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A Battery Charging System for Intermittent Generation from a Synchronous Generator with a Novel Maximum Power Point Tracking Control

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This paper proposed a battery charging system for intermittent generation from a synchronous generator with a novel Maximum Power Point Tracking (MPPT) control method. Analyzing the generation with boost chopper by the state space averaging method, the internal voltage of the generator, the output voltage and the resistance of the output of the boost chopper can be estimated by with only single current sensor. Even though the intermittent generation, the proposed the battery charging system is able to charge the battery constantly because of a bi-directional DC/DC converter and an Electric Double-Layer Capacitor (EDLC). The basic principle of the proposed MPPT control method and the proposed charging system are discussed, and then confirmed by digital computer simulation using PLECS. The simulation results reveal that the proposed MPPT controller controls the maximum power point and the proposed charging system is able to charge the battery constantly.

Keywords: MPPT, state space averaging method, boost chopper, intermittent generator, and synchronous generator.

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1. Introduction

Malaysia has a 42.8% share of the world palm oil industry [1]. Palm oil is one of plant oils such as soy and colza. The oil palm fruits are transferred to steam boiler to remove the husk in the milling process. The considerable quantities of steam are used in extracting palm oil. These steam energy is released to the air. The focus of this research utilizes this wasted energy.

The release pattern of the steam is intermittent. In general, Permanent Magnet Synchronous Generators (SGs) [2-4] are used for wind power generation. However, the maximum power point of SGs changes with the rotating speed of the turbines. Conventional maximum power point tracking (MPPT) control methods have been proposed using the hill-climbing method and the angle and current feedback method [5]. The hill-climbing method is to seek the maximum power point by calculating the generated power with a voltage and current sensors. The angle and current feedback method is to adjust the maximum power point by using the three sensors' information. However these methods need two or three sensors.

This paper proposes a battery charging system for intermittent generation from a synchronous generator with novel maximum power point tracking control. The charged battery is used in the agricultural equipment during the harvesting process. Analyzing the boost chopper for maximizing the generated power by the

state space averaging method, the internal voltage of the generator and the output voltage of the output of the boost chopper can be estimated by with only single current sensor. In intermittent period, the SG doesn't generate the power and the battery cannot charge. The bi-directional DC/DC converter and an Electric Double-Layer Capacitor (EDLC) is used for charging the battery constantly in every period [6].

Digital computer simulation is implemented to confirm the validity of the proposed method by using PLECS software. The results reveal that the proposed MPPT controller tracks the maximum power point and the proposed charging system is able to charge the battery constantly.

2. Characteristics of the Synchronous generator

The test circuit consists of the SG, a diode rectifier, smoothing capacitor and resistor. Fig. 1 shows the V-I characteristic of the SG in this paper. The voltage and current of the SG increases with the rotation speed. Fig. 2 shows the V-P characteristic of the SG. From Fig. 2, the maximum power point voltage is changed with the rotation speed. From these characteristics, the internal resistance of the SG around the maximum power point is 16.0 Ω.

The SG is modelled to demonstrate the characteristics on the digital computer simulation. The SG with the diode rectifier can replace the voltage source with the internal resistor. The approximated value of the voltage source is given as follows

$$v_M = (-0.0024^*w + 1.6041)^*i_{Rec}^2 + (0.0066^*w - 15.712)^*i_{Rec} + 0.0563^*w + 9.757 \quad (1)$$

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Fig. 1. V-I characteristic of the SG

Fig. 2. V-P characteristic of the SG

where w is the rotating speed [rpm] and i_{Rec} is the current value of diode rectifier. When the value of the rotating speed is small, the forward voltage of the diode rectifier is large to the rectified voltage because the generating voltage is small. However, the characteristics of SG include this nonlinear property. Therefore the accuracy of equation (1) is enough to analyze the proposed system.

3. System configuration

Fig. 3 shows a power circuit diagram of the proposed battery charging system. The proposed system consists of the turbine, SG, boost chopper, step-down chopper and bi-directional DC/DC converter. The generated power tracks the maximum power point using a boost chopper with the proposed MPPT control. The proposed MPPT controller uses only one sensor because the estimator estimates the terminal voltage v_T of C_{Rec} . The battery is demonstrated as a resistor R_B in this paper. A step-down chopper is used for charging the battery.

Fig. 3. A power circuit diagram of the proposed battery charging system.

(a) MPPT control block.

(b) Charge voltage control for a battery

(c) DC link voltage control

Fig. 4. A block diagram of Fig. 3

The generated power of the SG is discontinuous because of the intermittent working cycles of the steam. The electric double-layer capacitor C_{EDLC} is charged from the surplus power using a bi-directional DC/DC converter in the generating mode. In the non-generating mode, the bi-directional DC/DC converter acts as a boost chopper for charging the battery. The bi-directional DC/DC converter keeps the DC link voltage. Thus, the battery is charged constantly.

Fig. 4 shows a block diagram of Fig. 3. Fig. 4 (a) shows the MPPT control block. In section 4, the MPPT control method is described in detail. Fig. 4 (b) shows the charge voltage control for a battery. Fig. 4 (c) shows the DC link voltage control. The bidirectional DC/DC converter switches over by the generating and non-generating modes. v_{cc}^* is the reference value for switching over.

4. Proposed MPPT control method

Fig. 5 shows the basic system configuration of the steam generation system. The resistor R_O demonstrates the equivalent resistance of the step-down chopper and

Fig. 5. System configuration of the steam generation system using a boost chopper

Fig. 6. Relationship between the switching condition and i_L

Fig. 7. Equivalent circuit of the steam generation system during (MODE 1)

Fig. 8. Equivalent circuit of the steam generation system (MODE 2)

bi-directional DC/DC converter. The boost chopper harvests the generated power at the maximum power point. The input and output side of the boost chopper is connected the smoothing capacitors.

4.1 Analyzing the steam generation system

This section reveals that the output of the steam generation can estimate by using the linear analyzing result of the system. This paper uses the state space averaging method [7], [8] for this analyzing the boost chopper.

The boost chopper acts in continuous current mode (CCM). There are two modes in CCM. Fig. 6 shows the relationship between switching condition and i_L . D is the duty ratio during S1-on period and D' is the duty ratio during S1-off period. Thus, we analyze the two modes. The state equations of Fig. 7 and Fig. 8 set up where the state variable x is $(v_T \ i_L \ v_{C1})^T$.

Fig. 7 illustrates the equivalent circuit during G is ON. During G is ON, i_L increases from 0 to the peak value I_{LP} . r_{S1} is the ON-resistance of the switch S1, and r_L is the winding resistance of L . From Fig. 5, the state equation of the MODE 1 is given as follows

$$\frac{dv_T}{dt} = \frac{v_M}{R_M C_{Rec}} - \frac{i_L}{C_{Rec}} - \frac{v_T}{R_M C_{Rec}} \quad (2)$$

$$\frac{di_L}{dt} = \frac{v_T}{L} - \frac{r_L + r_S}{L} i_L, \quad (3)$$

$$\frac{dv_{C1}}{dt} = -\frac{v_{C1}}{R_O C_{Rec}}. \quad (4)$$

From these equations, the matrix is given by

$$\frac{dx}{dt} = A_1 x + b_1 v_M \quad (5)$$

where A_1 and b_1 are given by

$$A_1 = \begin{bmatrix} -\frac{1}{R_M C_{Rec}} & -\frac{1}{C_{Rec}} & 0 \\ \frac{1}{L} & \frac{r_L + r_S}{L} & 0 \\ 0 & 0 & -\frac{1}{R_O C_{Rec}} \end{bmatrix},$$

$$b_1 = \begin{bmatrix} \frac{1}{R_M C_{Rec}} \\ 0 \\ 0 \end{bmatrix}.$$

Fig. 8 illustrates the equivalent circuit during G is OFF. r_D is the conduction resistance of D . From Fig. 8, the state equation of the MODE 2 is given as follows

$$\frac{dv_T}{dt} = \frac{v_M}{R_M C_{Rec}} - \frac{i_L}{C_{Rec}} - \frac{v_T}{R_M C_{Rec}}, \quad (6)$$

$$\frac{di_L}{dt} = \frac{v_T}{L} - \frac{v_{C1}}{L} - \frac{r_L + r_D}{L} i_L, \quad (7)$$

$$\frac{dv_{C1}}{dt} = -\frac{v_{C1}}{R_O C_1} + \frac{i_L}{C_1}. \quad (8)$$

From these equations, the matrix is given by

$$\frac{d\bar{x}}{dt} = \mathbf{A}_2 \bar{x} + \mathbf{b}_2 v_M, \quad (9)$$

where $\mathbf{A}_2$ and $\mathbf{b}_2$ are given by

$$\mathbf{A}_2 = \begin{bmatrix} -\frac{1}{R_M C_{Rec}} & -\frac{1}{C_{Rec}} & 0 \\ \frac{1}{L} & \frac{r_L + r_D}{L} & -\frac{1}{L} \\ 0 & \frac{1}{C_1} & -\frac{1}{R_O C_1} \end{bmatrix},$$

$$\mathbf{b}_2 = \begin{bmatrix} \frac{1}{R_M C_{Rec}} \\ 0 \\ 0 \end{bmatrix}.$$

The state averaging equation is assumed as follows

$$\bar{x} = (\bar{v}_T \bar{i}_L \bar{v}_{C1})^T. \quad (10)$$

The state averaging equation can be derived as

$$\frac{d\bar{x}}{dt} = \mathbf{A} \bar{x} + \mathbf{b} V_M, \quad (11)$$

$$\mathbf{A} = D\mathbf{A}_1 + D'\mathbf{A}_2$$

$$= \begin{bmatrix} -\frac{1}{R_M C_{Rec}} & -\frac{1}{C_{Rec}} & 0 \\ \frac{1}{L} & -\frac{r}{L} & -\frac{D'}{L} \\ 0 & \frac{D'}{C_1} & -\frac{1}{R_O C_1} \end{bmatrix},$$

$$\mathbf{b} = D\mathbf{b}_1 + D'\mathbf{b}_2$$

$$= \begin{bmatrix} \frac{1}{R_M C_{Rec}} \\ 0 \\ 0 \end{bmatrix},$$

$$r = Dr_S + D'r_D + r_L.$$

The following equation can be written in the steady state

$$\frac{d\bar{x}}{dt} = \mathbf{0}. \quad (12)$$

Therefore V_T , I_L and V_{C1} in the steady state can be derived as

$$\begin{bmatrix} V_T \\ I_L \\ V_{C1} \end{bmatrix} = \frac{V_M}{r + R_O D'^2 + R_M} \begin{bmatrix} r + R_O D'^2 \\ 1 \\ R_O D' \end{bmatrix}. \quad (13)$$

The average value I_L of i_L is given as follows

$$I_L = \frac{1}{r + R_O D'^2 + R_M} V_M. \quad (14)$$

The internal voltage V_M of the steam generator is given by

$$V_M = (Dr_{S1} + D'r_{D1} + r_{L1} + R_O D'^2 + R_M) I_L. \quad (15)$$

The rectified voltage V_T can be expressed as

$$V_T = (Dr_S + D'r_D + r_L + R_O D_M'^2) I_L. \quad (16)$$

The output of the boost chopper R_O can be derived as

$$R_O = \frac{V_{C1}}{D'I_L}. \quad (17)$$

Therefore, V_M , V_T and R_O can be estimated by detecting only the inductor current i_L .

4.2 Proposed MPPT control method

From the analysis result in Section 4.1, V_T and V_M can be estimated by the inductor current. Fig. 9 shows the circuit diagram using the proposed MPPT control method. I_T is given by

$$I_T = \frac{V_M - V_T}{R_M}. \quad (18)$$

V_T can be estimated by Equations (16). The reference value of the boost chopper is given by

$$V_{ref}^* = I_T R_M. \quad (19)$$

The PI controller uses to track the reference and reduce the error, which is obtained by subtracting V_T from V_{ref}^* close to zero. The duty ratio D and D' are calculated by the output value v_C of the PI controller.

Thus the MPPT control method in this paper can be estimated the output of the synchronous generator with only current sensor by analyzing the boost chopper using state space averaging method. Hence, the voltage of the maximum power point can be decided without calculation of the power.

Fig. 9. A circuit diagram with the proposed MPPT control method

5. Simulation Results

Digital computer simulations using PLECS software were implemented to confirm the validity and viability of the proposed charging system.

5.1 Simulation results in only generating period

Fig. 10 shows the simulation result when the steam generator speed was 1200 rpm. V_T is the estimated terminal voltage, v_T is the terminal voltage, p is the generated power, v_{CI} is the DC link voltage and v_B is the battery voltage. V_T corresponded to v_T by using the estimator in the steady state. The generated power was 127.3 W which is generally similar to the results of Fig.1. The DC link voltage v_{CI} was 75 V and the voltage of the battery v_B was 13 V. All voltages tracked the reference voltage.

Fig. 11 shows the simulation results on V-P for each rotation speed. In Fig.10, the black points plotted the generated power point on the simulation results with the proposed MPPT control. The average error for the maximum power point voltage between the simulation results and the V-P characteristic was within 0.9%. The results reveal that the proposed MPPT controller can track the maximum power point.

5.2 Simulation results in all modes

Digital computer simulation with both the generating and intermittent modes was implemented in this section. Table 1 indicates a short model pattern of the steam discharge for the simulation. The period A, C and D are the generating mode. The period B and E are the intermittent mode.

Fig. 10. Simulation results with the proposed MPPT control method when the steam generator speed was 1200 rpm.

Fig. 11. Simulation results on V-P for each rotation speed.

Table 1 A pattern of the steam discharge.

Period	Time [s]	the steam generator speed [rpm]
A	0~0.2	800
B	0.2~0.4	10
C	0.4~0.6	1000
D	0.6~0.8	1200
E	0.8~1.0	10

Fig. 12 shows the simulation result with all modes. During the generating mode, the generated power is similar to the results of Fig.1. The DC link voltage v_{CI} was 75 V. The capacitor C_{EDLC} were charged from the surplus power using a bi-directional DC/DC converter in the generating mode. In the intermittent mode, the capacitor C_{EDLC} was discharged the electricity because

the bi-directional DC/DC converter acts as a boost chopper for charging the battery. The voltage of the battery v_B were 13 V during all modes. Therefore the battery was charged constantly. The simulation results reveal that the propose charging system is the validity.

6. Conclusion

This paper proposed a battery charging system for intermittent generation from a synchronous generator with novel MPPT control method.

Digital computer simulation revealed that the proposed MPPT controller with only a single sensor could track the maximum power point. From the simulation results, the average error for the maximum power point voltage between the simulation results and the V-P characteristic was within 0.9%. The proposed charging system was able to charge the battery constantly. These results revealed the proposed battery charging system is practicable.

Fig. 12. Simulation result when the steam generator worked in the intermittent generation.

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