

Maximum-Power-Point Tracking Method of Photovoltaic Using Only Single Current Sensor

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Abstract

This paper describes a novel strategy of maximum-power-point tracking for photovoltaic power generation systems. A unique feature of this method is capability to seek the maximum power point using only a single current sensor, i.e., a Hall-effect CT. Output power of the photovoltaic can be estimated with an average value and ripple amplitude of the detected current. A conventional hill-climbing method is employed to seek the maximum power point, using the output power obtained from only the current sensor. In this paper, not only a theoretical aspect of the proposed method is described, but also experimental results are presented to prove feasibility of the method.

1. Introduction

Photovoltaic power generation systems have intensively been investigated as an environment-friendly technology since 1970s because of their advantages of infinite energy resources and no CO₂ emission. However, low efficiency and high cost per unit output power are the biggest problem of the systems; which prevents the systems from being extensively used so far.

A technique to utilize effectively the photovoltaic is known as a maximum-power-point tracking (MPPT) method, which makes it possible to acquire as much power as possible from the photovoltaic. Since an electric characteristic of the output power to the operating voltage or current has a convex property, there exists only one optimum operating point on the power-voltage (or current) curve. The MPPT is a method to let the controller operate at the above-mentioned optimum operating point. There have been various kinds of MPPT methods reported and the most common technique of them is a hill-climbing method, which seeks the optimum operating point by changing the operating voltage or current until the power becomes the maximum [1]-[4]. Therefore, this method essentially requires power calculation using both the voltage sensor and the current sensor.

On the other hand, several other proposals have been made, which are completely different from the conventional hill-climbing based MPPT methods. Some of them determine the optimum operating current on the basis of a short-current detection of the photovoltaic [5], [6]. These methods utilize a property of the photovoltaic of which optimum operating current is proportional to its short current. One of them has a monitor photovoltaic cell to detect its short-current and another has a switch that intermittently and directly shorts the main photovoltaic. These methods do not require the voltage sensor but the monitor photovoltaic or the short-circuit switch must be implemented in the power converter.

As described above, several sensors and/or additional equipment are indispensable to achieve MPPT in the conventional system, which makes the system configuration considerably complicated.

Table I Ratings of GL418-TF

Rated maximum power	6.5 (W)
Rated output voltage	6 (V)

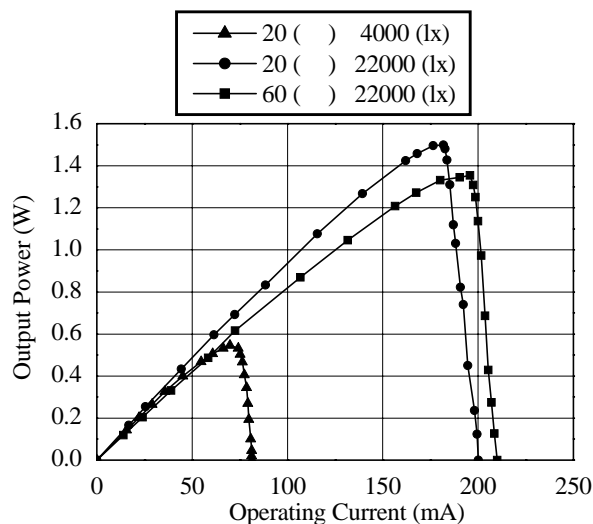


Fig. 1: Example of power-voltage characteristics.

This paper focuses on information included in current ripples, which are inherently generated by switching operation of the power converter, and proposes a technique capable to seek the maximum-power-point with only a single current sensor. Reducing sensor count or other equipment contributes to simplify circuit implementation and to reduce system cost. This paper discusses a theoretical aspect of the proposed technique and presents experimental results to demonstrate an excellent MPPT operation of the system.

2. Principle of Hill-Climbing Method

As described in the previous section, it is indispensable to operate the photovoltaic at the optimum operating point where the maximum power is available; hence the most important issue is how to find the optimum operating point in dealing with the photovoltaic. Fig. 1 shows an example of power-current characteristics measured with a commercially available photovoltaic panel (Showa Shell GL418-TF), of which electrical specifications are listed in Table I. As shown in the graph, the power-current characteristics of the photovoltaic have hill-shaped upward convexity and have different maximum points to be sought by the MPPT controller, depending on irradiance and temperature. In the hill-climbing method based system, gradient of the output power is directly calculated by changing the operating current and a peak of the hill is sought until the gradient is almost zero, where the maximum power is available. Since this method is based on actual output power detection of the photovoltaic, MPPT can be achieved even if the optimum operating point varies with the irradiance and/or the temperature. Also, the method is adaptive to environmental disturbances, e.g., surface contamination of the panel, electrical performance degradation over years, and so forth. However, it takes a considerably long time to seek the maximum power point because of the successive seeking operation as described above.

3. Power Estimation Algorithm Using Single Sensor Information

3. 1. Power Circuit Configuration

Fig. 2 shows power circuit configuration to be discussed in this paper. The system consists of a photovoltaic panel, a DC/DC converter, and a load resistor. The DC/DC converter is a simple boost chopper that has only a single current sensor. This circuit operates in a switching mode and is

regarded as a non linear system; thus analysis of the circuit is complicated. Therefore, an averaged state variable method is introduced to analyze the circuit, which allows dealing with the circuit as a linear system. In the linearization process, the photovoltaic is regarded as an equivalent circuit composed with a DC voltage source and a series connected internal resistance. It should be noted that both the equivalent voltage source and the series resistance are variant with respect to the operating point of the photovoltaic.

3. 2. Averaged State-Variable Equation of Power Circuit

Fig. 3(a) and Fig. 3(b) show equivalent circuits in an on-state and in an off state of the boost chopper. r_L , r_S and r_D are an equivalent resistance corresponding to reactor losses, an on-state resistance of the main switching device and an equivalent resistance of the diode forward drop, respectively. From the equivalent circuits shown in Fig. 3, the following state variable equation can be obtained in the on-state, where the state variables are a capacitor voltage v_C , a reactor current i_L and an output voltage v_o , i.e., $\mathbf{x} = [v_C \ i_L \ v_o]^T$:

$$\frac{d\mathbf{x}}{dt} = \mathbf{A}_{\text{ON}}\mathbf{x} + \mathbf{b}_{\text{ON}}V_{PV}, \quad (1)$$

where

$$\mathbf{A}_{\text{ON}} = \begin{bmatrix} -\frac{1}{R_{PV}C_1} & -\frac{1}{C_1} & 0 \\ \frac{1}{L} & -\frac{r_L+r_S}{L} & 0 \\ 0 & 0 & \frac{1}{R_L C_2} \end{bmatrix}, \text{ and } \mathbf{b}_{\text{ON}} = \begin{bmatrix} \frac{1}{R_{PV}C_1} \\ 0 \\ 0 \end{bmatrix}.$$

On the other hand, the state variable equation in the off-state is as follows:

$$\frac{d\mathbf{x}}{dt} = \mathbf{A}_{\text{OFF}}\mathbf{x} + \mathbf{b}_{\text{OFF}}V_{PV}, \quad (2)$$

where

$$\mathbf{A}_{\text{OFF}} = \begin{bmatrix} -\frac{1}{R_{PV}C_1} & -\frac{1}{C_1} & 0 \\ \frac{1}{L} & -\frac{r_L+r_D}{L} & -\frac{1}{L} \\ 0 & -\frac{1}{C_2} & \frac{1}{R_L C_2} \end{bmatrix}, \text{ and } \mathbf{b}_{\text{OFF}} = \begin{bmatrix} \frac{1}{R_{PV}C_1} \\ 0 \\ 0 \end{bmatrix}.$$

Assuming that the averaged state-variable vector is $\bar{\mathbf{x}} = [\bar{v}_C \ \bar{i}_L \ \bar{v}_o]^T$, the above equation can be transformed into the following expression:

$$\frac{d\bar{\mathbf{x}}}{dt} = \mathbf{A}\bar{\mathbf{x}} + \mathbf{b}V_{PV}, \quad (3)$$

where

$$\mathbf{A} = \mathbf{A}_{\text{ON}}D + \mathbf{A}_{\text{OFF}}D' \\ = \begin{bmatrix} -\frac{1}{R_{PV}C_1} & -\frac{1}{C_1} & 0 \\ \frac{1}{L} & -\frac{r_L+r_S D+r_D D'}{L} & -\frac{1}{L}D' \\ 0 & -\frac{1}{C_2}D' & \frac{1}{R_L C_2} \end{bmatrix}, \text{ and } \mathbf{b} = \mathbf{b}_{\text{ON}}D + \mathbf{b}_{\text{OFF}}D' = \begin{bmatrix} \frac{1}{R_{PV}C_1} \\ 0 \\ 0 \end{bmatrix}.$$

In the above equation, D and $D' (=1-D)$ are duty factors of the on-state and the off-state, respectively. Both D and D' are less than unity.

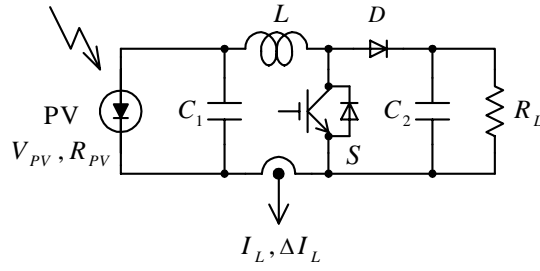


Fig. 2: Photovoltaic and boost chopper.

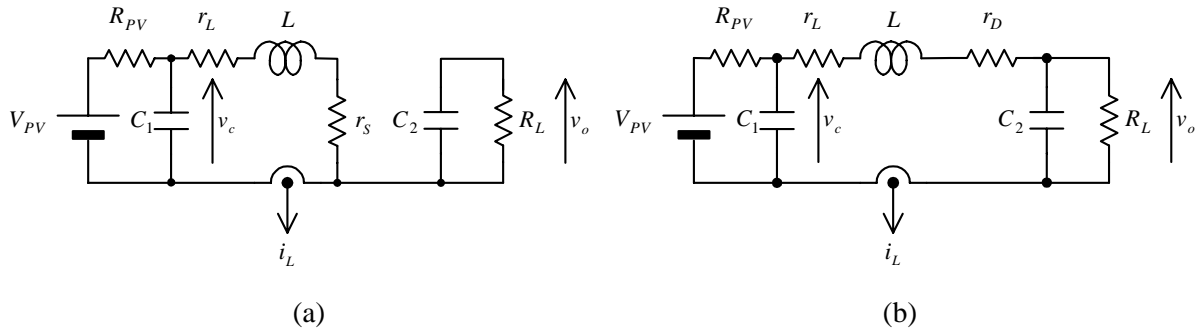


Fig. 3: Equivalent circuits of boost chopper.

(a) Equivalent circuit in on-state. (b) Equivalent circuit in off-state.

3. 3. Current Ripple Equation

Since $dx/dt = 0$ in a steady state, the capacitor voltage V_C , the reactor current I_L and the output voltage V_o in the steady state can be expressed as

$$\begin{bmatrix} V_C \\ I_L \\ V_o \end{bmatrix} = \frac{V_{PV}}{r_L + r_S D + r_D D' + R_{PV} + R_L D'^2} \begin{bmatrix} r_L + r_S D + r_D D' + R_L D'^2 \\ 1 \\ R_2 D' \end{bmatrix}. \quad (4)$$

Ripple amplitude of the reactor current Δi_L is derived by multiplying (1) by on-state duration as follows:

$$\Delta i_L = DT_s \left(\frac{1}{L} v_c - \frac{r_L + r_S}{L} i_L \right). \quad (5)$$

Approximating the capacitor voltage and the reactor current to those values in the steady state as obtained in (4), steady state ripple amplitude of the reactor current ΔI_L is derived as the following equation:

$$\Delta I_L = \frac{DT_s}{L} \frac{V_{PV}}{r_L + r_S D + r_D D' + R_{PV} + R_L D'^2} (r_S D + r_D D' - r_S + R_L D'^2), \quad (6)$$

where T_s is a switching period.

3. 4. Power Estimation with Only Current Information

The output power of the photovoltaic can be estimated as follows, paying attention to that V_{PV} , R_{PV} , V_C , V_o and R_L are all unknown:

$$W_o = \frac{V_o^2}{R_L} = \frac{L}{DT_s} \Delta I_L I_L + (r_S - r_D) D' I_L^2. \quad (7)$$

It should be noted that D , D' and T_s are known variables because they are manipulating

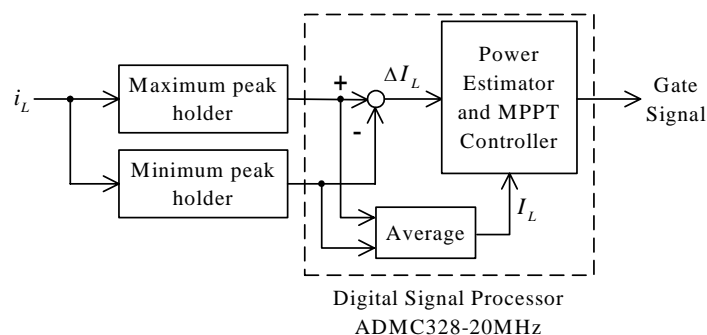


Fig. 4: Proposed MPPT technique.

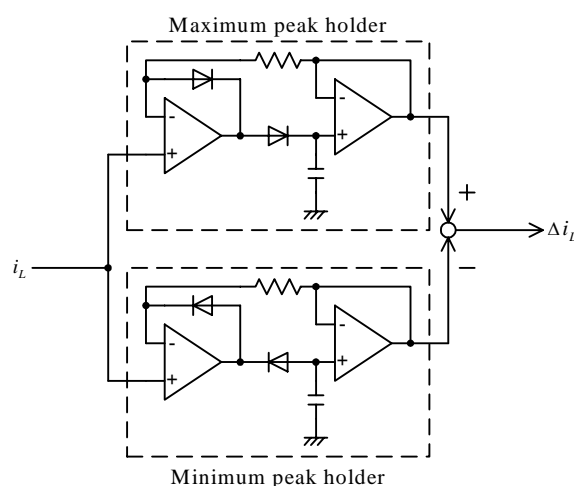


Fig. 5: Current ripple detector.

quantities specified by the controller and that L , r_s and r_D are variables of which values are preliminarily available. Therefore, (7) represents that the output power can be estimated with information of Δi_L and I_L from only the current sensor. The hill-climbing method allows MPPT by using the estimated output power.

4. MPPT Operation with Single Current Sensor

4. 1. Proposed MPPT System Configuration

Fig. 4 shows a block diagram of the proposed MPPT technique. As previously described, the system implementation is simplified because the photovoltaic power can be estimated with no voltage sensors and no short-current switches. The Hall-effect CT detects the reactor current including its ripples, and the ripple amplitude and the average current are calculated with some analog hardware and DSP (Analog Devices ADMC328-20MHz) based software. Since the switching frequency of the chopper is 10 (kHz), the current ripple detector is composed with a simple Op-amp based circuit as shown in Fig. 5, instead of use of high-speed A/D converters. By using this analog circuit, both the maximum peak and the minimum peak of the reactor current are held. The average current I_L is obtained from sum of the both peak values, while the current ripple amplitude Δi_L is calculated by difference between the two peak values.

4. 2. Operation of Current Ripple Detector

Fig. 6(a) and Fig. 6(b) show operations of the current ripple detector when the ripple amplitude is changed stepwise. Fig. 6(a) corresponds to the case of increasing the ripple amplitude, and Fig. 6(b) is the case of decreasing. As can be seen in Fig. 6(a), the current ripple detector properly tracks step changes of the ripple amplitude without large delays. However, Fig. 6(b) indicates that the current

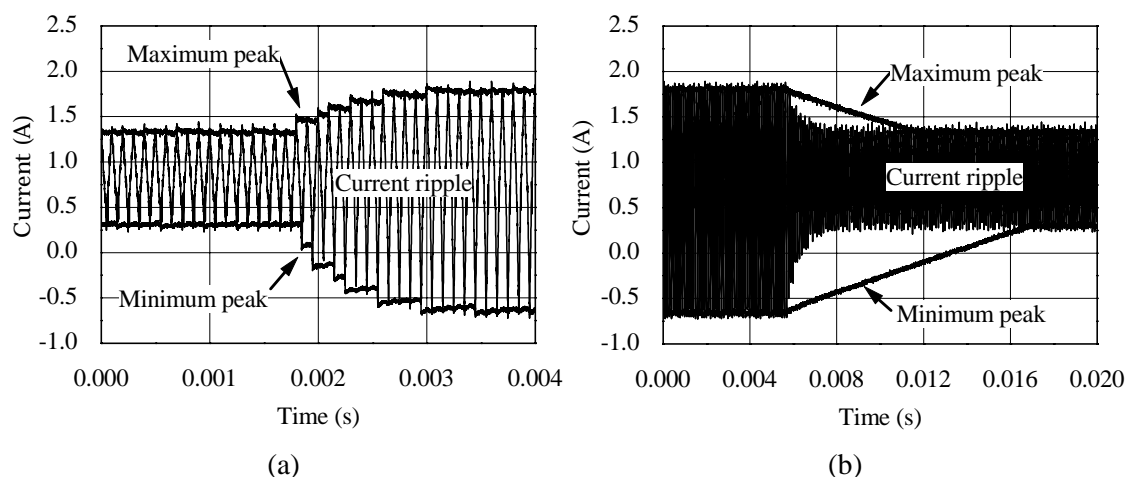


Fig. 6: Responses of current ripple detector.
(a) In case of increasing ripple. (b) In case of decreasing ripple.

Table II Ratings of S-270A

Rated maximum power	35 (W)
Rated output voltage	16.6 (V)

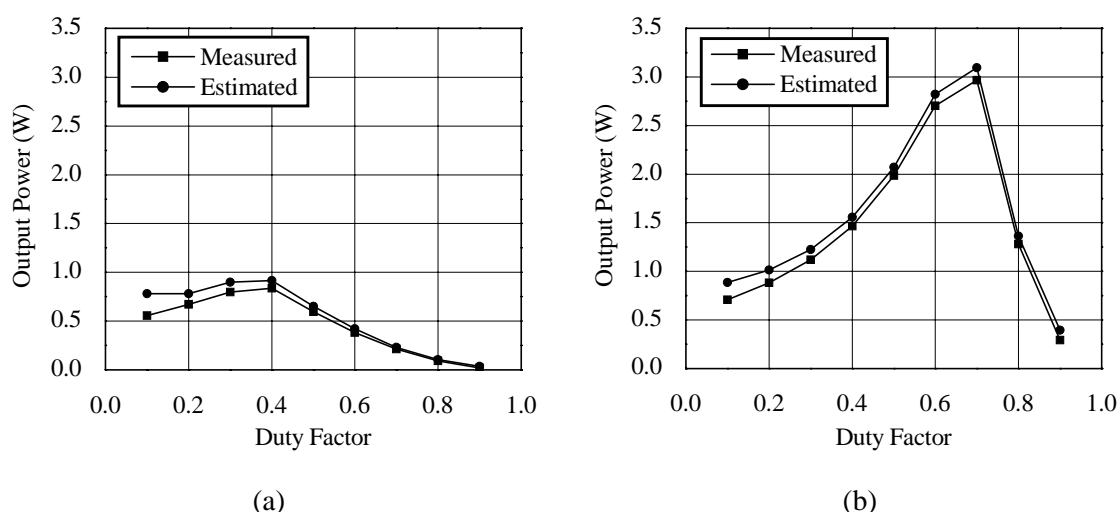


Fig. 7: Experimental results of measured and estimated output power.
(a) In case of low irradiance (251-315 (W/m²)). (b) In case of high irradiance (552-643 (W/m²)).

ripple detector requires approximately 8 (ms) and 14 (ms) to track the new maximum value and the new minimum value, respectively. These delays are caused by discharge time constant of the capacitors. However, the delays hardly affect the MPPT performance of the system because solar irradiation slowly varies in a few seconds.

4. 3. Evaluation of Estimated Power

Fig. 7 shows experimental results of measured output power and estimated output power, where the duty factor of the boost chopper is manually changed. A test photovoltaic panel is S-270A released by Sharp Co. whose electrical ratings are listed in Table II. When irradiance is relatively low as shown in Fig. 7(a), small error can be observed in a low-duty range but the estimated result agrees well with the measured values in the whole. It is confirmed that the maximum power point is observed at $D = 0.4$ in both estimated and measured results. Fig. 7(b) shows another experimental

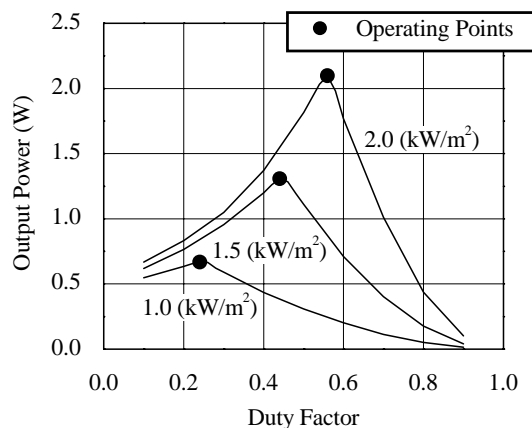


Fig. 8: Experimental result of proposed MPPT method.

result in the case of relatively high irradiance. As can be seen in the figure, excellent agreement is confirmed between the estimated and measured output power. Both results indicate that the maximum power can be obtained at $D = 0.7$. Since the optimum operating points are sought by the hill-climbing method as described before, absolute accuracy in estimating the output power is unnecessary. In other words, it is possible to seek the maximum power point as long as both the estimated and the measured characteristics have their peaks at the same duty factor.

Some errors can be seen between the estimated and measured output power in low duty factor range in Fig. 7. It is inferred that the resistance variation in the diode forward drop r_D is a cause of the estimation error because r_D is assumed to be constant in (7). When the duty factor is low, the diode terminal voltage does not saturate due to a low current, which leads increase of the equivalent resistance. Another cause of the estimation error must be caused by an error in detecting the current with the Hall-effect CT.

4. 4. Experimental Result of Proposed MPPT System

An experimental test was conducted to confirm performance of the proposed technique, using a test photovoltaic of GL418-TF listed in Table I. During the experiment, surface temperature of the test photovoltaic panel was kept almost constant at 50 (°C). Fig. 8 shows that the MPPT controller based on the proposed technique successfully reached the maximum power point even though the irradiance varies widely. As can be confirmed in this experimental result, the MPPT operation is possible with only a single current sensor.

4. 5. Discussion on Parameter Sensitivity

Parameter sensitivity was examined through computer simulations. Fig. 9 shows duty factor error between the estimated and measured maximum power points. According to the power estimation algorithm expressed as (7), an inductance mismatch may detrimentally affect the estimation performance and the MPPT performance. Therefore; the duty factor error between the estimated and measured maximum power points was examined, changing the inductance in (7) from 10 to 200 (%) of real inductance used in the chopper and changing the load resistance. As can be seen in the figure, the inductance mismatch hardly affects the MPPT performance and the load resistance is almost independent of the performance.

5. Conclusion

This paper has proposed a novel strategy of maximum-power-point tracking of a photovoltaic, which can be implemented with only a single current sensor. Possibility of estimating the output power of the photovoltaic with only the current sensor has been discussed and been examined through various experimental tests.

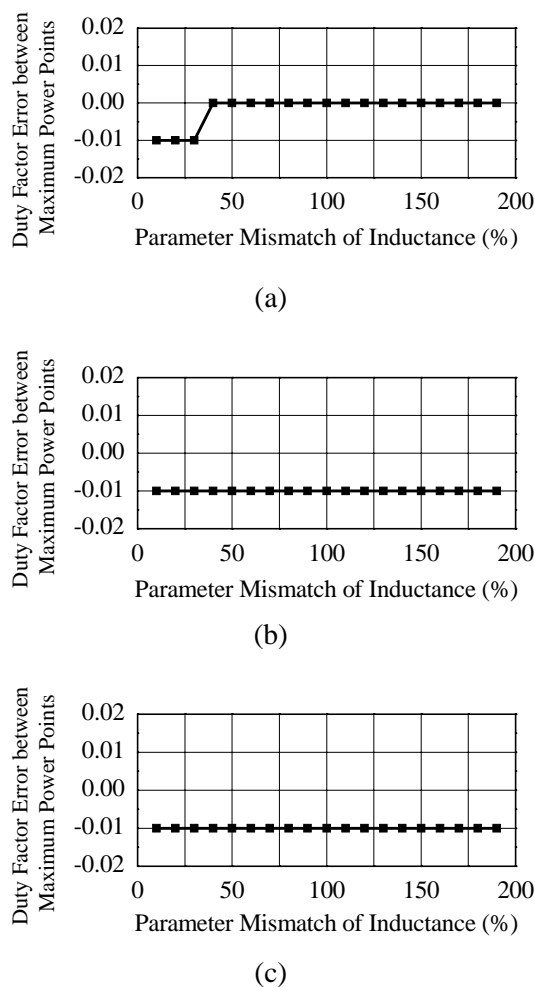


Fig. 9: Parameter sensitivity of proposed method.

(a) $R_L = 20 (\Omega)$. (b) $R_L = 50 (\Omega)$. (c) $R_L = 100 (\Omega)$.

In the theoretical analysis, it has been clarified that the output power can be estimated with information only from the current sensor, i.e., an average value and ripple amplitude of the current. Also, a simple circuit configuration to make the current-ripple detection possible has been illustrated.

Operating characteristics of the current ripple detector have been examined and proper estimation result of the output power has been confirmed through the experimental tests. Consequently, the MPPT using only the single current sensor has been achieved with excellent accuracy.

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