Implementation of High Step-Up Solar Power Optimizer for DC Micro Grid Application

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Abstract—This paper proposed a novel high step-up solar power optimizer (SPO), which efficiently harvests maximum energy from photovoltaic (PV) panel then output to DC micro-grid. It combines coupled inductor and switched-capacitor technologies to achieve high step-up voltage gain. The leakage inductance energy of the coupled inductor can be recycled to reduce the voltage stress and power losses. Therefore, low voltage rating and low conduction resistance switch can be selected to improve system efficiency. Laboratory prototypes of the proposed SPO with an input voltage arrange of 20 ~ 40 V and the maximum output 400 V / 300 W is implemented to verify the performance and MPPT accuracy when connected to DC micro-grid simulator.

I. INTRODUCTION

An alternative product, Solar Power Optimizer (SPO), is developed to maximum the energy harvest from each individual PV panel. SPO as a DC-DC converter with maximum power point tracking (MPPT), which lifts panel voltage to meet the optimum voltage levels for DC micro-grid connection or through a DC-AC inverter to electricity. Fig. 1 shows the energy of a single PV panel through SPO to DC micro-grid system. The 400-V DC micro-grid system has been proposed as an energy efficient distribution option for data center system and telecommunication facilities [1]. The SPO attempts to improve utilization of distributed renewable resource and its lower system cost. It’s potential to improve efficiency of PV system, anti-shadow effect and to monitoring PV module status [2]. Many SPO employ various step-up DC-DC converter topologies have included conventional boost converter, the switched-inductor and switched-capacitor types [3], transformerless switched-capacitor type [4], the boost type integrated with the coupled inductor [5], the voltage-lift type [6], and the capacitor-diode voltage multiplier [7]. In regards to increasing voltage gain, once the leakage inductance energy of the coupled inductor can be recycled, then the voltage stress on the active switch is reduced, meaning the coupled inductor and the voltage multiplier or voltage lift techniques are able to accomplish the goal of achieving higher voltage gain [8]-[10].

Figure 1. Multiple parallel SPOs configuration for DC micro-grid system.

Figure 2. Circuit configuration of proposed SPO.

The proposed SPO is shown in Fig. 2; its configuration includes a coupled inductor $T_1$ with the floating active switch.
S, the primary winding \(N_1\) of a coupled inductor \(T_1\) is similar to the input inductor of the conventional boost converter, that capacitor \(C_1\) and diode \(D_1\) recycle leakage-inductor energy from \(N_1\). The secondary winding \(N_2\) is connected with another pair of capacitors \(C_2\) and \(C_3\) and with diodes \(D_2\) and \(D_3\). The rectifier diode \(D_4\) connects to its output capacitor \(C_0\) and load \(R\). The features of the proposed converter are: 1) the voltage conversion ratio is efficiently increased by the switched-capacitor and coupled-capacitor techniques; 2) the leakage inductance energy of the coupled inductor can be recycled to increase the efficiency; and the voltage spike on the active switch has been restrained; 3) the floating active switch isolates the PV panel’s energy during non-operating conditions, thus preventing any potential electric hazard to humans or facilities.

II. OPERATING PRINCIPLES

The operating principles for continuous-conduction mode (CCM) are now presented in detail. Fig. 3 illustrates a typical waveform of several major components during one switching period. In order to simplify the circuit analysis of the proposed converter, the following assumptions are made: (1) All components are ideal, except for the leakage inductance of coupled inductor \(T_1\). (2) The capacitors \(C_1 \sim C_3\) and \(C_0\) are sufficiently large that the voltages across them are considered to be constant. (3) The turn ratio \(n\) of the coupled inductor \(T_1\) winding is equal to \(N_2/N_1\). The three operating modes are described as follows.

- **Mode I \([t_0, t_1]\):** During this interval, switch \(S\) on, and only diode \(D_2\) is conducting. The source energy \(V_{in}\) is series-connected with \(C_1\), \(C_2\), \(C_3\), secondary winding \(N_2\), and \(L_{k2}\) to charge output capacitor \(C_0\) and load \(R\); meanwhile magnetizing inductor \(L_m\) is also receiving energy from \(V_{in}\). The current flow path is shown in Fig. 4(a). This mode ends when switch \(S\) is turned off at \(t = t_1\).

- **Mode II \([t_1, t_2]\):** During this transition interval, switch \(S\) off, diodes \(D_1\) and \(D_2\) are conducting. The energy stored in leakage inductor \(L_{k1}\) flows through diode \(D_1\) to charge capacitor \(C_1\) instantly. The energy stored in

![Figure 3. Typical waveforms of the proposed SPO at CCM operation.](image)

![Figure 4. Current flow path in three operating modes during one switching period in CCM operation: (a) Mode I, (b) Mode II, (c) Mode III.](image)
magnetizing inductor $L_m$ is delivering its energy through $T_1$, $D_2$ and $D_3$ to charge capacitor $C_2$ and $C_3$. The current flow path is shown in Fig. 4(b). The energy stored in capacitors $C_0$ is constantly discharged to the load $R$. This mode ends when current $i_{Lk}$ is zero at $t = t_2$.

- **Mode III** [$t_2$, $t_3$]: During this interval, magnetizing inductor $L_m$ is constantly transferring energy to secondary winding $N_2$, $D_2$, and $D_3$ to charge capacitor $C_2$ and $C_3$. The current flow path is shown in Fig. 4(c), and diode $D_2$ and $D_3$ are conducting. The energy stored in capacitor $C_0$ is constantly discharged to the load $R$. This mode ends when switch $S$ is turned on at the beginning of the next switching period.

### III. STEADY-STATE ANALYSIS

The steady-state analysis is only considered at CCM operation, and the leakage inductances at primary and secondary sides are ignored. Applying a volt-second balance on the magnetizing inductance $L_m$ yields

$$\int_0^{DT_s} (V_{in}) dt + \int_0^{DT_s} (-V_{C1}) dt = 0,$$  

and

$$\int_0^{DT_s} (nV_{in}) dt + \int_0^{DT_s} (-V_{C2}) dt = 0.$$  

From which the voltage across capacitor $C_1$ and $C_2$ are obtained as follows:

$$V_{C1} = \frac{D}{1-D} V_{in},$$

and

$$V_{C2} = \frac{nD}{1-D} V_{in}.$$  

During mode I, the output voltage $V_o = V_{in} + V_{C1} + V_{N2} + V_{C2} + V_{C3}$. The voltage gain $M_{CCM}$ can be found as follows:

$$M_{CCM} = \frac{V_o}{V_{in}} = 1 + n + nD$$  

The boundary normalized magnetizing inductance time constant $\tau_{LmB}$ can be found:

$$\tau_{LmB} = \frac{D(D-1)^2}{2(n^2 + D(n + 1))}.$$  

![Figure 5](image1.png)  

**Figure 5.** The voltage gain $M_{CCM}$ as a function of duty ratio $D$ by various turns ratios.

![Figure 6](image2.png)  

**Figure 6.** The voltage gain $M_{CCM}$ as a function of duty ratio $D$ for the proposed converter, as compared with [7] and [8] under CCM operation and with $n = 4$.

![Figure 7](image3.png)  

**Figure 7.** The magnetizing inductance and turn ratios $n$ as a function of duty ratio $D$ when $M_{CCM} = 20$.

### IV. EXPERIMENTAL RESULTS

Two 400 V/300 W SPO prototypes are presented to verify the feasibility and multi-SPO on-grid condition, and to measure individual MPPT result. Its specification as input voltage, $V_{in} : 20 \sim 40$ V; switching frequency, $f_s : 50$ kHz. The maximum voltage gain is 20 at input voltage is 20 V. Refer to Fig. 5 and (5). When turn ratios is $n = 4$ that duty ratio will be $D = 0.625$. The magnetizing inductance can be obtained by Fig. 7, $L_m = 20.86 \mu$H, but the actual magnetizing inductance measured as 21.87$\mu$H and the leakage inductance is about 0.22 $\mu$H. The component parameters of SPO have selected as capacitors $C_1$ is 68 $\mu$F, $C_2$ and $C_3$ are 220 $\mu$F, and $C_0$ is 100 $\mu$F; diodes $D_1$ is MBR30100CT, $D_2$ and $D_3$ both are using...
UF3003, output diode $D_4$ is BYR29-600; IXFX150N15 is selected for active switch $S$. The parameters of two SPOs are identically. The switching signal of active switch $S$ is modulated and controlled by TMS320LF2407 with MPPT function.

Fig. 8 is shown experimental waveforms of major components during full load and the condition of input voltage is 20 V. The waveforms in Fig. 9 are measured on the same components but the input voltage is changed to 40 V. These current and voltage waveforms are agreed with operating principle and the steady-state analysis.

Fig.10 shows that the maximum efficiency is up to 96.7 % at light load operation when either input voltage is 20 V or 40V. The full load efficiency still reaches 94.6 % when input voltage is 40 V. Once the input voltage drops to 20 V, that full load efficiency will down to 91.1 %. For on-grid test and individual MPPT accuracy measurement, the modular solar array simulator (Agilent E4360) provides two different MPPT curves, 200 W and 120 W, to SPOs respectively. Fig. 11 appears two SPO’s maximum power tracing point distribution by different MPPT simulation curves. One SPO is applied by the 200-W MPPT simulation curve; its highest MPPT accuracy ratio is 99.6 %. Another SPO tracing 120-W curve and performs 99.8 % of highest MPPT accuracy ratio. Both SPOs are connected to 400 V DC bus which provided by a DC grid and load simulator.

V. CONCLUSION

The novel high step-up SPO adopts the coupled inductor with proper turn ratio design and switched-capacitor technology to achieve high voltage gain is 20 times higher than input voltage. Because leakage inductance energy of coupled inductor is recycled, and the voltage stress across the active switch $S$ is constrained; the low $R_{DS(ON)}$ of active switch can be selected to improve the maximum efficiency up to 96.7 % , and full load efficiency achieves 94.6 % and 91.1 % at high and low line input, respectively. The highest MPPT accuracy is respectively 99.6 % and 99.8 % during DC micro-grid simulator connection. However, a 300 W novel SPO with high step-up and MPPT functions is implemented and performs good MPPT ability.

ACKNOWLEDGMENT

The authors gratefully acknowledge financial support from NSC, Taiwan under project no. NSC 98-2221-E-006-247-MY3, Bureau of Energy, Ministry of Economic Affairs (project no. 100-D0204-2).

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