Scheme design and experimental verification of programmable current source for giant magnetostrictive actuator based on field programmable gate array

Caofeng Yu, Lei Dai, and Meijun Xiong

Cite as: AIP Advances 9, 115009 (2019); https://doi.org/10.1063/1.5120044
Submitted: 15 July 2019 . Accepted: 31 October 2019 . Published Online: 14 November 2019

© 2019 Author(s).
Scheme design and experimental verification of programmable current source for giant magnetostrictive actuator based on field programmable gate array

Caofeng Yu,1,2,a) Lei Dai,1 and Meijun Xiong1

AFFILIATIONS
1 School of Mechanical Engineering, Anhui University of Science and Technology, No. 168 Taifeng Street, Huainan 232001, Anhui, People's Republic of China
2 Anhui Key Laboratory of Mine Intelligent Equipment and Technology, Anhui University of Science and Technology, Huainan 232001, Anhui, People's Republic of China
a) E-mail: yucaofeng@126.com

ABSTRACT
In order to meet the requirements of a giant magnetostrictive actuator for a microstep, high precision, and wide range of input power supply, a design scheme of the high performance programmable current source based on a field programmable gate array processor and the OPA549 amplifier is proposed. Based on the circuit principle of the microstepping continuous adjustment current source, the microstepping control circuit and the constant current source control circuit are designed and the feasibility of the design scheme is verified by circuit simulation and experimental test. The results show that the current output range of the programmable current source is 0 A–6.99 A and the minimum step value is 1.7 mA. The output current precision can reach 1.10% in circuit simulation and 4.38% in experimental test. The research results show that the proposed design scheme of the programmable current source satisfies the requirements of the giant magnetostrictive actuator.

© 2019 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/). https://doi.org/10.1063/1.5120044

I. INTRODUCTION

Giant magnetostrictive material (GMM) is a highly efficient functional material that can realize mutual conversion between electromagnetic energy and mechanical energy. The giant magnetostrictive materials can be used to develop microactuators, microvibrators, microvalves, micropumps, and microsensors and have important application prospects in aerospace, integrated circuits, and precision machining.1,2

Giant magnetostrictive actuators (GMAs) made of giant magnetostrictive material can achieve micrometer-scale displacement. When the coil winding in the giant magnetostrictive actuator is energized, the magnetic field generated inside it will drive the giant magnetostrictive material to deform and drive the load to generate displacement. According to the characteristics of giant magnetostrictive materials, the output displacement of GMA is related to the magnitude of the magnetic field produced by the electromagnetic coil in a certain range and the magnitude of the magnetic field is related to the current entering into the electromagnetic coil. Therefore, in order to obtain a larger output displacement of GMA, it is hoped that the input current regulation range of GMA will be as large as possible. The minimum elongation deformation of GMA is related to the minimum magnetic field produced by the electromagnetic coil, and the minimum magnetic field is related to the minimum current entering the electromagnetic coil. Therefore, in order to get the minimum step size of GMA, it is hoped that the input current of GMA is as small as possible. The premise of realizing the commercial promotion of GMA is to
control its operation cost. At present, the cost of GMA largely depends on the price of high-precision programmable power supply and a high-precision displacement sensor. Reducing the cost of the programmable power supply is one of the effective means to reduce the cost of GMA. In our team’s previous research, a three-channel programmable high-precision power supply (IT6332B) was used, which was purchased from ITECH Electronics. Its maximum output current is 6 A, the minimum step of output current is 1 mA, the price is about 5000 RMB, and its performance basically meets the requirements of GMA. When it is used as the power supply, the maximum displacement of GMA is 30.8 μm and the minimum step of output displacement is 10 nm. The resolution is 10 nm. However, in order to further improve the maximum output displacement of GMA and reduce the cost of the GMA system, the design of a programmable current source with a small step, high precision, and wide output range is of great significance to the improvement of the performance of the giant magnetostrictive actuator and its application and popularization. References 6 and 7 used pulse width modulation (PWM) technology to control high-power MOSFET tubes to output controllable current. Reference 8 controlled the output current of the IRF640 power switch tube by PWM technology. Komurcugil proposed a model-based current control (MBCC) approach with a compensation of dc-side inductor current ripple, active damping, and virtual time constant for single-phase grid-tied quasi-Z-source inverters with an inductance capacitance inductance (LCL) filter. Zorica presented a systematic design procedure of the high frequency DC-DC multiresonant converter as a constant current source optimized for interfacing an electrolyzer stack to the DC voltage source. Guo proposed a current design scheme of constant current source, and the overall scheme is determined by considering the factors such as cost and index.

Next, it is designed and hardware selected of power supply circuit, constant current circuit, and control circuit, and the hardware circuit is built. Qu analyzed conditions under which any extra design freedom can be allowed for a double-sided LC compensation circuit in order to achieve load-independent output and zero reactive power input. A detailed analysis is given for the double-sided LC compensation achieving zero reactive power input and constant current output, without being constrained by the transformer parameters. These schemes control the output values by controlling the average current and cannot achieve the transient constant current output.

The field programmable gate array (FPGA) is a high-performance programmable timing and combination logic circuit. It can build various logic circuits with certain logic functions in a field programmable general logic device. The individual logic circuits are independent of each other and can be executed in parallel, mainly in the design of logic circuits requiring fast and high density. FPGA is selected as the power controller of GMA, which can develop multichannel power supply. As the FPGA is a parallel execution program, there is no time delay between channels, which can meet the requirements of GMA for a multichannel input, microstepping, high precision, and wide range of input current. Therefore, based on the circuit principle of the microstepping continuous adjustable current source, the microstepping control circuit and constant current source control circuit are designed and a design scheme of the high performance programmable current source based on the FPGA processor and the OPA549 power amplifier is proposed in this paper. The feasibility of the design scheme is verified by circuit simulation and experimental test.

II. WORKING PRINCIPLE OF GIANT MAGNETOSTRICTIVE ACTUATOR

Figure 1 is a structural diagram and a photo of the giant magnetostrictive actuator. The working principle can be briefly described as follows: the coil winding is energized to generate a driving magnetic field, and the giant magnetostrictive material is elongated and deformed under the action of a magnetic field to push the output rod to generate displacement. The driving force and displacement are mainly determined by the power supply capability of the power supply.

The work principle of the worktable is as follows: input the coordinates of the ideal point \((x_0, y_0)\) through the computer and calculate the current values \((I_x, I_y)\) of X-GMA and Y-GMA, respectively, through the inverse model. Then, the displacement sensor is used to collect the displacement of the X direction and the Y direction of the micropositioning worktable. Finally, the closed-loop control of the output displacement is realized by the PID control strategy, and the precision positioning function of the worktable is realized.

![FIG. 1. (a) Schematic diagram of the giant magnetostrictive actuator and (b) the photo of the real object.](image-url)
III. DESIGN OF POWER SUPPLY FOR GIANT MAGNETOSTRICTIVE ACTUATOR

Figure 2 is a schematic diagram of the operation schematic of the giant magnetostrictive actuator, which mainly consists of a giant magnetostrictive actuator, a high-precision programmable power supply, a high-precision displacement sensor, a DSP control board, a data acquisition card, a water circulation cooling system, and a host computer monitoring system. Among them, the giant magnetostrictive actuator needs to be provided with large amplitude, wide range, and high adjustment precision current in operation, so that the program-controlled current source is mainly aimed at high-precision regulation and high-current output. Its design scheme is shown in Fig. 3. The host computer sends information to the FPGA processor through the serial port, and then the FPGA processor sends the received serial port information to the digital D/A module TLV5618. The TLV5618 module outputs the corresponding voltage value through the interpretation of the serial port information and transmits it to the OPA549 power amplifier module. The OPA549 power module converts the input voltage value $U_{IN}$ into a corresponding current value $I_{OUT}$ and passes it into the coil winding of the GMA. The gain of the OPA549 operational amplifier is $K$, and the power supply provides $\pm 30$ V voltage $U_D$.

IV. HARDWARE DESIGN OF THE PROGRAMMABLE CURRENT SOURCE SELECTION OF DIGITAL-TO-ANALOG CONVERTER FOR CONTROLLER AND AMPLIFIER

In this paper, a field programmable gate array (FPGA) is chosen as the controller, OPA549 is chosen as the amplifier, and TLV5618 is chosen as the digital-to-analog converter in which the FPGA can execute the program in parallel to meet the needs of GMA’s fast response. The function of OPA549 is to convert the input voltage signal into current signal, which can output 8 A current steadily under the power supply of $\pm 30$ V. TLV5618 is a dual 12-bit voltage output digital-to-analog converter and its output voltage formula is as follows:

$$U_{OUT} = 2 \times \text{REF} \times \frac{\text{CODE}}{2^N} \text{(V)},$$

where $U_{OUT}$ is the output voltage, $\text{REF}$ is the voltage of the reference voltage source, $\text{CODE}$ is the digital voltage input value, and the range is 0 to $2^N - 1$ ($N \leq 12$).

A. Circuit design of programmable current source

1. Circuit design of current amplification

The main circuit of the programmable current source is the circuit design of the OPA549 operational amplifier. The OPA549 operational amplifier is part of the OCL power amplifier. It is powered by a $\pm 30$ V symmetrical DC supply. When the load is not connected, the output voltage is 0 V, and its output can be directly connected to the load without connecting a coupling capacitor. Figure 4 shows the designed current amplifying circuit in which the voltage signal $U_r^+$ output from the TLV5618 enters the positive input terminal of the amplifier and the output current $I_c$ is equal to the current $I_s$ flowing through the sampling resistor $R_s$. Using the "virtual short" and "virtual break" characteristics of the operational amplifier circuit, the following formulæ can be obtained:

$$U_r^+ = U_r^-,$$

$$U_r^- = I_s R_s,$$

$$I_c = I_s,$$

$$I_c = \frac{U_r^+}{R_s}.$$

where $R_s$ is the sampling resistor and its value is 550 mΩ, $R_L$ is the load resistance, $I_s$ is the current flowing through the sampling resistor, and $I_c$ is the output current.

It can be seen from Eq. (5) that the output current $I_c$ is proportional to the input voltage $U_r^+$ and the current flowing through
FIG. 5. Partial circuit diagram of TLV5618.

The sampling resistor $R_s$ can be measured by an external ammeter, that is, the magnitude of the current flowing into the coil winding of the giant magnetostrictive actuator can be determined. The OPA549 power amplifier is provided with a current limiting protection circuit. The resistance of the capacitor $C_1$ is set to 0.1 $\mu$F, and the resistor $R_{cl}$ is a current limiting resistor. The relationship between the value and the current is as follows:

$$I_m = \frac{15800 \times 4.75}{7500 + R_{cl}} \text{ (A)}.$$  \hspace{1cm} (6)

In Eq. (6), $I_m$ is the maximum output current and $R_{cl}$ is the current limiting resistor. The magnitude of the resistance determines the maximum output current of the power amplifier. The maximum output current of the OPA549 power amplifier is 8 A, and the peak output current is 10 A. In order to output the current safely, set the maximum output current to 9 A. Then, the formula can be calculated that the resistance of $R_{cl}$ should be set to 838.9 $\Omega$.

2. Conversion circuit design of digital-to-analog

The TLV5618 is a 12-bit dual channel voltage output DAC that sets the output voltage by setting a voltage code value. The reference voltage of the TLV5618 is provided by the voltage regulator module LM4040-2.0, and its digital-to-analog conversion circuit is shown in Fig. 5.

In Fig. 5, the DIN, SCLK, and CS of the TLV5618 are the FPGA data and control inputs; VDD is the device power supply; REF is the reference power supply, and the reference power supply uses the LM4040-2.0 regulator chip, which provides an accurate and stable 2.048 V voltage. OUTA and OUTB are two voltage output ports connected to the grounding resistor to maintain the voltage output.

V. DESIGN OF THE PROGRAM AND CIRCUIT SIMULATION

A. Control program design

The software design mainly includes the FPGA program for driving TLV5618 and the serial communication program with the host computer. The programming is based on the Quartus II 13.0 programming software written in Verilog HD. First, create a project folder, open Quartus II13.0 to create a new project, and write the main program, initializing program, serial communication program, and TLV5618 driver, and the program flow chart is shown in Fig. 6. After the program starts execution, first enter the serial communication program to detect whether the host computer sends data. If there is no data reception, enter the DAC program and set the output voltage to output 0 V. If the data are received, send the received data to the DAC program. The DAC program sets the output port and output speed according to the first 4 bits of the 16-bit data and...
then outputs the corresponding voltage value according to the last 12 bits of data. The output range of the voltage is 0 V–4.096 V.

B. Circuit simulation

The simulation software uses the powerful and easy-to-use TINA-TI circuit simulation tool developed by TI. It uses the SPICE engine, which contains a large number of integrated devices and active and passive devices from TI. According to the operational requirements of the OPA549, the circuit shown in Fig. 7 is designed using the TINA-TI software. A voltmeter is provided at the output and input and voltage feedback to measure the voltage change, and an ammeter is connected to the load circuit to observe the current change.

In Fig. 7, voltage generator VG1 analog output is 0 V–4.096 V. OPA549 is powered by a ±30 V power supply. $I_{lim}$ is connected to 0.1 μF capacitor $C_1$ and 838.9 Ω current limiting resistor $R_1$, grounded, and connected to the REF terminal. Sampling resistor $R_2$ and the load resistor are connected in series at the output. Before the sampling resistor, the pilot line enters the negative input terminal of the OPA549 operational amplifier. $R_2$ is a 50 W high-power resistor with a resistance of 0.55 Ω. The load resistor $R_3$ is the excitation coil of the GMA. After physical measurement, the resistance is approximately set to 3 Ω. The voltmeter VM1 and the ammeter AM1 are connected to the load to measure the output current and voltage values. The voltmeters VM2 and VM3 measure the feedback terminal voltage and the input terminal voltage, respectively. The preset values and the corresponding current output values of the software simulation experiment are provided in Table I.

As shown in Table I, the initial output current is 1.57 mA due to the manufacturing accuracy of the device itself, and there is an error in the output of the current when there is no input voltage. The data in Table I are converted into the current comparison curves of Fig. 8 and the current error percentage curve of Fig. 9. It can be

| Voltage (mV) | Expected current values (A) | Output current values (A) | Error (%) |
|------------|-----------------------------|--------------------------|-----------|
| 0          | 0.000                       | 0.00157                  |           |
| 100        | 0.181                       | 0.183                    | 1.10      |
| 300        | 0.545                       | 0.547                    | 0.37      |
| 600        | 1.091                       | 1.093                    | 0.18      |
| 800        | 1.454                       | 1.456                    | 0.14      |
| 1000       | 1.818                       | 1.821                    | 0.17      |
| 2000       | 3.636                       | 3.641                    | 0.14      |
| 2500       | 4.545                       | 4.551                    | 0.13      |
| 3000       | 5.454                       | 5.462                    | 0.15      |
| 3500       | 6.363                       | 6.372                    | 0.14      |
| 3850       | 6.999                       | 7.012                    | 0.17      |

FIG. 7. Design diagram of circuit simulation.

FIG. 8. Comparison curves of the expected current and simulated current.

FIG. 9. Error percentage curve of the simulated current.
seen from Fig. 9 that the error between the simulated current and the expected current appears to be relatively large at the beginning, and then with the current increase, the error is getting smaller and smaller and the error percentage has never exceeded 1.10% within the allowable range. Through the circuit simulation, when the output voltage of TLV5168 module is 0.001 V, the output current value of the current source is 1.818 mA, and so the minimum step value of the programmable current source output is 1.818 mA.

VI. EXPERIMENTAL VERIFICATION

Based on the circuit software simulation, the experimental device is built as shown in Fig. 10.

The measured resistance of the coil winding of the giant magnetostrictive actuator is 3 Ω; the purchased sampling resistor is a 50 W metal heat sink resistor, and its resistance is measured to be 0.55 Ω. The measured data of programmable current source are shown in Table II.

Figures 11 and 12 are the comparison diagram and error percentage based on the experimental results and error data in Table II, respectively. Due to the limitations of the experimental devices and conditions, the current error value is large, but it can be seen from the data changes in Table II and Figs. 11 and 12 that most of the current value errors are maintained within 3.37%.

In order to further verify the minimum resolution of the designed current source, an experimental platform is built, as shown in Fig. 13. The experimental data obtained by the experiment are shown in Table III, and the change curves for the minimum step of the designed current source are shown in Fig. 14.

According to Table III and Fig. 14, the minimum resolution of the programmable current source is about 1.7 mA, which is close to the theoretical value of 1.818 mA, which verifies the correctness of the simulation results. Due to the limitations of the experimental devices and the small adjustment range, the maximum current value error is 4.38%.

### TABLE II. Experimental results of the programmable current source.

| Voltage (mV) | Expected current values(A) | Experimental values (A) | Error (%) |
|-------------|-----------------------------|-------------------------|-----------|
| 0           | 0.000                       | 0.000                   | 0         |
| 100         | 0.181                       | 0.178                   | −1.66     |
| 300         | 0.545                       | 0.527                   | −3.30     |
| 600         | 1.091                       | 1.059                   | −2.93     |
| 800         | 1.454                       | 1.405                   | −3.37     |
| 1000        | 1.818                       | 1.764                   | −2.97     |
| 2000        | 3.636                       | 3.541                   | −2.61     |
| 2500        | 4.545                       | 4.409                   | −2.99     |
| 3000        | 5.454                       | 5.286                   | −3.08     |
| 3500        | 6.363                       | 6.173                   | −2.99     |
| 3850        | 6.999                       | 6.769                   | −3.29     |

FIG. 10. Experimental device of the programmable current source.

FIG. 11. Comparison diagram of the expected current and experimental current.

FIG. 12. Error percentage diagram of the experimental current.
In order to verify that the minimum step value of GMA under the action of the designed programmable current source can meet the needs of GMA, an experimental platform is built, as shown in Fig. 15. In order to accurately measure the minimum output displacement of GMA, a dual-frequency laser interferometer with a resolution of 1 nm is used as the displacement measuring device of GMA. The experimental process is as follows: the minimum step values of the 12-bit DAC module, the 14-bit DAC module, and the IT6332B programmable current source are connected to the driving coil of GMA, respectively, and the output displacement of GMA is measured. A total of 10 steps are tested, and the change curves are shown in Fig. 16.

Through the experimental results and Fig. 16, it is found that the output displacement of GMA is about 15 nm when the minimum step current (1.818 mA) of the 12-bit DAC is connected, 10 nm when the minimum step current (1 mA) of the IT6332B power supply is connected, and 6 nm when the minimum step current (0.6 mA) of

TABLE III. Experimental results.

| Voltage (mV) | Expected current values (mA) | Experimental values (mA) | Error (%) | Step (mA) |
|-------------|------------------------------|--------------------------|-----------|-----------|
| 30          | 54.5                         | 52.7                     | −3.30     |           |
| 31          | 56.3                         | 54.3                     | −3.55     | 1.6       |
| 32          | 58.1                         | 55.9                     | −3.79     | 1.6       |
| 33          | 59.9                         | 57.6                     | −3.84     | 1.7       |
| 34          | 61.7                         | 59.4                     | −3.73     | 1.8       |
| 35          | 63.5                         | 61.1                     | −3.78     | 1.7       |
| 36          | 65.3                         | 62.6                     | −4.13     | 1.5       |
| 37          | 67.1                         | 64.2                     | −4.32     | 1.6       |
| 38          | 68.9                         | 65.9                     | −4.35     | 1.7       |
| 39          | 70.7                         | 67.6                     | −4.38     | 1.7       |
| 40          | 72.5                         | 69.4                     | −4.28     | 1.8       |
FIG. 17. An experimental platform for maximum current testing.

the 14-bit DAC is connected. It shows that the minimum output current can be reduced by accessing the 14-bit DAC module, which can better meet the needs of GMA.

In order to verify that the maximum output current of the designed programmable current source can meet the needs of GMA, an experimental platform is built as shown in Fig. 17 and the experimental process is as follows: measuring the output displacement of the IT6322B power source and the designed programmable current source, respectively, in which the range of the IT6332B power source is 0–6 A, and the range of the designed programmable current source is 0–7 A. The experimental results are shown in Fig. 18.

Through the experimental results and Fig. 18, it is found that that the maximum displacement of GMA is 33.7 μm when using the proposed current source and 30.8 μm when using the IT6332B power source. This shows that the designed programmable current source can increase the maximum output displacement of GMA by 9.4%, which can better meet the needs of GMA.

VII. CONCLUSION

The above research shows that the design scheme of the GMA programmable current source based on FPGA and OPA549 is feasible, specifically stated as follows:

1. The maximum output current of the programmable current source based on FPGA is close to 7 A, which exceeds the maximum output value of the IT6332B programmable current source in the laboratory, while the maximum output current of the IT6332B programmable power source in the laboratory is only 6 A.

2. The minimum output current of the programmable current source based on FPGA is 1.7 mA, which is larger than the minimum output current of the IT6332B programmable current source in the laboratory. The minimum output current of the IT6332B programmable current source in the laboratory is 1 mA. The main reason is that the number of digits of the DAC module is 12 bits and the minimum resolution is 1 mV, corresponding to 1.7 mA. If the DAC module with 14 or 16 bits or higher bits is used, its minimum resolution can be less than 1 mA. The minimum output displacement test of GMA shows that the minimum output displacement of GMA driven by FPGA is 15 nm, which can meet the needs of GMA for minimum current.

3. The cost of the programmable current source based on FPGA using 12-bit DAC modules can be controlled within 500 RMB, while the price of the IT6332B programmable current source in the laboratory is 5000 RMB, which greatly reduces the operation cost of GMA and meets the GMA’s demand for reducing the operation cost.

ACKNOWLEDGMENTS

This work was supported by the National Natural Science Foundation of China (Grant No. 51675003), the China Postdoctoral Science Foundation (Grant No. 2019M652159), the National Science Research Projects in Colleges and Universities of Anhui Province (Grant No. KJ2019A0111), the Anhui Provincial Natural Science Foundation (Grant No. 1908085ME159), and the Anhui University of Science and Technology (Grant No. QN2018102).

REFERENCES

1. C. Yu, C. Wang, and H. Deng, “Magnetic field optimization and performance analysis of giant magnetostrictive actuator,” Mod. Manuf. Eng. 8, 136–140 (2015).
2. E. Jiang, X. Zhu, Y. Shao et al., “Alternative driven SMA smart structure based on constant current source for vibration control,” J. Vib. Meas. Diagn. 33(2), 204–209 (2013).
3. C. Yu, C. Wang, T. Xie et al., “Development of drive system of high performance micro positioning worktable based on giant magnetostrictive material,” J. Mech. Eng. 55(9), 136–143 (2019).
4. H. T. Ng, S. I. Chu et al., “Research on full-digital hysteresis current controlled controllable current source,” Power Syst. Technol. 85(2), 582–586 (2012).
C. Yu, C. Wang, H. Deng et al., “Hysteresis nonlinearity modeling and position control for a precision positioning stage based on a giant magnetostrictive actuator,” J. Syst. Eng. Sci. 6(4), 59468–59476 (2016).

C. Hu, “Design on power supply of giant magnetostrictive actuator,” M.Sc. dissertation (Harbin Institute of Technology, 2010).

H. Mo, R. Yang, H. Yu et al., “Design and implementation of the electric drive system for giant magnetostrictive micro-vibration,” Noise Vib. Control 37(2), 33–37 (2017).

S. Zeng, “Design on power supply of inertia impact motor based on rare earth giant magnetostrictive materials,” M.Sc. dissertation (Nanchang University, 2013).

H. Komurcugil, S. Bayhan, F. Bagheri et al., “Model-based current control for single-phase grid-tied quasi-Z-source inverter with virtual time constant,” IEEE Trans. Ind. Electron. 65(10), 8277–8286 (2018).

S. Zeng, S. Vukšić, and T. Betti, “Design considerations of the multi-resonant converter as a constant current source for electrolyser utilisation,” Int. J. Electr. Power Energy Syst. 111, 237–247 (2019).

X. Guo, C. Yang, and D. Liu, “Design and implementation of a numerical control high-precision low-temperature drift constant current source,” in International Conference on Communications, Signal Processing, and Systems (Springer, Singapore, 2018), pp. 513–522.

X. Qu, H. Chu, Z. Huang et al., “Wide design range of constant output current using double-sided LC compensation circuits for inductive-power-transfer applications,” IEEE Trans. Power Electron. 34(3), 2364–2374 (2018).

J. Li, J. Zhao, and J. A. Rogers, “Materials and designs for power supply systems in skin-interfaced electronics,” Acc. Chem. Res. 52(1), 53–62 (2018).

Q. Tang, M. H. Yeh, G. Liu et al., “Whirligig-inspired triboelectric nanogenerator with ultrahigh specific output as reliable portable instant power supply for personal health monitoring devices,” Nano Energy 47, 74–80 (2018).

M. A. Rajaeifar, S. S. Hemayati, M. Tabatabaei et al., “A review on beet sugar industry with a focus on implementation of waste-to-energy strategy for power supply,” Renewable Sustainable Energy Rev. 103, 423–442 (2019).

P. Tang, “Research and design of high-precision and programmable voltage source based on FPGA,” M.Sc. dissertation (Guangdong University of Technology, 2012).

Y. Huang, Q. Li, and Q. Zhao, “Design of STM32-based programmable high-precision current source system,” Instrum. Tech. Sens. 11(11), 42–48 (2015).

H. Wang, H. Wang, and L. Li, “The constant-current source design with OPA49,” Meas. Control Technol. 30(9), 4–7 (2011).