v_{an,y}, i_{al,y}))$ of the 12-pulse DCM SMR with two healthy SMR cells at $P_{dc} = 1966\text{W}$. Table 4.1 lists the corresponding steady-state characteristics. The results indicate that: (i) Each SMR cell is normally operated; (ii) The DC output voltages are well regulated at 700V with very small ripples for the 12-pulse nature; (iii) The line currents in grid side have been synthesized to lowly distorted sine-waves with high power factor and low THDi; (iv) The two three-phase AC voltages on secondary side of Y-Y and $\text{Y-}\Delta$ transformers have 30 - degree phase shift; and (v) The efficiency and THDi under heavier load are slightly better.

B. Dynamic Response

The simulated and measured results of the 12-pulse DCM boost SMR with healthy cells due to a step load change of ($R_{dc} = 300 \rightarrow 250\Omega$) are shown in Figs. 4.1(d) and 4.1(e). It can be seen that the dynamic responses will become faster and the DC output voltage dips are reduced when the gain of PI controller is higher. The same, v_{cont} will increase to regulate the output DC voltage to be 700V.

Table 4.1: Measured steady-state characteristics of the 12-pulse DCM SMR with two healthy SMR cells under two loads

$V_{ac} = 220\text{V/60Hz}$, $V_{dc} = 700\text{V}$, $R_{dc} = 300\Omega$						
	i_{an}	i_{bn}	i_{cn}	P_{ac}(W)	P_{dc}(W)	η(%)
rms value (A)	5.183	5.162	5.225	1954.9	1620.0	82.87
THD_i(%)	7.76	7.49	7.42			
PF	0.9976	0.9976	0.9976			
$V_{ac} = 220\text{V/60Hz}$, $V_{dc} = 700\text{V}$, $R_{dc} = 250\Omega$						
	i_{an}	i_{bn}	i_{cn}	P_{ac}(W)	P_{dc}(W)	η(%)
rms value (A)	6.072	5.989	6.124	2291.6	1924.0	83.96
THD_i(%)	6.93	6.73	6.81			
PF	0.9978	0.9978	0.9978			

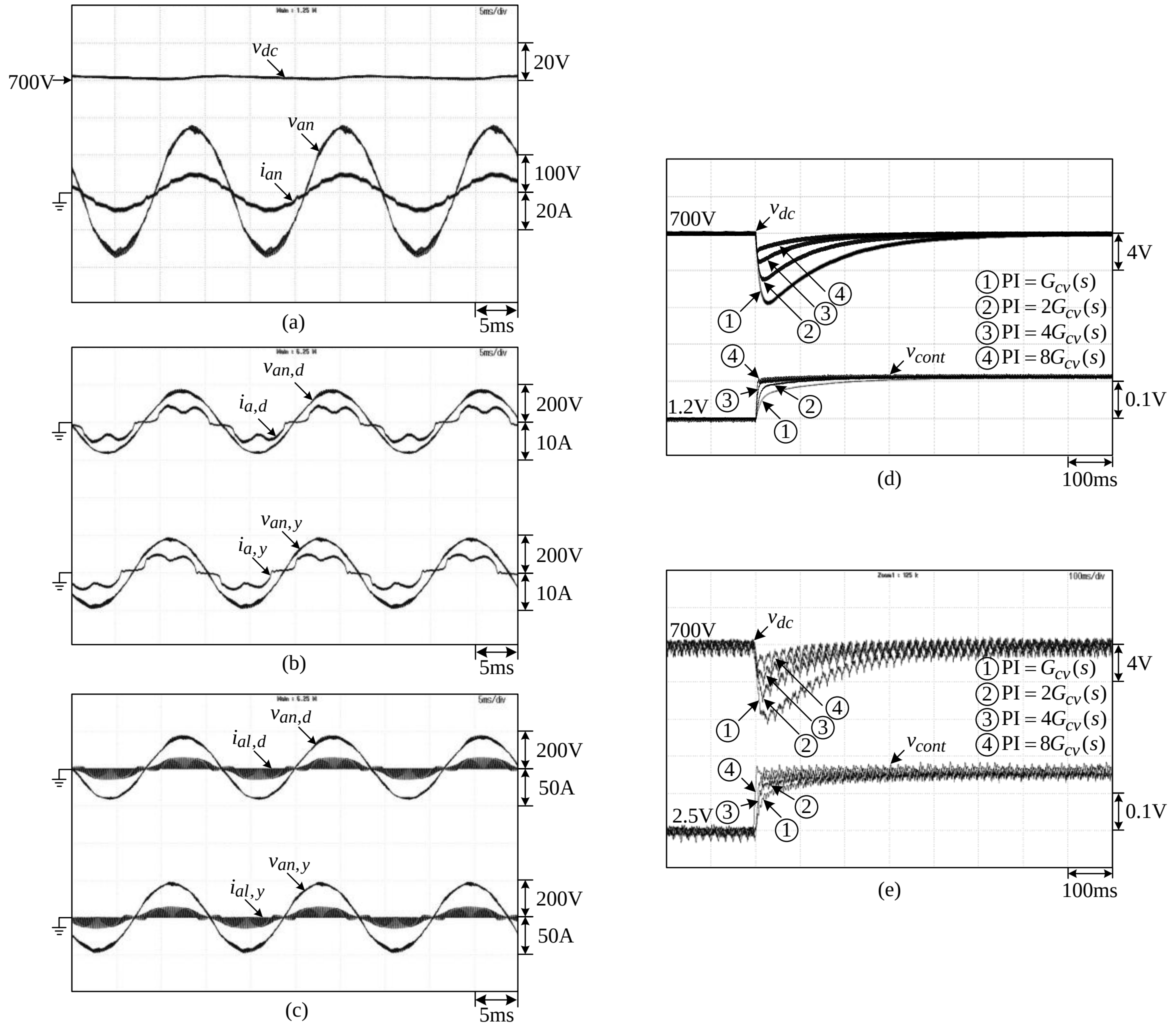


Fig. 4.1. Measured results of the 12-pulse DCM SMR with healthy two SMR cells at $P_{dc} = 1966$W; (a) (v_{dc}), (v_{an}, i_{an}); (b) $(v_{an,d}, i_{an,d})$, $(v_{an,y}, i_{an,y})$; (c) $(v_{an,d}, i_{al,d})$, $(v_{an,y}, i_{al,y})$. Responses of (v_{dc}, v_{cont}) of the developed 12-pulse boost DCM SMR with healthy cells due to a step load change under different PI controllers: (e) Simulated result; (f) measured result.

4.4. Measured Results under One Faulted Cell

Fault Scenario: The switch of the lower Y-cell in Fig. 1.1 is disabled. This SMR cell becomes the diode rectifier, and only the upper Δ-cell can perform the DC-link voltage regulation control.

A. Steady-state Characteristics

Fig. 4.2 shows the measured (v_{dc}, v_{an}, i_{an}), $(v_{an,d}, i_{an,d}, v_{an,y}, i_{an,y})$, $(v_{an,d}, i_{al,d}, v_{an,y}, i_{al,y})$ and $(v_{dc}, v_{dc,d}, v_{dc,y})$ of the 12-pulse DCM SMR with one faulted cell at $P_{dc} = 1966\text{W}$. The corresponding steady-state characteristics are listed in Table 4.2.

Comparing the results to those presented in Sec. 4.3 one can find the following facts: (i) Since the Y-cell SMR becomes a rectifier without PFC and voltage regulating capability, the DC output voltage is reduced to about 300V. And the peaky line drawn currents are resulted; (ii) The 12-pulse converter output voltage still can be regulated at 700V by the healthy Δ-cell SMR. The normal DCM operation can be observed. However, the ripple is obviously increased; (iii) Both the power factor and THDi become worse.

B. Dynamic Response

Figs. 4.2(e) and 4.2(f) show the simulated and measured results of the developed 12-pulse boost DCM SMR with one faulted SMR cell (Y-cell) due to a step load change of ($R_{dc} = 300 \rightarrow 250\Omega$) by different PI controllers. Some comments can be made from the measured results: (i) Since only the Δ-cell SMR possesses the PWM control ability, the voltage load regulation response is degraded with larger dips and longer restore times; (ii) Larger voltage ripples are also observed; (iii) However, well-regulated DC-link voltage is preserved.

Table 4.2: Measured results of the 12-pulse DCM SMR with one faulted SMR cell under two loads

$V_{ac} = 220$V/60Hz, $V_{dc} = 700$V, $R_{dc} = 300\Omega$						
	i_{an}	i_{bn}	i_{cn}	P_{ac}(W)	P_{dc}(W)	η(%)
rms value (A)	5.317	5.248	5.372	1944.3	1611.0	82.86
THD_i(%)	25.39	25.18	24.66			
PF	0.9660	0.9671	0.9679			
$V_{ac} = 220$V/60Hz, $V_{dc} = 700$V, $R_{dc} = 250\Omega$						
	i_{an}	i_{bn}	i_{cn}	P_{ac}(W)	P_{dc}(W)	η(%)
rms value (A)	6.321	6.222	6.366	2307.2	1925.0	83.43
THD_i(%)	24.02	23.68	23.49			
PF	0.9690	0.9699	0.9703			

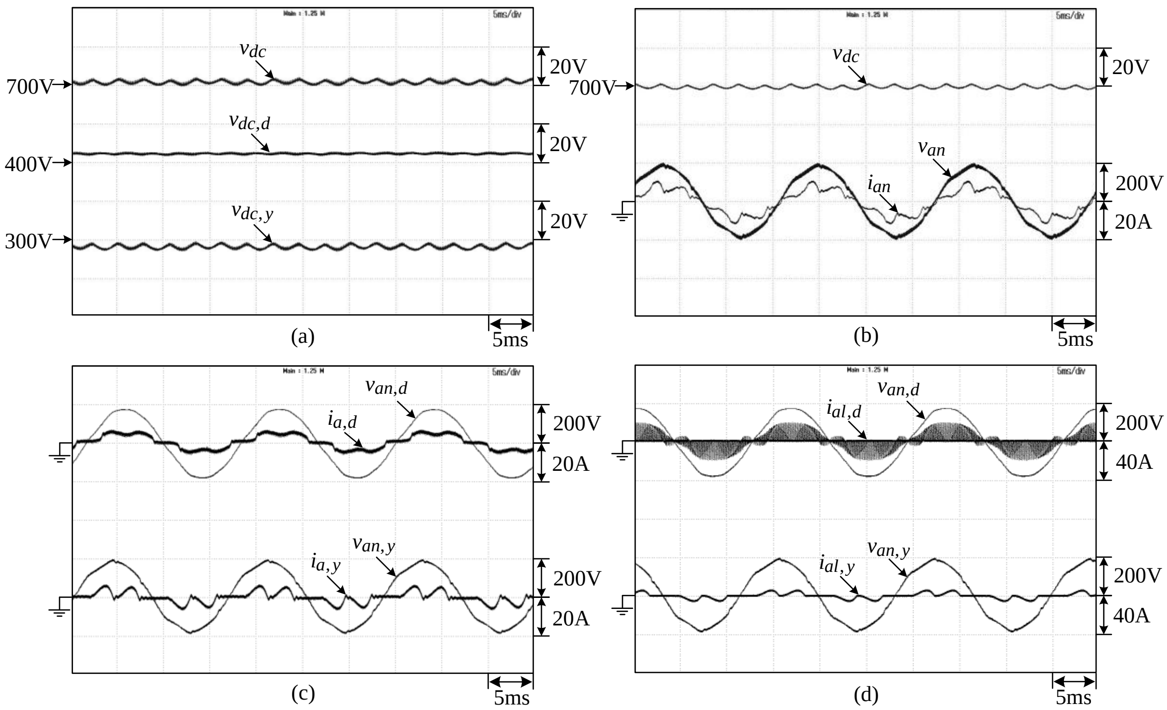


Fig. 4.2. Measured results of the 12-pulse DCM SMR with one faulted cell at $P_{dc} = 1966$W : (a) (v_{dc}, v_{an}, i_{an}); (b) $(v_{an,d}, i_{an,d}, v_{an,y}, i_{an,y})$; (c) $(v_{an,d}, i_{al,d}, v_{an,y}, i_{al,y})$; (d) $(v_{dc}, v_{dc,d}, v_{dc,y})$. Responses of (v_{dc}, v_{cont}) of the developed 12-pulse boost DCM SMR with one faulted SMR cell (Y-cell) due to a step load change under different PI controllers: (e) Simulated result; (f) measured result

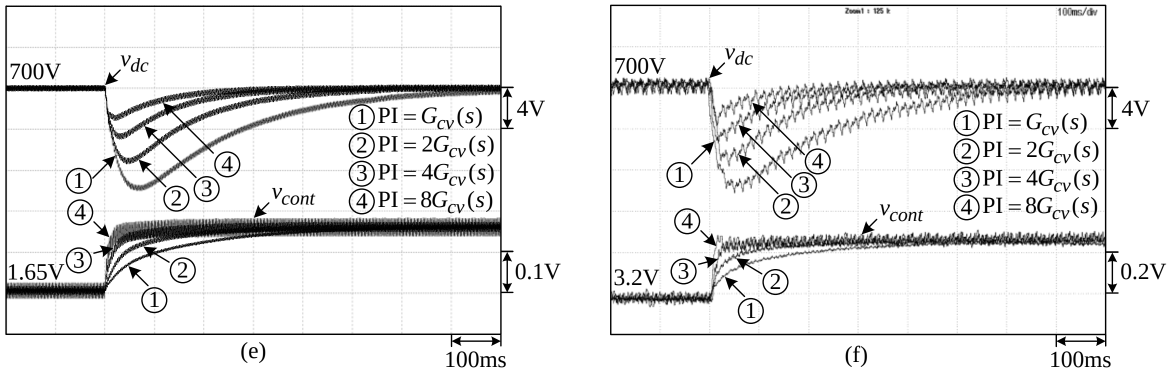


Fig. 4.2. Continued

4.5. Measured Results under Two Faulted Cells

Under this case, the two DCM SMR cells are faulted to become the diode rectifiers, the detailed results are presented in the final report.

4.6. Transient Response for Sudden Fault Occurrence

To test the voltage regulation transient response speed of the established 12-pulse DCM SMR, the switch in Y-cell is suddenly disabled. Quick voltage regulation responses are obtained by the designed control scheme (The details can be referred to the final report).

5. Conclusions

This special topic has developed a 12-pulse AC/DC converter using two three-phase DCM SMRs. The major contributions are summarized below:

(1) A and a $Y-\Delta$ transformer banks are constructed to let the serially connected two SMRs be powered by two three-phase balanced voltages with 30-degree phase shift from the same grid AC source.

(2) The power circuit of the DCM SMR cell is properly designed. The SMR is stably operated under DCM with rough PFC function without applying current control. Then the intuitive and practical design approach for designing the PI voltage feedback controller is proposed to preserve well-regulated DC output voltage. The effectiveness of the proposed approach is verified by simulated and measured results.

(3) The 12-pulse AC/DC converter with two DCM SMR cells in healthy condition is established. The satisfactory steady-state and dynamic operation characteristics are demonstrated experimentally.

(4) The following fault-tolerant operations and controls are conducted: (i) One cell is faulted and becomes a diode rectifier. Even only one cell remains the control ability, the DC-link voltage of the whole 12-pulse AC/DC converter can still be successfully regulated; and (ii) The constituted two SMR cells are all disabled. The 12-pulse SMR is naturally changed to a 12-pulse rectifier. The DC-link voltage is still established, but the voltage regulation control capability is lost.

(5) The operating characteristics under all cases are comparatively evaluated by simulated and measured results.

心 得

周芳毅：

The reason for me to choose this special topic is that I had no background knowledge in power electronics before entering this lab, and I want to try some regions that I have never learned. At first, my partner and I study some reference sources and select some related courses to gain some knowledge in power electronics and electric machinery, such as

DC-DC converter, three phase transformers, simulation software, etc. Then, we start to learn some simulation techniques, this help us so much in our circuit design. Finally, we spend most of our time in establishing our circuits, which is also the most interesting and needs much patience.

I really learned many experiences and techniques of designing and establishing circuits during this year. There are many difficulties I haven’t encountered before joining this lab. For example, some elements will burn up when voltages on them is larger than their rating value, there will be some non-ideality in our real control circuits or power circuits. To deal with these problem, patience and experiences are really needed. Except for establishing our circuits, we also learned a lot of things in presenting measured results.

Finally, I would like to appreciate my professor and upperclassmen for helping us in our special topic, such like, teaching us some associated knowledge and some techniques in dealing with non-idealities in our circuits. Besides, whenever we have troubles in our projects, our professor and our upperclassmen will always give us some advices, and they always show their patience to us. With their help, we find the directions in designing and establishing our circuits and finally finishing this special topic. I really appreciate for all the things I have learned and enjoyed in the special topic and all the members in this lab.

楊松諭：

I am relieved that the special topic is finally finished. At the beginning, I never thought I would choose power electronics as my special topic. But after I followed my partner to talk with the professor. I was quite interested in power electronics and decided to choose this topic. At first, our professor gave us the goal. Then, we start to establish our circuits and do experiments while learning what we need for our special topic.

The lifetime in the laboratory is a precious treasure which makes me grow up a lot. During this year, we had encountered many difficulties such as the noise in our circuits. At that time, we had a lot of discussions and asked the seniors for advices. Thinking together and trying new ideas when we come up with them. Although we have failed many times, we have also gained experience and insight from it.

We had spent more than 18 hours a week for doing experiment, learning and thinking. I gradually learned the correct attitude of research and the spirit of keeping improving. For this, I would like to thank my teacher C. M. Liaw and the lab members who helped us a lot. Thanks to their guidance, we found the direction in researching, and finally completed our research of special topic. Finally, I knew I was not doing well enough, make professors and lab upperclassmen worry about me. But I will change myself and be better in the future. Also, I hope both my partner and the upperclassmen in lab can have a good future.