

湖南大学

# 毕业设计

题 目 如果你的毕设标题像我的一样很

长会怎么样呢就像这样它真的长

学 院 信息科学与工程学院

专 业 拿烙铁的姿势要和拿笔一样

班 级 班级 1999

学 生 革命群众

学 号 201999999999

指导教师 一位长者刘慈欣

二〇二三 年 六 月 二十八 日



## 摘要

近日，由教务处教学质量与评估办公室编写的《“四路并举”赋能专业建设新样态》成功入选教育部《全国普通高校本科教育教学质量报告》(以下简称《质量报告》)应用典型案例，并将编入由高等教育出版社出版的《数智助鉴以鉴促强——落实质量主体责任高校在行动》一书。

《质量报告》是在教育部教育督导局指导下，由教育部教育质量评估中心会同有关高校、教育研究机构等单位组建的学术团队联合研制，系统反映我国普通高校本科教育教学质量发展状况的年度报告。应用案例征集活动旨在选树一批高校教学质量管理优秀典型，巩固本科教育教学改革成果，完善体制机制建设。

入选案例《“四路并举”赋能专业建设新样态》系统总结了学校近年来深化专业综合改革的建设举措以及成效。以“需求驱动、质量带动、产业拉动、内外联动”为引擎，围绕“四新”专业建设主线，推动本科专业供给侧改革，优化专业布局动态调整，积极搭建产教融合育人平台，持续推进专业建设高水平发展，提高专业人才培养质量。

近年来，学校高度重视本科教育教学工作，始终坚持以习近平新时代中国特色社会主义思想为指导，落实立德树人根本任务，推动学校本科教育内涵建设和高质量发展。学校将充分学习和研究《质量报告》，进一步扎实做好本科教育教学质量常态监测、编制发布本科教学质量报告和专业人才培养状况报告等工作。以数据分析报告为重要依据，积极引导各专业明确定位、强化特色、加强优势、提升质量，构筑高水平人才培养体系，不断提升育人成效。

**关键词:** 关键词 1；关键词 2；关键词 3

## ABSTRACT

The University has established 4 national-level distinctive specialties, 5 national-level quality courses, 2 national-level exemplary bilingual courses, 2 national-level quality public audio and video courses, 6 specialties training for Outstanding Engineers, 16 provincial-level distinct specialties, 9 specialties jointly supported by the school and enterprise, 53 provincial-level top-grade courses and 5 provincial-level experimental teaching centers. In recent years, the faculties have undertaken 6 national teaching and research projects and 55 provincial projects, published 8 textbooks guided by China, and won 3 national "Teaching Achievements" awards and 75 provincial "Teaching and Research Achievements" awards. In addition, the University has successively won a wide variety of honors for innovation and creativity, such as the "Challenge Cup" Extracurricular and Academic Contest, and China Undergraduate Mathematical Contest in Modeling. The students have won 3133 provincial or national awards, of which 48 are first prizes and 125 are second prizes at the national level.

In recent years, the university has undertaken 347 national research projects including funds from the National Science and Technology Support Program, 973 project program, 863 project program, and support from the Natural Science Foundation of China, and Social Science Foundation of China, and 814 provincial projects. The University has won 238 national and provincial prizes for research achievements, one second prize of National Award for Technological Invention and 3 second prizes of National Award for Science and Technology Progress, and obtained 666 national patents. 4799 papers were indexed by SCI, EI or ISTP. 214 academic works, translations or textbooks were published. Eight journals are currently sponsored by the University of Jinan, including "China Powder Science and Technology", "Chinese Journal of Cancer Prevention and Treatment", and "Journal of University of Jinan".

**Key words:** keyword1; keyword2; keyword3

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# 1 基础功能测试

```
#include <stdio.h>
int main(){
    /* 我的第一个 C 程序 */
    printf("Hello, World! \n");
    return 0;
}
```

## 1.1 文字与段落

这是文字 [1]，这是参考文献的交叉引用 [2]。

这是段落。这是段落。这是段落。这是段落。这是段落。这是段落。这是段落。  
这是段落。这是段落。这是段落。这是段落。这是段落。这是段落。这是段落。这是  
段落。这是段落。这是段落。这是段落。

### 1.1.1 文字与段落

这是文字，这是参考文献的交叉引用 [3]。

这是段落 [4]，这是参考文献的交叉引用 [5]。这是段落。这是段落。这是段落。  
这是段落。这是段落。这是段落。这是段落。这是段落。这是段落。这是段落。这是  
段落。这是段落。这是段落。这是段落。这是段落。这是段落。这是段落。

## 1.2 图表

### 1.2.1 图片



图 1: 这是图表

### 1.2.2 表格

序号	姓名	性别	年龄	身高/cm	体重/kg
1	张三	M	16	163	50
2	王红	F	15	159	47
3	李二	M	17	165	52

表 1: 这是表格

## 2 基础功能测试

## 2.1 文字与段落

这是文字。

## 2.1.1 文字与段落

这是文字。

2.2 图表

### 2.2.1 图片



图 2: 这是图表

### 2.2.2 表格

序号	姓名	性别	年龄	身高/cm	体重/kg
1	张三	M	16	163	50
2	王红	F	15	159	47
3	李二	M	17	165	52

表 2: 这是表格

### 3 基础功能测试

#### 3.1 文字与段落

这是文字。

这是段落。

##### 3.1.1 文字与段落

这是文字。

这是段落。

#### 3.2 图表

##### 3.2.1 图片



图 3: 这是图表

##### 3.2.2 表格

序号	姓名	性别	年龄	身高/cm	体重/kg
1	张三	M	16	163	50
2	王红	F	15	159	47
3	李二	M	17	165	52

表 3: 这是表格

4 基础功能测试

## 4.1 文字与段落

这是文字。

### 4.1.1 文字与段落

这是文字。

4.2 图表

#### 4.2.1 图片



图 4: 这是图表

#### 4.2.2 表格

序号	姓名	性别	年龄	身高/cm	体重/kg
1	张三	M	16	163	50
2	王红	F	15	159	47
3	李二	M	17	165	52

表 4: 这是表格

## 结 论

这是 ch2-basic/conclusion.tex 的内容。

## 参 考 文 献

- [1] 赵凯华, 罗蔚茵, 张三, 等. 新概念物理教程: 力学 [M]. 北京: 高等教育出版社, 1995.
- [2] SHANNON C E. A mathematical theory of communication[J]. The Bell system technical journal, 1948, 27(3): 379–423.
- [3] NASH JR J. Non-cooperative games[G] // Essays on Game Theory. [S.l.]: Edward Elgar Publishing, 1996: 22–33.
- [4] 汪昂. 本草备要 [M]. 石印本, 增补. 上海: 同文书局, 1912.
- [5] TURING A M. Computing machinery and intelligence[M]. [S.l.]: Springer, 2009.

## 致 谢

这是 ch2-basic/thanks.tex 的内容。

## 附录

这是 ch2-basic/appendix.tex 的内容。

湖南大学

# 毕业设计附件

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指导教师 一位长者刘慈欣

二〇二三 年 六 月 二十八 日

## 附件目录

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- 一、毕业设计任务书
- 二、毕业设计方案
- 三、毕业设计外文资料翻译
- 四、毕业设计开题评分表
- 五、毕业设计中期检查评分表
- 六、毕业设计日常考核评分表
- 七、毕业设计评阅评分表
- 八、毕业设计答辩评分表
- 九、毕业设计指导教师评语
- 十、毕业设计评阅人评语
- 十一、毕业设计答辩小组评语
- 十二、毕业设计答辩委员会意见

# 毕业设计任务书

学院 信息科学与工程学院 专业 拿烙铁的姿势要和拿笔一样

学生 革命群众 学号 201999999999

设计题目 高性能异构并行硬件加速计算平台的设计与实现

## 一、毕业设计的内容

做个 app 做个网页端，跑点数据分析人工智能的界面，指着那一块电路板和芯片说这是边缘计算部署，规划和控制由 jetson 通过 lattice planner 和 lqr pid 计算，结果传输到硬件平台执行，实现实时的避障和规划。

## 二、毕业设计的要求

构建“大思政”视野下高校生涯教育“544”一体化教育模式，以“三聚焦”，促“三提升”，融入学生成长全过程，打通学生成才全链条，引导大学生树立正确的世界观、人生观、价值观，不断提升思想政治教育的指导性、感染力和针对性。

## 三、毕业设计进程安排

序 号	阶段任务	日 期

## 四、文献查询方向及范围

数据库、网络资源、中英文文献、书籍及相关硕博论文资料

毕业设计起止时间： 2023 年 1 月 1 日—— 2023 年 6 月 28 日

指导教师（签字） \_\_\_\_\_

系主任（签字） \_\_\_\_\_

2023 年 6 月 28 日

湖南大学

# 毕业设计方案

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二〇二三 年 六 月 二十八 日

# 毕业设计方案

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学院 信息科学与工程学院 专业 拿烙铁的姿势要和拿笔一样

学生 革命群众 学号 201999999999

设计题目 高性能异构并行硬件加速计算平台的设计与实现

## 一、选题背景与意义

1.国内外研究现状

没有。

没有。

2.选题的目的及意义

没有。

没有

## 二、设计内容

1.设计内容研究

没有

2.预期研究结果

毕业论文一篇

## 三、设计方案

1.设计思路

没有

2.设计方法

没有

3.设计手段

没有

## 四、参考文献

没有

没有

没有

没有

没有

没有

# 毕业设计方案

## 五、指导教师评语

指导教师（签字）\_\_\_\_\_

2023 年 月 日

## 六、审核意见

系主任（签字）\_\_\_\_\_

2023 年 月 日

湖南大学

# 毕业设计外文资料翻译

题 目 如果你的毕设标题像我的一样很长会怎么样呢就像这样它真的长

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二〇二三 年 六 月 二十三 日



Article

# Development of a DC-Side Direct Current Controlled Active Ripple Filter for Eliminating the Double-Line-Frequency Current Ripple in a Single-Phase DC/AC Conversion System <sup>†</sup>

**Ying-Chieh Chen** <sup>1</sup>, **Liang-Rui Chen** <sup>1</sup>, **Ching-Ming Lai** <sup>2,\*</sup> , **Yuan-Chih Lin** <sup>3</sup> and **Ting-Jung Kuo** <sup>2</sup>

<sup>1</sup> Department of Electrical Engineering, National Changhua University of Education, Changhua 500, Taiwan; ycc@ncut.edu.tw (Y.-C.C.); lrchen@cc.ncue.edu.tw (L.-R.C.)

<sup>2</sup> Department of Electrical Engineering, National Chung Hsing University, Taichung 402, Taiwan; tingjungk@gmail.com

<sup>3</sup> Department of Electrical Engineering, National Taiwan University, Taipei 106, Taiwan; gero.lin1980@gmail.com

\* Correspondence: pecmlai@nchu.edu.tw

† This paper is an extended version of our paper published in IEEE International Conference on Awareness Science and Technology, Taichung, Taiwan, 8–10 November 2017; pp. 234–237.

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**Abstract:** The objective of this paper is to propose an active ripple filter (ARF) using the patented DC-side direct current control for eliminating the double-line-frequency current ripple in a single-phase DC/AC conversion system. The proposed ARF and its control strategies can not only prolong the usage life of the DC energy source but also improve the DC/AC system performance. At first, the phenomena of double-line-frequency current ripple and the operation principle of the ARF are illustrated. Then, steady-state analysis, small-signal model, and control loop design of the ARF architecture are derived. The proposed control system includes: (1) a DC current control loop to provide the excellent ripple eliminating performance on the output of the DC energy source; (2) a voltage control loop for the high-side DC-bus voltage of the ARF to achieve good steady-state and transient-state responses; (3) a voltage feedforward loop for the low-side voltage of the ARF to cancel the voltage fluctuation caused by the instability of the DC energy source. Finally, the feasibility of the proposed concept can be verified by the system simulation, and the experimental results show that the nearly zero double-line-frequency current ripple on the DC-side in a single-phase DC/AC conversion system can be achieved.

**Keywords:** double-line-frequency current ripple; active ripple filter (ARF); single-phase DC/AC

## 1. Introduction

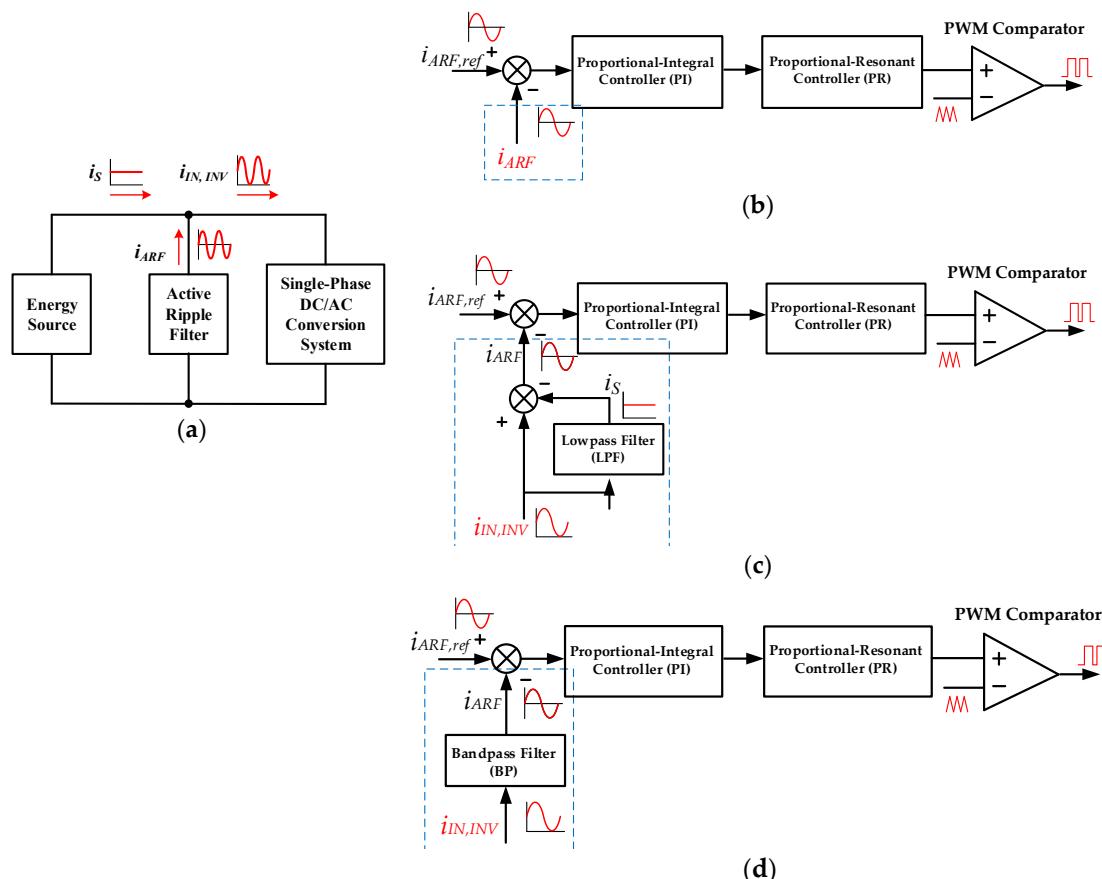
In recent years, the green energy conversion technologies for distributed generation system have become major industrial developments in the global trend of energy conservation and carbon reduction. Single-phase DC–AC power converters are generally used to supply AC loads in such applications [1–5]. The power generated by DC/AC conversion technologies according to user demands, and is then provided for stand-alone AC loads [6–8] or fed into the utility grid [9].

In a single-phase DC/AC conversion system, the DC input or AC output of the power converter would generate double-line-frequency instantaneous power in addition to the average power. Assuming that all the components of the converter are ideal, according to the law of conservation of energy, the instantaneous power at the DC input must be equal to that at the AC output.

The instantaneous power will cause the energy storage component such as the inductor or capacitor to have double-line-frequency ripples, thus affecting the stability of the DC or AC sides of the power converter [10–25]. As for a further comment in [10], the double-line-frequency current ripple will reduce the lifetime and performance of DC energy source [10], and increase the input filter size. Therefore, the problem of double-line-frequency instantaneous power should not be neglected while developing high performance power converters [11–25].

Previous studies have attempted to use passive or active ripple filters (ARF) to eliminate double-line-frequency instantaneous power. The passive ripple filter increases the size of the energy storage components on the low-voltage or high-voltage sides of the single-phase DC/AC conversion system [9,16], or designs an appropriate inductor–capacitor (LC) series resonant circuit to suppress the double-line-frequency ripple on the high-voltage bus [17]. Although the aforementioned practices can be employed to yield low-current ripple, which are relatively ideal, their main disadvantage is that a considerably large electrolytic capacitor (E-cap) or inductor is required. In addition, the E-cap which is generally paralleled to the low- or high-voltage bus, may heat up due to long-term absorption of ripple components. Moreover, the equivalent series resistor (ESR) heats up along with the larger ripples on the E-cap, which not only causes the additional power consumption, but also reduces the lifetime of E-cap [20,21].

ARF technique is the power electronics circuit with energy storage elements [4] for eliminating the problem of double-line-frequency instantaneous power, and the power decoupling method is commonly used for the control strategy of the ARF [4,5]. Therefore, considering the size, cost, and characteristics of passive components, passive ripple filters have been gradually replaced by the ARF [11–15,18–25]. As a reference for research origin, the general ARF scheme and its conventional control diagrams for the single-phase DC/AC conversion system applications are shown in Figure 1.



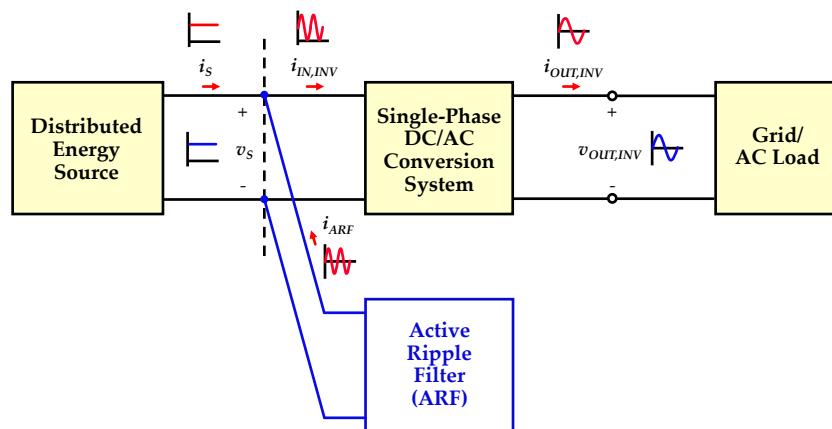
**Figure 1.** The general ARF scheme (a); and its conventional control diagrams (b–d) for the single-phase DC/AC conversion system applications.

According to the different current measurement locations of the ARF as shown in Figure 1a, the conventional control diagram of the ARF can be classified into (1) the input current sensing point of the ARF, as shown in Figure 1b; and (2) the input current sensing point of the single-phase DC/AC power conversion system, as shown in Figure 1c,d. For locating the input current sensing point of the ARF, the proportional-resonant (PR) controller and the proportional-integral (PI) controller are cascade interconnection to achieve the zero steady-state error for tracking AC reference. For locating the input current sensing point of the single-phase DC/AC power conversion system, it requires the low pass filter (Figure 1c) or bandpass filter (Figure 1d) to filter the DC component of the input current of the single-phase DC/AC power conversion system. In summary, the ARF must provide AC current, which is difficult to control, and the above-mentioned methods cause the design process of system controller as well as its parameters more complicated and difficult indeed.

In this study, an ARF using the DC-side direct current control for eliminating the double-line-frequency current ripple in a single-phase DC/AC conversion system would be proposed. Compared with the other conventional control diagrams as shown in Figure 1b–d, the DC-side direct current control strategy is relatively simple to implement. The current command and feedback signals are DC values, hence the nearly zero-steady state error can be fulfilled easily. The steady-state analysis, small-signal model and control loop design of the proposed ARF architecture are derived.

## 2. Principle of Double-Line-Frequency Instantaneous Power

Figure 2 illustrates a single-phase DC/AC conversion system, and characteristic waveforms of the system for the power flows without and with the ARF are presented in Figure 3.



**Figure 2.** Integration of the ARF into a single-phase DC/AC conversion system [26].

The key waveforms without the ARF are shown in Figure 3a. In this figure, the instantaneous output voltage, output current, and output power of the single-phase DC/AC conversion system are expressed as  $v_{OUT,INV}$ ,  $i_{OUT,INV}$ , and  $p_{OUT,INV}$ , respectively, as follows:

$$v_{OUT,INV} = V_m \sin(\omega_L t) \quad (1)$$

$$i_{OUT,INV} = I_m \sin(\omega_L t) \quad (2)$$

$$P_{OUT,INV} = v_{OUT,INV} \cdot i_{OUT,INV} \quad (3)$$

According to the conservation of energy and the assumption that the energy dissipation of the system can be neglected, the output power of the energy source  $p_S$  can be expressed as follows:

$$p_S = p_{OUT,INV} = P_S + p_R \quad (4)$$

$$P_S = \frac{V_m I_m}{2} \quad (5)$$

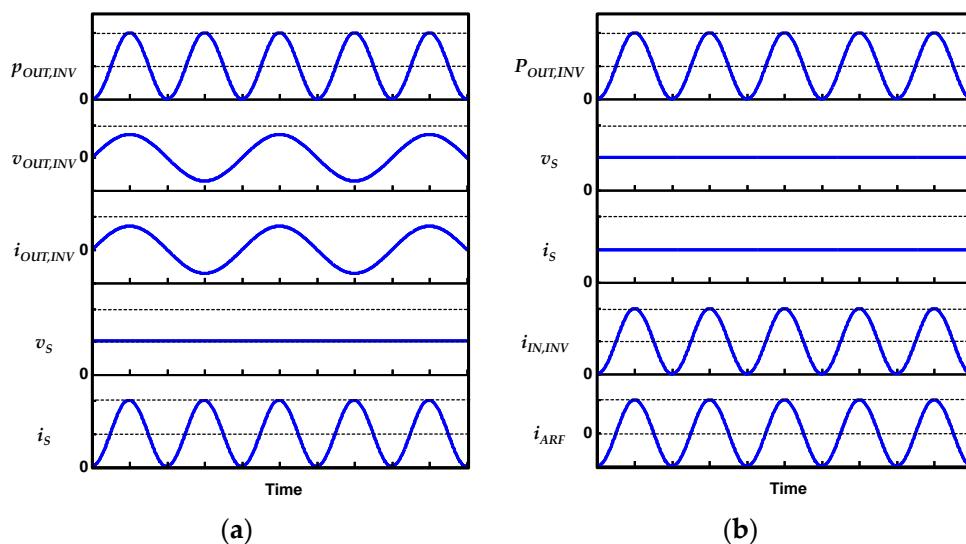
$$p_R = \frac{V_m I_m}{2} \cos(2\omega_L t \pm \pi) \quad (6)$$

where  $P_S$  is the average power and  $p_R$  refers to the double-line-frequency ripple power generated by the product of  $v_{OUT,INV}$  and  $i_{OUT,INV}$ .

Assuming that the energy source provides pure DC voltage (i.e.,  $v_S \approx V_S$ ), and the output current of the energy source can be derived as follows:

$$i_S = I_S + i_R = \frac{P_S}{V_S} + \frac{P_S}{V_S} \cos(2\omega_L t \pm \pi) \quad (7)$$

where  $I_S$  and  $i_R$  refer to the DC current and the AC (ripple) current provided by the energy source, respectively.



**Figure 3.** Key waveforms to illustrate the operating principles for double-line-frequency components of a single-phase DC/AC conversion system [26]: (a) without the ARF and (b) with the ARF.

According to (7), the double-line-frequency ripple power generated by the single-phase DC/AC conversion system was completely reflected on the current provided by the energy source. As a result, the current ripple would suffer the performance of the energy source and substantially reduce its service life [27–30]. Figure 3b illustrates the key waveforms of the single-phase DC/AC conversion system after the integration of the ARF. In this figure,  $i_{IN,INV}$  and  $i_{ARF}$  are respectively defined as the input current of the single-phase DC/AC conversion system and the compensating current provided by the ARF. It can be seen from Figure 2,  $i_{IN,INV}$  can be directly expressed as follows:

$$i_{IN,INV} = I_S + i_{ARF}. \quad (8)$$

The double-line-frequency ripple components were provided by the ARF, as shown in (9):

$$i_{ARF} = i_R = \frac{P_S}{V_S} \cos(2\omega_L t \pm \pi). \quad (9)$$

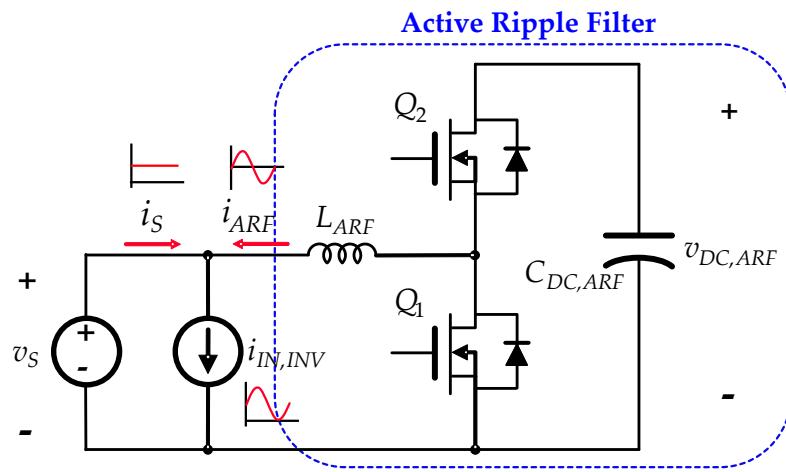
### 3. Operating Principles of the ARF

The ARF must possess the ability of bidirectional power flow to provide double-line-frequency current ripple and thus yield a pure DC current of the energy source. As shown in Figure 4, the circuit architecture of the ARF is a bidirectional buck-boost converter. The polarities of the output current of

the ARF can be divided into the boost and buck modes. When the polarity of the output current is positive, the ARF operates in a buck mode. By contrast, when the polarity of the output current is negative, the ARF operates in a boost mode.

The assumptions are made in analyzing the ARF:

- (1) the ARF operates in continuous conduction mode (CCM);
- (2) the drive signals for active switches  $Q_1$  and  $Q_2$  of the ARF are respectively defined as  $d_1$  and  $d_2$ ;
- (3) the DC-bus voltage  $v_{DC,ARF}$  could be approximated as a constant value, i.e.,  $v_{DC,ARF} \approx V_{DC,ARF}$ ;
- (4) all voltages and currents in the ARF are periodic in steady-state condition; for simplicity, it is assumed that all the components of the ARF in Figure 4 are idealized.



**Figure 4.** Circuit architecture of the ARF.

### 3.1. Buck Mode

Figure 5a illustrates the circuit architecture of the ARF operated in the buck mode. When  $Q_1$  was turned off and  $Q_2$  was turned on, the relation between current  $i_{ARF}$  and voltage of inductor  $L_{ARF}$  can be calculated using the equation as follows:

$$\frac{di_{ARF}}{dt} = \frac{V_{DC,ARF} - V_S}{L_{ARF}} \quad (10)$$

when  $Q_1$  was turned on and  $Q_2$  was turned off, the relation between current  $i_{ARF}$  and voltage of inductor  $L_{ARF}$  can be calculated using the equation as follows:

$$\frac{di_{ARF}}{dt} = -\frac{V_S}{L_{ARF}}. \quad (11)$$

According to the volt-second balance principle of the inductor  $L_{ARF}$ , the voltage conversion ratio between the low-voltage and high-voltage sides of the ARF can be derived as follows:

$$\frac{V_{DC,ARF}}{V_S} = \frac{d_1 + d_2}{d_2}. \quad (12)$$

### 3.2. Boost Mode

Figure 5b illustrates the circuit architecture of the ARF operated in the boost mode. When  $Q_1$  was turned off and  $Q_2$  was turned on, the relation between current  $i_{ARF}$  and voltage of inductor  $L_{ARF}$  can be calculated using the equation as follows:

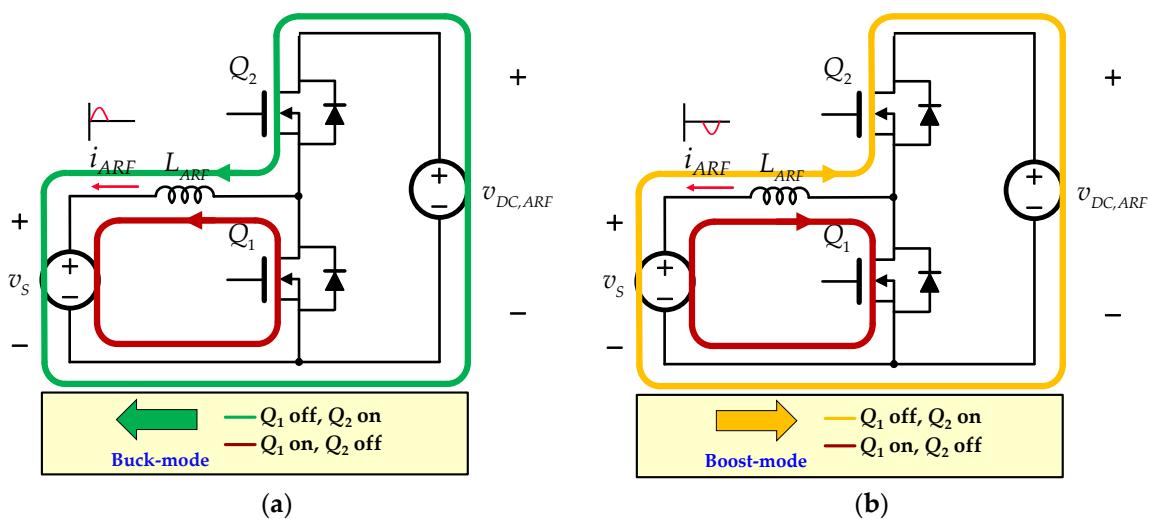
$$\frac{di_{ARF}}{dt} = -\frac{V_S - V_{DC,ARF}}{L_{ARF}} \quad (13)$$

when  $Q_1$  was turned on and  $Q_2$  was turned off, the relation between current  $i_{ARF}$  and voltage of inductor  $L_{ARF}$  can be calculated using the equation as follows:

$$\frac{di_{ARF}}{dt} = -\frac{V_S}{L_{ARF}}. \quad (14)$$

Likewise, according to the volt-second balance principle of inductor  $L_{ARF}$ , the result of (12) was also applicable to the boost mode due to the ARF has the bidirectional power flow characteristic. If the drive signals of switches  $Q_1$  and  $Q_2$  are assumed to be complementary (i.e.,  $d_1 = 1 - d_2$ ), then the voltage conversion ratio of the ARF can be simplified as follows:

$$\frac{V_{DC,ARF}}{V_S} = \frac{1}{1 - d_1}. \quad (15)$$



**Figure 5.** Circuit architecture of the ARF [26]: (a) the buck mode and (b) the boost mode.

#### 4. Control Strategy of the ARF

Figure 6 illustrates the developed control system for the ARF. At first, it can be seen that the DC-bus voltage ( $v_{DC,ARF}$ ) is sensed and compared with the voltage reference to produce an error signal. Second, the voltage controller receives the error signal to produce the average power reference signal,  $p_{s,ref}$ , which is divided by the feedforward compensation signal (i.e., energy source voltage,  $v_S$ ) to generate the current reference,  $i_{S,ref}$ . In the inner current control loop, the energy source current ( $i_S$ ) is sensed and compared with the current reference to generate the modulated signal ( $v_{con}$ ) of the pulse width modulation (PWM) generator.

It is noted that the ARF must provide AC current (i.e. ripple current), which is difficult to control. In this study, the current reference and the sensed signals are all DC value, hence the nearly zero-steady state error can be fulfilled easily. In other words, this study proposes a method of indirectly regulating the output AC current of the ARF by directly controlling the input DC current of the energy source. According to Figure 7, the controller design of the outer voltage loop and inner current loop of the ARF was illustrated as follows.

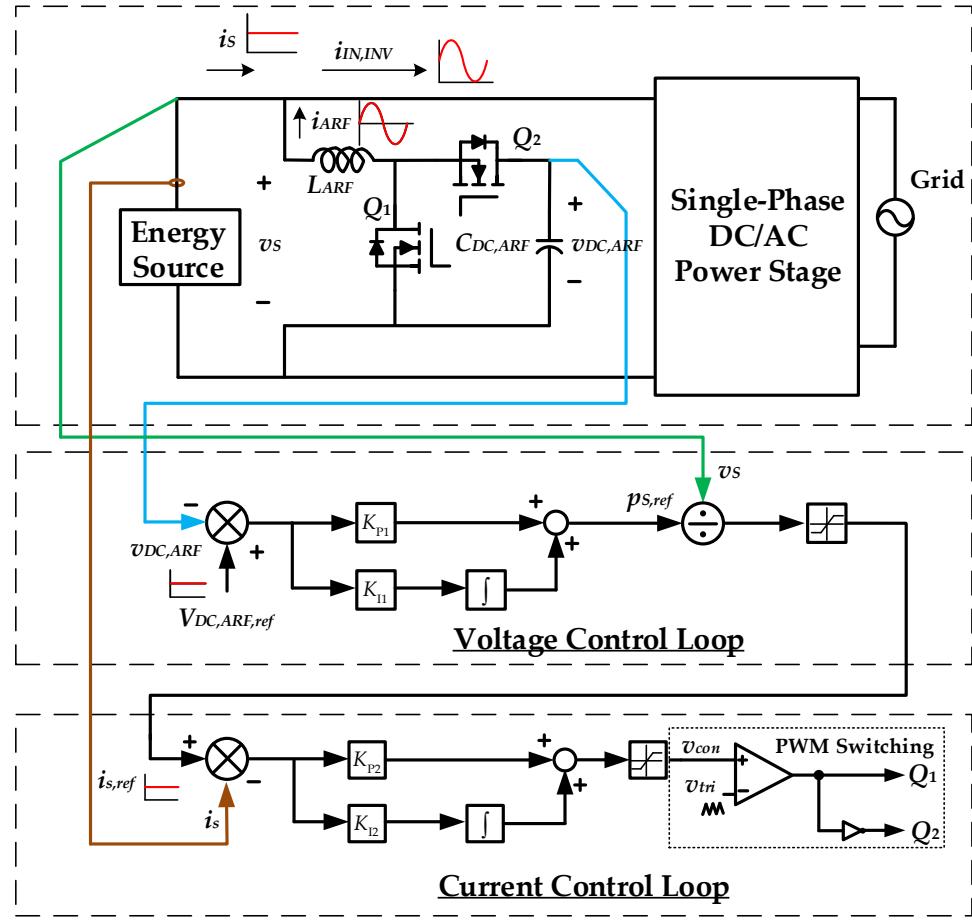


Figure 6. The developed control system for the ARF.

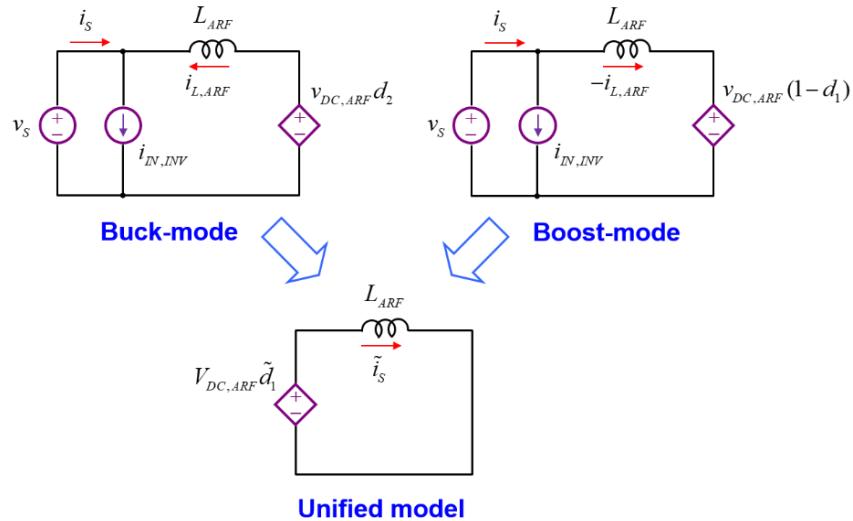


Figure 7. Small-signal equivalent circuit of the current loop.

#### 4.1. Designing the Controller of the Current Loop

Considering the buck mode operation, the inductor voltage in one switching period can be expressed as follows:

$$v_{L,ARF} = L_{ARF} \frac{di_{L,ARF}}{dt} = v_{DC,ARF}d_2 - v_s. \quad (16)$$

Perturbation was introduced into the inductor current and the drive signal  $d_2$  of  $Q_2$ , and  $d_1 = 1 - d_2$ . This study assumed that  $v_S$  and  $v_{DC,ARF}$  operated in a stable DC status. Thus, (16) can be rewritten as follows:

$$L_{ARF} \frac{d\tilde{i}_{L,ARF}}{dt} = -V_{DC,ARF}\tilde{d}_1 \quad (17)$$

when the converter was operated in the boost mode, the inductor voltage in one switching cycle can be expressed as:

$$v_{L,ARF} = L_{ARF} \frac{di_{L,ARF}}{dt} = v_{DC,ARF}(1 - d_1) - v_S. \quad (18)$$

Perturbation was introduced into the inductor current and the drive signal  $d_1$  of  $Q_1$ . Similarly,  $v_S$  and  $v_{DC,ARF}$  were assumed to operate in a stable DC status.

Accordingly, (18) can be further expressed as:

$$L_{ARF} \frac{d(\tilde{i}_{L,ARF})}{dt} = -V_{DC,ARF}\tilde{d}_1. \quad (19)$$

An observation of (17) and (19) indicated that the small-signal models derived in the buck and boost operational modes were the same. In addition, this study controlled the output current of the ARF indirectly by controlling the output current of the energy source to regulate the required current ripple provided by the ARF. Therefore, the derived small-signal model must undergo minor modifications. According to (8), the three branch currents of the input side of the ARF-integrated single-phase DC/AC conversion system were interrelated. This study assumed that the input current  $i_{IN,INV}$  required by the single-phase DC/AC conversion system can be regarded as a definite value in consideration of small signals. In other words, perturbation in the current provided by the energy source would be directly reflected on the output current of the ARF.

Therefore, the introduction of perturbation into the two signals in (8) would result in the following equation:

$$\tilde{i}_S = -\tilde{i}_{L,ARF}. \quad (20)$$

Substituting (17) or (19) into the equation, performing the Laplace transform, and deriving the transfer function of the small-signal model of the current loop is as follows:

$$G_c = \frac{\tilde{i}_S}{\tilde{d}_1} = \frac{V_{DC,ARF}}{sL_{ARF}}. \quad (21)$$

The equivalent circuit derived in the aforementioned process is illustrated in Figure 7. The parameters were  $V_{DC,ARF} = 100$  V and  $L_{ARF} = 250$   $\mu$ H, and the open-loop gain of the current loop is expressed as (22).

$$L_c(s) = \frac{\tilde{i}_S}{\tilde{v}_{con}} = F_m G_c(s) = \frac{4000}{s} \quad (22)$$

where  $F_m$  is the equivalent small-signal gain of pulse-width modulation, as follows

$$F_m = \frac{1}{V_{tri}} = \frac{1}{100} \quad (23)$$

where  $V_{tri}$  is the peak value of the carrier wave of the PWM generator.

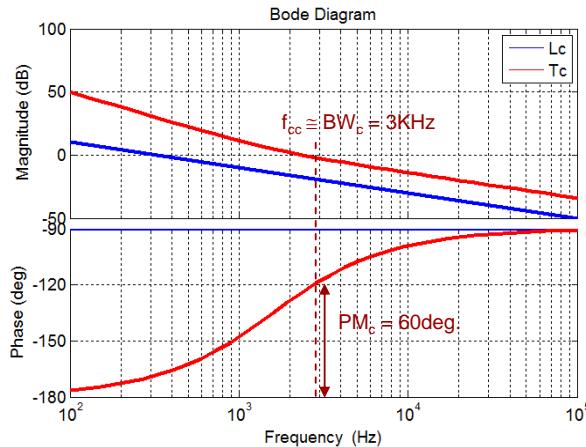
According to Figure 7, the open-loop gain of the current loop was in a first-order integral form. Therefore, the controller only needed to be in a proportional-integral (PI) form to achieve satisfactory control. The form and parameters of the designed PI controller are presented as follows:

$$C_c(s) = K_{P1} + \frac{K_{I1}}{s} = K_{pc} \cdot \frac{s + z_c}{s} = 4.5 \cdot \frac{s + 10000}{s}. \quad (24)$$

After incorporating the compensation from the controller, the open-loop gain of the current loop is expressed as follows:

$$T_c(s) = C_c(s)L_c(s) = 18000 \cdot \frac{s + 10000}{s^2}. \quad (25)$$

The bode plot of the response frequency of the current loop after receiving compensation from the controller is also illustrated in Figure 8. According to the figure, the zero crossover frequency (i.e., closed-loop bandwidth) was 3 kHz, and the phase margin was 60°. In other words, the closed-loop control enabled the ARF to attain sufficient response and stability.



**Figure 8.** Bode plot of the frequency response of the current loop.

#### 4.2. Designing the Controller of the Voltage Loop

In practice, the capacitor voltage on the high-voltage side of the ARF also involved double-line-frequency components. Consequently, the compensation current command may be affected through feedback control, resulting in the failure to completely eliminate the double-line-frequency components at the output side of the single-phase DC/AC conversion system. To prevent this problem, the bandwidth of the voltage loop on the high-voltage side of the ARF must be substantially lower than the double-line-frequency to ensure that the current command remains unaffected.

According to Figure 9, the small-signal model of the voltage loop was derived as follows from the perspective of power, where  $p_{CH}$  and  $i_{CH}$  refer to the power and current of the capacitor energy storage on the high-voltage side of the ARF.

$$p_{RIP} = p_{IN,INV} - p_S = -p_{CH} \quad (26)$$

$$v_S i_{L,ARF} = -v_{DC,ARF} i_{CH}. \quad (27)$$

Assuming the stable operation of  $v_S$  and  $v_{DC,ARF}$ , to consider (20) and substitute perturbation into  $i_S$  and  $i_{CH}$ . Thus, (27) can be rewritten as:

$$\frac{\tilde{i}_{CH}}{\tilde{i}_S} = \frac{V_S}{V_{DC,ARF}}. \quad (28)$$

Multiplying (28) by the capacitive resistance on the high-voltage side, to perform the Laplace transform, and then the transfer function of the small-signal model of the voltage loop can be expressed as follows:

$$G_v = \frac{\tilde{v}_{DC,ARF}}{\tilde{i}_S} = \frac{V_S}{s V_{DC,ARF} C_{DC,ARF}}. \quad (29)$$

The parameters of the small-signal model of the voltage loop included  $v_S = 36$  V,  $V_{DC,ARF} = 100$  V, and  $C_{DC,ARF} = 3400 \mu\text{F}$ . The open-loop gain of the voltage loop is as follows:

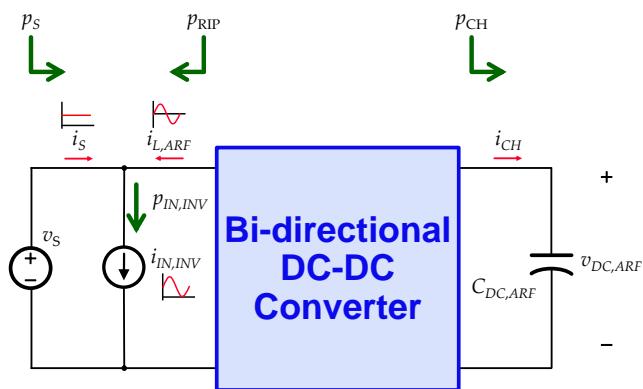
$$L_v(s) = \frac{\tilde{v}_{DC,ARF}}{\tilde{p}_{S,ref}} = \frac{P_v(s)}{V_S} = \frac{2.941}{s}. \quad (30)$$

Notice that (30), which includes the feedforward term of the  $S$  at denominator, which can eliminate fluctuation caused by  $v_S$ . Similar to the current loop, the open-loop gain of the voltage loops was in a first-order integral form as well. Therefore, the PI form can be used on the controller. The parameters of the controller are expressed as follows:

$$C_v(s) = K_{P2} + \frac{K_{I2}}{s} = K_{pv} \cdot \frac{s + z_v}{s} = 16 \cdot \frac{s + 20}{s}. \quad (31)$$

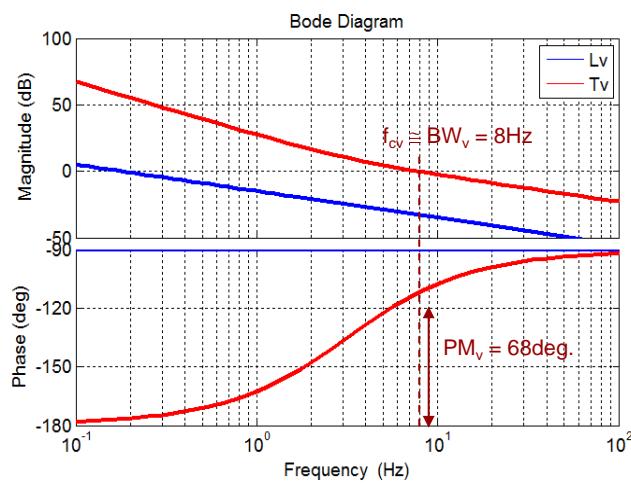
After incorporating the compensation from the controller, the open-loop gain of the voltage loop is presented as follows:

$$T_v(s) = C_v(s)L_v(s) = 47.05 \cdot \frac{s + 20}{s^2}. \quad (32)$$



**Figure 9.** Small-signal equivalent circuit of the voltage loop.

Figure 10 illustrates the open-loop gain of the voltage loop before and after compensation. The figure shows that, after compensation, the zero crossover frequency was 8 Hz and the phase margin was 68°. The closed-loop control improved the stability of the capacitor voltage on the high-voltage side of the ARF.

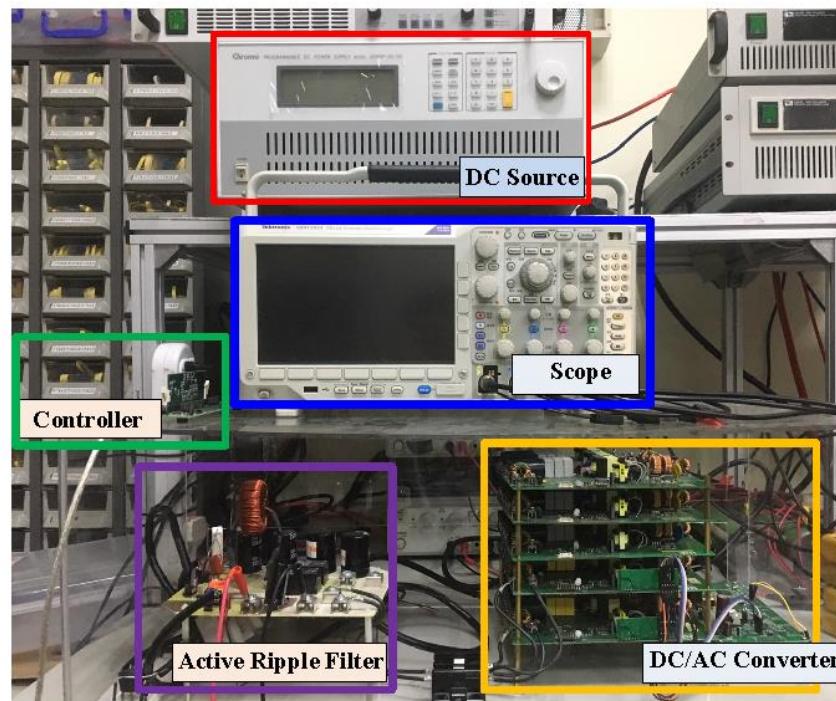


**Figure 10.** Bode plot of the response frequency of the voltage loop.

## 5. Simulation and Experimental Results

MATLAB® and PSIM® software were used to analyze and verify the feasibility of the proposed method. The specifications of the system are listed as follows: an input DC voltage of 36 V for the distributed energy source, an output AC voltage of 110 Vrms, and a rated power output of 500 W for single-phase DC/AC grid-connected operation [31]. The experimental platform was implemented,

as shown in Figure 11. The parameters of circuit components and the specification of the experimental platform are listed in Tables 1 and 2, respectively.



**Figure 11.** Experimental platform of a 500 W single-phase DC/AC conversion integrated with ARF.

**Table 1.** Component parameters of the ARF circuit.

Component	Symbol	Value/Model
Inductance	$L_{ARF}$	$250 \mu\text{H}$
MOSFET	$Q_1, Q_2$	FDA59N30
Capacitance	$C_{DC, ARF}$	$3400 \mu\text{F}/250\text{V}$

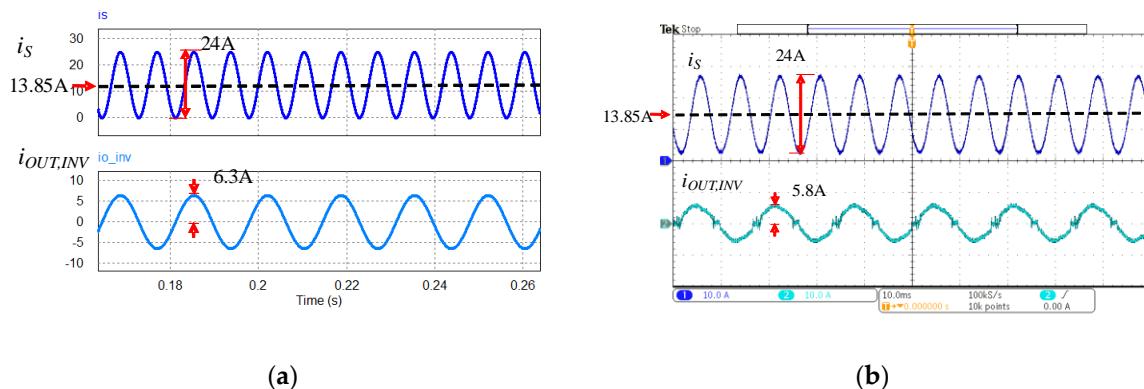
**Table 2.** Equipment of the experimental platform.

Type	Model
DC Source	Chroma 62050P-100-100
Scope	Tektronix MDO3024
Power Analyzers	Yokogawa WT310

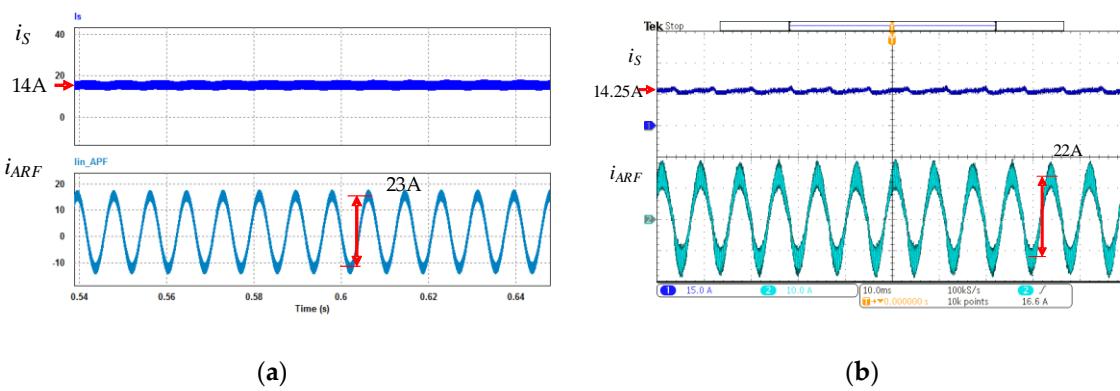
The simulation and experimental results at 500 W before the ARF were integrated into the distributed energy source as shown in Figure 12a,b, respectively. The distributed energy source provides an average current of 13.85 A, the peak-to-peak value of the double-line-frequency current ripple is 24 A.

The only difference is that the peak value of the output current of the single-phase DC/AC conversion system are 6.3 A and 5.8 A, respectively. As shown in the results, the ripples strongly affect the service life of the DC energy source and reduces the operating efficiency of the power system.

Next, after integration of the ARF, the double-line-frequency current ripple is suppressed, the average current is 14 A and 14.25 A, the peak-to-peak value of the inductor current is 23 A and 22 A, the results are shown in Figure 13a,b, respectively. In this case, the life service of the distributed energy source not only increased, but the performance of the power system was also enhanced.

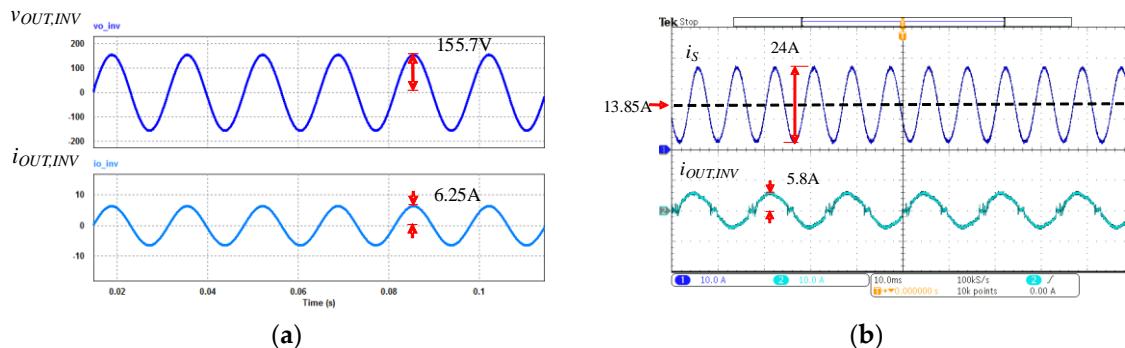


**Figure 12.** The output currents of the distributed energy source before the ARF was integrated: (a) Simulation result and (b) experimental result.



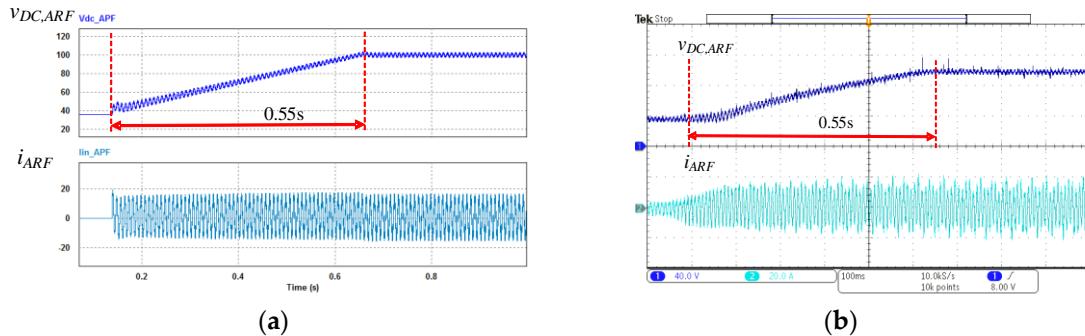
**Figure 13.** Steady-state of the output voltage and inductor current of the ARF: (a) Simulation result and (b) experimental result.

Figure 14 shows the simulation and experimental results of the DC/AC output voltage and output current at 500 W when the ARF was integrated, respectively. In Figure 14a (simulation), the peak voltage of 155.7 V, the peak value of the output current is 6.25 A. In Figure 14b (experiments), the peak current of the output current is 5.8 A.



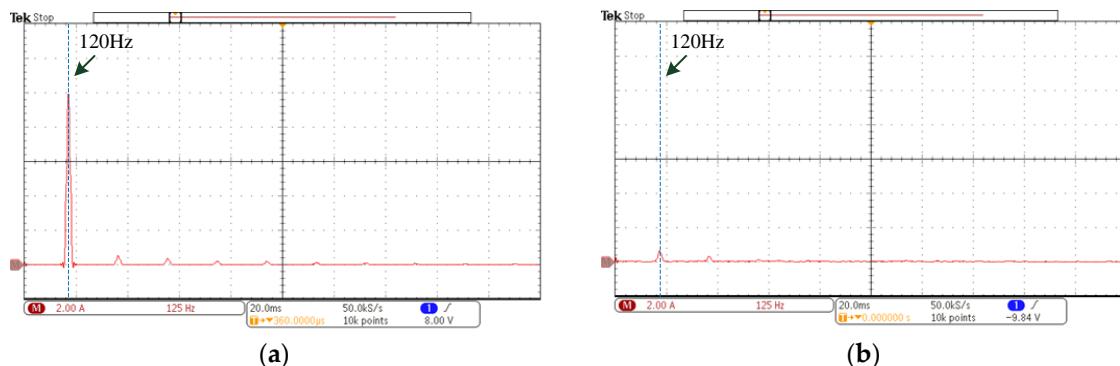
**Figure 14.** The output voltage and current of the proposed single-phase DC/AC conversion system. (a) Simulation result and (b) experimental result.

To add a soft-start circuit made the output of the system start up smoothly, the current remained stable, the output voltage increased to 100 V smoothly without overshoot, and the soft-start time was about 0.55 s. The results are shown in Figure 15a,b, respectively.



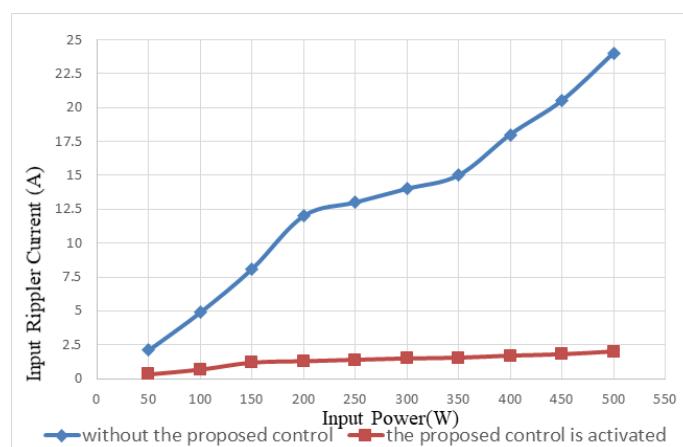
**Figure 15.** The bus voltage and inductor current of the ARF during the soft start process: (a) Simulation result and (b) experimental result.

As seen in Figures 12–15, the simulation coincided with experimental results to validate the proposed method. These results correspond with the calculations in the steady-state analysis as well. Figure 16a illustrates spectrum of the input current at 120 Hz before the integration of ARF and Figure 16b verifies the double-line-frequency current ripple of the input side is significantly reduced.

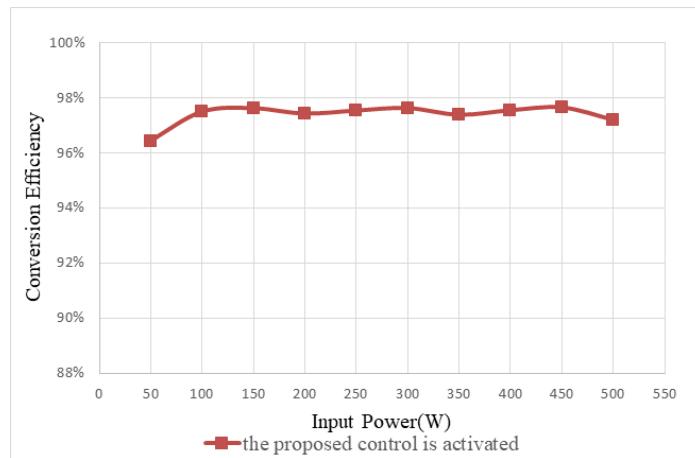


**Figure 16.** Experimental results of measurement input DC current spectrum in 120Hz: (a) before DC energy source integrates with ARF and (b) DC energy source integrates with ARF.

By observing Figure 17, in the full load case, the peak-to-peak current ripple is 24 A, which is 175% of the average value. When ripple suppression was enabled, the peak-to-peak current ripple reduced to 2 A, which was 14% of the average value. Therefore, it can be proved that energy source was integrated with ARF and the double-line-frequency current ripple of the energy source could be significantly reduced. Figure 18 show that the highest conversion efficiency is about 97%.



**Figure 17.** Measured results are compared with proposed method under different loads.



**Figure 18.** Conversion efficiency of the proposed method under different loads.

Finally, the comparison dataset for the system integrated with, and without the ARF, the actual efficiencies are measured by a WT310 power analyzer under different loads, as listed in Table 3.

**Table 3.** Measured ARF dataset.

Without Proposed ARF				With Proposed ARF			
$V_S$ (V)	$I_S$ (A)	$I_{S,RIP-pp}$ (A)	$P_S$ (W)	$I_S$ (A)	$I_{S,RIP-pp}$ (A)	$P_S$ (W)	$\eta$ (%)
36	1.35	2.1	48.6	1.4	0.35	50.4	96.4
36	2.72	4.9	97.92	2.79	0.7	100.44	97.4
36	4.1	8.1	147.6	4.2	1.2	151.2	97.6
36	5.67	12	204.12	5.82	1.3	209.52	97.4
36	7.12	13	256.32	7.3	1.4	262.8	97.5
36	8.22	14	295.92	8.42	1.5	303.12	97.6
36	9.66	15	347.76	9.92	1.55	357.12	97.3
36	11.12	18	400.32	11.4	1.7	410.4	97.5
36	12.45	20.5	448.2	12.75	1.8	459	97.6
36	13.85	24	498.6	14.25	2	513	97.1

## 6. Conclusions

In this paper, simulations and experiments were carried out to demonstrate that the proposed ARF and its DC-side direct current control system structure could be potentially applied to produce a zero-ripple input current single-phase DC/AC architecture (patented [32,33]). The proposed control system has a DC current control loop, a voltage control loop, and a voltage feedforward control loop. The efficacy of the proposed method is verified experimentally under steady-state conditions. The results show that the proposed ARF and its control strategies offers many advantages, such as a fast dynamic response, simple implementation, a nearly zero-steady state error, and the elimination of the double-line-frequency current ripple in a single-phase DC/AC conversion system above 90%.

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**Conflicts of Interest:** The authors declare no conflict of interest.

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