An Evolutionary Method to Achieve the Maximum Efficiency Tracking with Multi-Objective Optimization Based on the Genetic Algorithm

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***Abstract*—A genetic algorithm based method to optimize efficiency of a power converter during running process is proposed in this paper. Compared with the conventional PWM, PFM and multi-mode control techniques, both the duty cycle and the switching frequency are regulated by the proposed method. Benefit from this multi-objective optimization, the maximum efficiency of the converter at a specific load can be approached by choosing and evolving the operating points adaptively. Critical issues, such as the input current sensing, the electrical stress limiting of the power devices and the error compensation of the fitness value, are investigated in order to implement the proposed algorithm. A digital controlled Boost converter based on a microcontroller is built to verify the effectiveness of the algorithm. According to the comparison with conventional control techniques, the peak efficiency with genetic algorithm optimization is 2% higher, and the light load efficiency is optimized over 10%.**

Keywords—Efficiency optimization, Genetic algorithm, Digital control, Boost converter.

I. INTRODUCTION

High efficiency is one of the most urgent demands of the power converters [1-3]. Unfortunately, in modern power converters, the current pulse width modulation (PWM) and pulse frequency modulation (PFM) techniques both have drawbacks, for instance, the unnecessarily high switching frequency when the load current decreases. Neither of these two modulation techniques reaches the maximum efficiency over the entire load range [4-5].

In order to decrease the energy waste, maximum efficiency tracking over the entire load range becomes concerned.

Multi-mode control, which is usually a combination of PWM, PFM and burst mode according to the varies load, is applied to improve the efficiency [6-8]. However, complexity of designing is greatly increased by the pre-modeling and pre-training. Also, maximum efficiency tracking is still a doubt.

In fact, there is only one control variable at a time, either the duty cycle or the switching frequency, for the conventional PWM, PFM, and multi-mode control techniques. For instance, in PWM control, every steady-state is a reflection of one single duty cycle t_{ON}/T_S because of the fixed frequency. Also, steady-state in PFM control is regulated by frequency, for the constant on-time. When $[t_{ON}, T_S]$ becomes a solution of steady-state, $V_O=g(t_{ON}, T_S)$ is a 2-D curve in the $\{t_{ON}, T_S, V_O\}$ space. In this condition, maximum efficiency tracking is quite difficult because of the restricted operating point.

Since one steady-state V_O can be achieved by infinite solutions $[t_{ON}, T_S]$ as long as t_{ON}/T_S is constant, maximum efficiency tracking can be achieved by finding the most efficient $[t_{ON}, T_S]$ according to the load. Distinguish from the existing methods which require pre-modeling and complex algorithm, genetic algorithm is an easy way to track the maximum efficiency by evolving continuously [9]. Genetic algorithm (GA) is the most widely used evolution algorithm for the simple fitness, selection and mutation procedure [10-11]. With GA-optimization, finding the maximum efficiency turns to be seeking the best solution in a 3-D plane $V_O=g(t_{ON}, T_S)$.

This paper proposes a new consideration to optimize the efficiency of power converter based on GA, which employs efficiency as fitness value and switching frequency as the gene. Furthermore, critical issues, such as the input current sensing, the electrical stress limiting of the power devices and the error compensation of the fitness value, are investigated in order to implement the proposed algorithm.

The paper is organized as follows. Section II describes operating principle and algorithm of a Boost converter with a GA-optimization loop; Section III discusses the efficiency calculation, compensation and the design notes of the converter; and finally, a prototype is built and tested to verify the proposed GA-optimization in Section IV.

II. BOOST CONVERTER WITH GENETIC ALGORITHM

As illustrated in Fig.1, two digital feedback loops are adopted for GA based efficiency optimization in a Boost converter. A voltage mode feedback loop with a PI controller regulates the output voltage V_O. Meanwhile, an extra GA feedback loop is employed to optimize the efficiency. The input current I_{IN} and output current I_O are sensed by resistors R_{CS1} and R_{CS2}, respectively.

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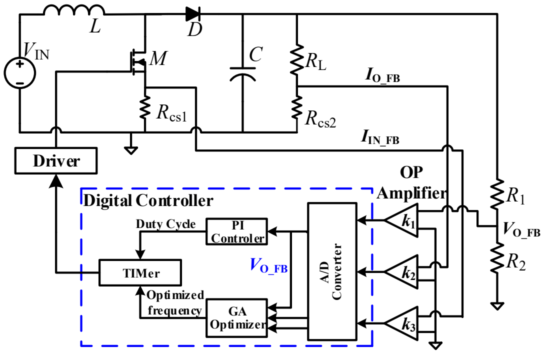


Fig. 1 Boost converter with dual loops

In the dual loop Boost converter, both switching frequency f_S and on-time t_{ON} are variables to determine the V_O. The GA feedback loop is configured to adjust the f_S of the converter, while duty cycle $d_{ON}=t_{ON}/f_S$ is determined by the voltage feedback loop.

Flow chart and the algorithm of the digital controller in T_n (represents for the nth period) are illustrated in Fig.2 and Fig.3, respectively. The internal program consists of 3 parts, including calculation in the main loop, voltage regulator & current bias sample in interrupt 1 and input current capture in interrupt 2. As Fig.2 shows, the calculated $d_{ON(n+1)}$ based on $V_{O(n)}$ regulates $V_{O(n+1)}$.

The detailed procedure of the $f_{S(n+1)}$ optimization is illustrated in Fig.3. In order to ensure the effect of the optimization, the GA loop would not operate until V_O becomes stable. Steady-state is defined by the error of V_O during m continuous periods satisfy

$$\left|k_1\frac{R_2}{R_1+R_2}V_{O(m)}-V_{O\_REF}\right|<V_{O\_REF}\cdot 10\% \tag{1}$$

In equation (1), k_1 represents for the coefficient of the Operational amplifier; V_{O_REF} represents for the internal reference. When equation (1) is satisfied, GA loop starts to optimize the f_S until a maximum number of iteration is reached.

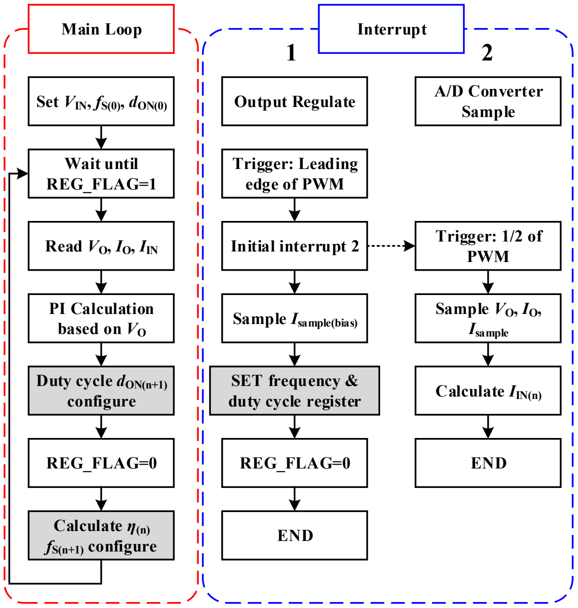


Fig. 2 Flow chart of the control program

Assume the input voltage V_{IN} is constant and has been defined in the digital controller, the efficiency η of the Boost converter is chosen as the fitness value of the GA-optimization, which is calculated by the microcontroller as

$$\eta=\frac{V_O I_O}{V_{IN} I_{IN}} \tag{2}$$

In a single GA-optimization trial, a series of random individual $[t_{ON}, T_S]_{1\ldots n}$ which satisfy equation (1) are applied to the Boost converter during n periods, and $\eta_{1\ldots n}$ are evaluated in next period with equation (2). After abandoning 2 most inefficient solutions, the calculated $\eta_{1\ldots n\text{-}2}$ are summed as a total fitness

$$\eta_{sum}=\sum_{k=1}^{n-2}\eta_k \tag{3}$$

The next generation is generated randomly according to the ratio of each individual in the total fitness

$$P_j=\frac{\eta_j}{\eta_{sum}} \tag{4}$$

The method of generating consists of mutating and interbreeding. After several generations, the fitness value of each individual $[t_{ON}, T_S]_{1\ldots n}$ becomes equal, most individuals in this generation reaches the maximum efficiency. One of the best individual is picked with a typical load current and stored as $[I_O, t_{ON}, T_S]$. When the I_O is close to previous optimized condition, the individual is recalled and applied.

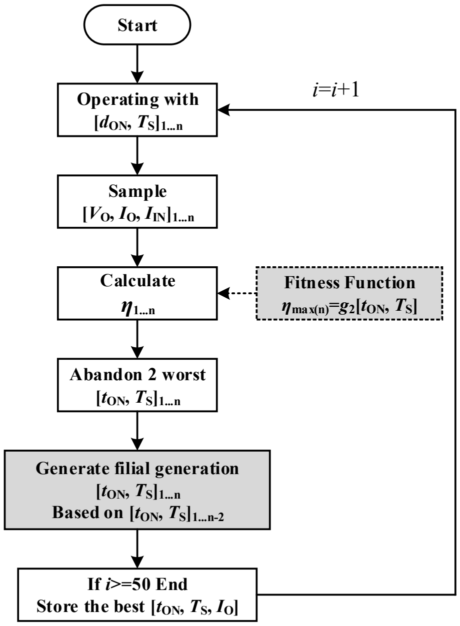


Fig. 3 Algorithm of GA-optimization loop

III. SAMPLE AND CONTROL STRATEGY

a) Input current sensing

The DC output values V_O and I_O in equation (2) are easy to sample. Unfortunately, I_{IN} is difficult to sample directly because of the sawtooth waveform, as shown in Fig.4. Thus, a special method should be considered based on the operating principle of the Boost converter.

In a Boost converter, the inductor L is charged during on-time t_{ON} of M. Thereby, the average input current can be reflexed by the bias and peak current of I_D. However, capturing the accurate peak value of I_D seems impossible because of the delay of both the power stage and instruction cycle of the microcontroller. Luckily, in a digital power converter, duty cycle is often decided in the previous period, so that capturing the input current at t=0 and t=0.5t_{ON} of each period is much easier. The input current sensing strategy is demonstrated in Fig.4.

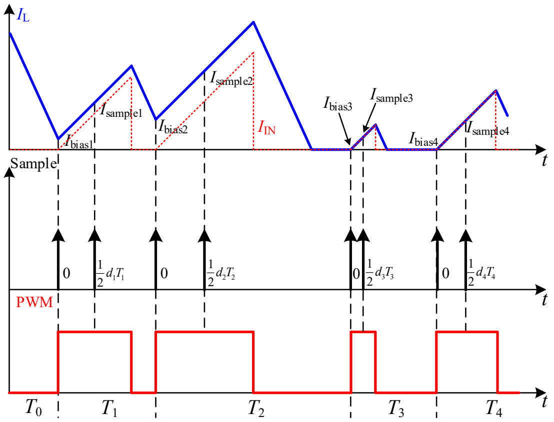


Fig. 4 Time diagram of the input current sensing

According to Fig.4, I_{IN} can be expressed as

$$I_{IN} = \frac{t_{ON}}{T_S}\left(I_{sample} - I_{bias}\right) \tag{5}$$

In equation (5), I_{bias} is captured by the interrupt 1, I_{sample} is captured by the interrupt 2, t_{ON} and T_S are determined by the PWM module and initialized by interrupt 1.

An advantage of this strategy is eliminating the influence of the delay. Assume that the sample delay is Δt, the error Δi between sampled current and actual current is

$$\Delta i = \frac{V_{IN} - V_O}{L}\Delta t \tag{6}$$

The errors are canceled when delays of I_{sample} and I_{bias} are the same, thus an accurate I_{IN} can be sampled.

According to these considerations, a precise input current is sample and calculated for evaluating the fitness value η.

b) Individual limitations during the GA-Optimization

Stable output voltage/current is the most important performance of a power converter, thus every single individual $[t_{ON}, T_S]$ of GA-optimization should ensure the stability of V_O. Theoretically, V_O of Boost converter is stable when

$$V_O = \frac{T_S}{T_S - t_{ON}}V_{IN} \tag{7}$$

However, in an actual converter, several rules should be satisfied, such as the current stress on the power devices M and D should be safe; the magnetic core of L cannot be saturated; and the most important is the loop must be stable.

The reliability of the M, D and L is ensured by a limited $[t_{ON}, T_S]$ range. For instance, during the entire load current range, I_{IN} should be restricted by

$$\frac{L \cdot \Delta I_{IN}}{N \cdot A_e} < B_{max} \tag{8}$$

In equation (8), N, A_e and B_{max} are pre-defined turns, core area and maximum magnetic flux density, respectively. According to the voltage-second balance of the Boost converter, f_S is also limited by

$$f_S > \frac{V_{IN}\left(V_O - V_{IN}\right)}{V_O N A_e B_{max}} \tag{9}$$

Thus, the reliability of the converter is ensured.

The stability of the voltage feedback loop is also concerned. The parameters of digital PI controller are computed in advance according to load resistance and the lowest frequency calculated in equation (9).

c) Fitness value calculation and compensation

The fitness value, which is the calculated efficiency, is the most important parameter in the GA-optimization.

However, the calculated efficiency cannot exactly match the measured value, because the accuracy of the internal A/D converter is finite, meanwhile, noise in the circuit is unavoidable. Thus the calculated efficiency should be compensated in order to reduce the error.

Different I_{IN} are calculated (I_{cal}) and measured (I_{cal}) under several typical f_S with the loop opened. Matlab is used to process the data [f_S, I_{real}, I_{cal}]. In the end, a 3-D graph is drawn to reveal the approximate relationship between calculation and measurement with minimum error, as shown in Fig.5.

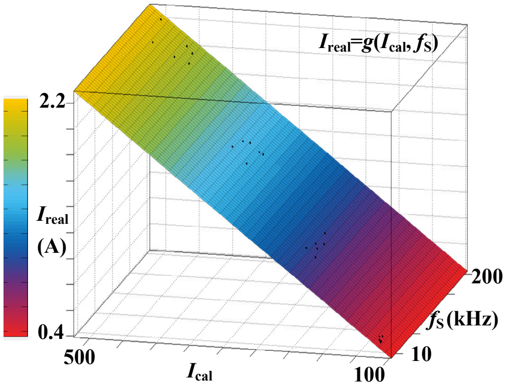


Fig.5 Curve fitting with Matlab to compensate the error

According to the 3-D image shown in Fig.5, f_S does not influence the error, thus a linear coefficient is employed to compensate the error during the fitness value evaluation.

IV. EXPERIMENTAL RESULTS

A prototype is built to verify the proposed method, as shown in Fig.6. Parameters of the Boost converter is listed in Table 1.

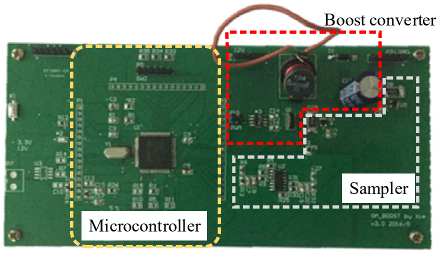


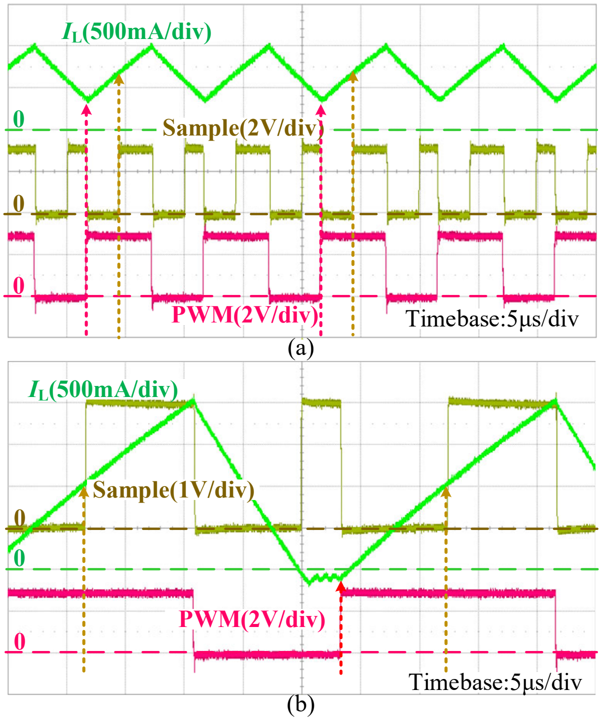
Fig.6 Photograph of the prototype

Table 1 Parameters of the Boost converter

Parameter/Component	Value
Input voltage, V_{IN}	6V
Output voltage, V_O	12V
Output current, I_O	1A
Inductor, L	100μH(Coilcraft)
Output capacitor, C	330μF
Switching frequency, f_S	200kHz
Power MOSFET, M	IRFU024N(Infineon)
Rectifier diode, D	UF4007(Fairchild)
Voltage sensor, R_1/R_2	22kΩ/1kΩ
Current sensor, R_{CS1}, R_{CS2}	10mΩ
Closed loop gain $k_1/k_2/k_3$	2/20/20
Voltage amplifier	OPA4350UA(TI)
Current amplifier	INA193(TI)
Microcontroller	STM32F407VGT6(ST)
Gate-drive chip	IR4427(Infineon)

Fig.7 (a)(b) show the waveform of I_{IN} capturing both under heavy and light load conditions. The PWM and Sample signals are output of the microcontroller. The color of the arrow illustrates the sampling time. It is proved that the proposed current sensing strategy is effective no matter whether the converter is under CCM or DCM. Also, switching frequency does not influence the accuracy of the sampling.

The output voltage ripple of the converter is illustrated in Fig.8. The steady-state error of V_O is around 100mV.



(a)

(b)

Fig. 1 Input current capturing strategy under (a)CCM heavy load condition; (b)DCM light load condition

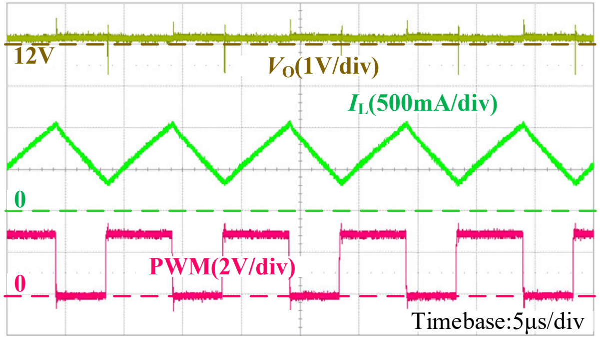


Fig.8 Ripple of the output voltage

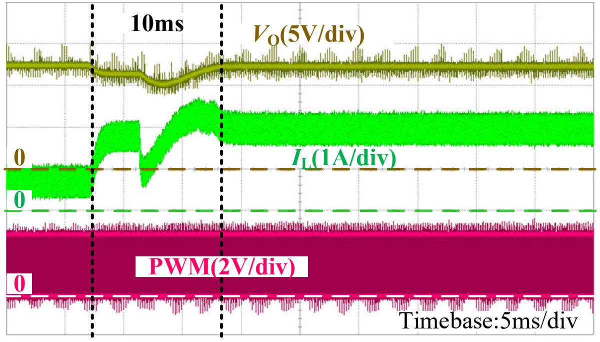


Fig. 9 Waveform during Load transient from 0.1A to 1A

Fig.7 (a)(b) show the waveform of I_{IN} capturing both under heavy and light load conditions. The color of the arrow illustrates the sampling time. It is proved that the proposed current sensing strategy is effective no matter whether the converter is under CCM or DCM. Also, switching frequency does not influence the accuracy of the sampling.

The output voltage ripple of the converter is illustrated in Fig.8. The steady-state error of V_O is around 100mV.

Performance of the PI controller is tested, as shown in Fig.9. The transient performance of 10ms is acceptable at quite a low frequency (50kHz).

In the end, efficiency over the entire load range is messured to verify the effect of GA-optimization, under 4 control strategies, PWM control, PFM control, multi-mode control and the GA-optimization, as shown in Fig.10. The peak efficiency with GA-optimization is 2% higher, and the light load efficiency is optimized over 10%.

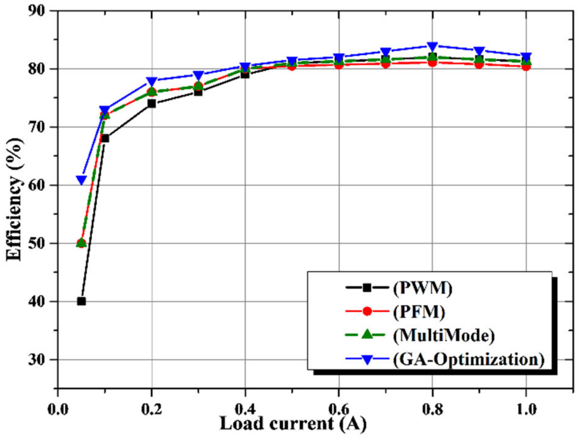


Fig.10 The efficiency comparison of the proposed GA-optimization and other control techniques

According to the test results, the validity of the proposed GA-optimization is proved. What's more, GA-optimization does not require complicated control strategies applied in multi-mode control technique, because of the ability of evolution.

It is expected that the GA-optimization would be used to improve efficiency in other converters, for instance, self-adaptive dead time control in phase leg configurations, and accurate synchronous rectifier driving scheme control.

V. CONCLUSION

This paper proposes an efficiency optimization method based on GA. The evolutional GA-optimization improves the efficiency of the converter over the entire load range by choosing and evolving the operating points adaptively. The input current sensing, the electrical stress limiting of the power devices and the error compensation of the fitness value are discussed in order to implement the GA-optimization. A microcontroller based Boost converter with both voltage feedback loop and GA-optimization loop is realized and evaluated. Experimental results show that accurate current sensing is achieved during all the operating modes of the converter. Compared to those with PWM/PFM/multi-mode control, the Boost converter with GA-optimization has the best efficiency performance over the entire load range.

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REFERENCES

[1] D. K. Kim, S. Moon, C. O. Yeon and G. W. Moon, "High-Efficiency LLC Resonant Converter With High Voltage Gain Using an Auxiliary LC Resonant Circuit," in *IEEE Transactions on Power Electronics*, vol. 31, no. 10, pp. 6901-6909, Oct. 2016.

[2] T. D. Yeo; D. Kwon; S. T. Khang; J. W. Yu, "Design of Maximum Efficiency Tracking Control Scheme for Closed Loop Wireless Power Charging System Employing Series Resonant Tank," in *IEEE Transactions on Power Electronics*, vol.pp, no.99, pp.1-1

[3] D. Reusch and J. Strydom, "Evaluation of Gallium Nitride Transistors in High Frequency Resonant and Soft-Switching DC–DC Converters," in *IEEE Transactions on Power Electronics*, vol. 30, no. 9, pp. 5151-5158, Sept. 2015.

[4] L. An and D. D. C. Lu, "Design of a Single-Switch DC/DC Converter for a PV-Battery-Powered Pump System With PFM+PWM Control," in *IEEE Transactions on Industrial Electronics*, vol. 62, no. 2, pp. 910-921, Feb. 2015.

[5] J. Zhang, H. Zeng and T. Jiang, "A Primary-Side Control Scheme for High-Power-Factor LED Driver With TRIAC Dimming Capability," in *IEEE Transactions on Power Electronics*, vol. 27, no. 11, pp. 4619-4629, Nov. 2012.

[6] C. Wang; S. Xu; X. Fan; S. Lu; W. Sun, "A Novel Digital Control Method for Improving Dynamic Responses of Multimode Primary-Side Regulation Flyback Converter," in *IEEE Transactions on Power Electronics* , vol.pp, no.99, pp.1-1

[7] B. Y. Chen and Y. S. Lai, "Switching Control Technique of Phase-Shift-Controlled Full-Bridge Converter to Improve Efficiency Under Light-Load and Standby Conditions Without Additional Auxiliary Components," in *IEEE Transactions on Power Electronics*, vol. 25, no. 4, pp. 1001-1012, April 2010.

[8] G. G. Oggier and M. Ordonez, "High-Efficiency DAB Converter Using Switching Sequences and Burst Mode," in *IEEE Transactions on Power Electronics*, vol. 31, no. 3, pp. 2069-2082, March 2016.

[9] J. D. van Wyk and F. C. Lee, "On a Future for Power Electronics," in *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 1, no. 2, pp. 59-72, June 2013.

[10] S. E. De León-Aldaco, H. Calleja and J. Aguayo Alquicira, "Metaheuristic Optimization Methods Applied to Power Converters: A Review," in *IEEE Transactions on Power Electronics*, vol. 30, no. 12, pp. 6791-6803, Dec. 2015.

[11] A. Kessal and L. Rahmani, "Ga-Optimized Parameters of Sliding-Mode Controller Based on Both Output voltage and Input Current With an Application in the PFC of AC/DC Converters," in *IEEE Transactions on Power Electronics*, vol. 29, no. 6, pp. 3159-3165, June 2014.