DOUBLE INPUT BUCK CONVERTER WITH ONE CYCLE CONTROL FOR SOLAR ENERGY

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Abstract
As great advance in renewable energy has been made, the price for electricity produced with renewable energy drops. The national average electricity price is about 10 cents per kWh. The price for certain kinds of renewable energy are lower than 10 cents per kWh. As the cost of conventional energy resources is increasing every year, the receding trend in the cost of renewable technologies is encouraging, making renewable energy an economical means of power generation in the near future. Renewable energy technologies not only can solve the climate change and reduce the dependence on foreign energy import; it is also suitable for distributed power generation. In remote areas, where there are no transmission lines or the cost of building new transmission lines is high, renewable energy can provide power without expensive and complicated grid infrastructure. This work proposed and evaluated a new power circuit that can deal with the problem of the intermittent nature and slow response of the renewable energy. This report explains an OCC (one cycle control) method for MIC which is simpler compared to other control methods. The working of OCC is explained in details. It is seen that with OCC, no current regulator is required, and the design conditions of the output voltage regulator in different operating modes are the same. Thus, control design is simple. The proposed circuit integrates different renewable energy sources with energy storage devices
Keywords: *One cycle control, double input buck converter, renewable energy sources, multiple input converters*

Introduction

Due to the environmental problem, e.g., climate change, and political and economical reasons, e.g., less dependence on the foreign energy import, high oil price, renewable energy has attracted enormous attention. Investment worldwide in renewable energy has gone from below $10 billion in 1995 to over $70 billion in 2007. Since 2000, renewable electricity installations in the U.S., excluding hydro power, have nearly doubled, and in 2007 there is 33 GW of installed capacity. Wind power and solar power are the fastest growing renewable energy sectors. In 2007, wind capacity installations grew 45% and solar PV grew 40% from the previous year.

As great advance in renewable energy has been made, the price for electricity produced with renewable energy drops. The national average electricity price is about 10 cents per kWh. The price for certain kinds of renewable energy are lower than 10 cents per kWh. As the cost of conventional energy resources is increasing every year, the receding trend in the cost of renewable technologies is encouraging, making renewable energy an economical means of power generation in the near future.[1-3] Renewable energy technologies not only can solve the climate change and reduce the dependence on foreign energy import; it is also suitable for distributed power generation. In remote areas, where there are no transmission lines or the cost of building new transmission lines is high, renewable energy can provide power without expensive and complicated grid infrastructure. Distributed power generation system has several advantages: It can reduce or avoid the necessity to build new transmission/distribution lines or upgrade existing ones; It can be configured to meet peak power needs; It can diversify the energy sources and increase the reliability of the grid network; It can be configured to provide premium power, when coupled with uninterruptible power supply (UPS);It can be located close to the user and can be installed in small increments to match the load requirement of the customer. In spite of the advances made in renewable energy, there are some inherent problems. One is the intermittent nature. The output power from renewable energy sources is not constant. Another problem is slow response compared with electric load. Electric loads may change their power demand in very short time. However, it takes much longer time to change the output power from renewable energy sources.

A unique feature of renewable energy application is that renewable energy sources are operated in their optimal operating points. Since the cost of implementing renewable energy sources is high, it is desirable to get as much power as possible from the renewable energy sources. Maximum power points are tracked during the operation. Therefore, the power output from these sources tends to be constant, no matter how much the load power is. This concept is like hybrid vehicles. [4]The engine, which provides power to a electric motor, is operated at its optimal operating point, no matter how much power the electric motor requires. The difference between the power coming from the engine and the power required by the motor is compensated by energy storage. In this paper solar and commercial grid acts as the hybrid system. The control topology is one cycle control. It is used to reduce the transient effects in the output. Early day's converter topology used to interface the renewable energy sources are several single input converters. In that case the number of input is high and also the control circuit is different for different input.[5-7] So the number of component is high, hence the system cost is high. Multiple input converters are capable for replacing several single input converters in order to reduce complexity and the cost of hybrid power systems. It consists of one output loop and several input loop. So input sources share the output filter. Here the output loop coupled with input loop. Hence this system is also complex.

According to control strategy, the first used method is supervisory control. It has many modes of operation. Hence the system is complex. After that come across to decoupling matrixes. It highly depends upon transfer function. Here the original transfer function will vary with input voltage and load. So the parameter must be tuned accordingly. Hence the system is complex. All these methods are linear feedback control technique. So it need both the voltage and current regulator [8] So in this paper we are using one cycle control. It's a kind of non-linear technique which achieves dynamic control of the average value of switched variable. Now in this paper the converter circuit used is double input buck converter. It reduces the number of components and eliminates the complexity in control loop [9]. Renewable energy sources such as photovoltaic (PV) solar energy and wind energy rely heavily on the climate and weather conditions. As a consequence, the available power is intermittent and stochastic [10-11] So, multiple renewable energy sources that are mutually complementary could be combined to maintain continuous power delivery to the load. Such a system is referred to as a hybrid power system[12] In hybrid power systems, the use of an MIC (Multiple input converters) instead of several single-input converters has a simpler circuit and lower cost. However, the MIC is a typical multiple-input multiple-output coupling system and has many operating modes under the power management strategy, so the closed-loop design is complicated. This paper explains an OCC (one cycle control) method for MIC which is simpler compared to other control methods. The working of OCC is explained in details. It is seen that with OCC, no current regulator is required, and the design conditions of the output voltage regulator in different operating modes are the same. Thus, control design is simple [13-15].

Circuit Diagram

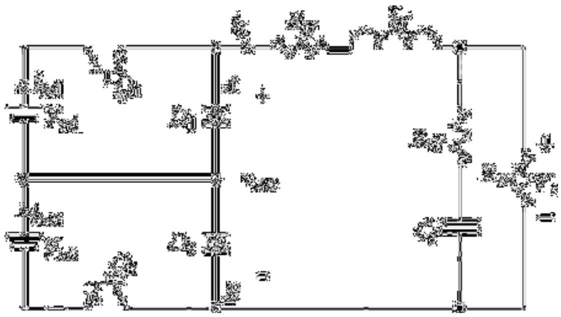

Fig 1 Example of a figure caption

The DIBC is shown in Fig. 1, where Vin1 and Vin2 are the two input sources, Q1 and Q2 are the switches, D1 and D2 are the freewheeling diodes, Lf is the filter inductor, RLf is the parasitical resistor of Lf , Cf is the filter capacitor, and Rcf is the equivalent series resistor of Cf . Two input sources of DIBC can deliver energy to the load simultaneously or individually. According to Fig. 1, the output voltage and input currents at steady state are given by [16-20]

$$V_o = \bar{v}_{AB} = D_{y1}V_{in1} + D_{y2}V_{in2} \quad (1)$$

$$I_{in1} = D_{y1}I_L \quad (2)$$

$$I_{in2} = D_{y2}I_L \quad (3)$$

where Dy1 and Dy2 are duty cycles of Q1 and Q2 at steady state, respectively, Iin1 and Iin2 are the average values of the input currents of the two sources, respectively, and IL is the average value of the inductor current. Because there are two duty cycles, besides the output voltage, another variable could be regulated. This provides the possibility of achieving power management. The power management of the DIBC includes the output voltage regulation and the input power distribution over the two input sources [21-24].

For example, in a hybrid PV–fuel cell system, the solar energy is a renewable energy that serves as the main power source, while fuel cell is the backup power source. The objective of the power management is that the demanded power of the load should be provided by PV arrays as much as possible and the rest are provided by fuel cell. In this paper, the PV arrays are defined as input source 1, which is the main power source, and the backup power source, such as fuel cell or commercial grid is defined as input source 2. Suppose that the demanded load power is Po and the available power of input source 1 is P1max, two operating modes of DIBC are defined as follows [25-28]. Operating mode I: When P1max < Po, the two input sources power the load simultaneously. This implies that input source 1 operates under MPPT control to provide maximum power P1max, while input source 2 regulates the output voltage and thus provide the rest of the demanded load power. Operating mode II: When P1max > Po, the load power is provided by input source 1, and input source 2 is shut down. This implies that input source 1 regulates the output voltage, so the input power of the source 1 is determined by the demanded power of the load instead of the MPPT controller [29-31].

One Cycle Control Concept

A switch operates according to the switch function k (t) at a frequency fs = l/Ts

$K(t)= 1, \quad 0 < t < t_{on}$ (4)

In each cycle, the switch is on for a time duration TON and is off for a time duration TOFF where TON+ TOFF= Ts.The duty-ratio d = ToN/Ts modulated by an analog control reference V r e f (t) . The input signal x(t) at the input node of the switch is chopped by the switch and transferred to the output node of the switch to form a switched variable y(t).The frequency and the pulse width of the switched variable y(t) is the same as that of the switch function k (t) , while the envelope of the switched variable y (t) is the same as the input signal x(t), as shown in Fig. 2

$Y(t) = k(t)\, x(t)$ (5)

Suppose the switch frequency fs is much higher than the frequency bandwidth of either the input signal x(t) or the control reference $V_{ref}(t)$; then the effective signal carried in the switch output, i.e. the average of the switched variable is

$Y(t) = 1/T_s \int x(t)\, dt$ (6)

$= x(t) * 1/T_s \int dt$ (7)

$= x(t)d(t)$ (8)

The switched variable y(t) at the output node of the switch is the product of the input signal x(t) and the duty-ratio d(t) therefore, the switch is nonlinear. If the duty-ratio of the switch is modulated such that the integration of the switched variable at the switch output is exactly equal to the integration of the control reference in each cycle

$\int x(t)\, dt = \int V_{ref}(t)\, dt$ (9)

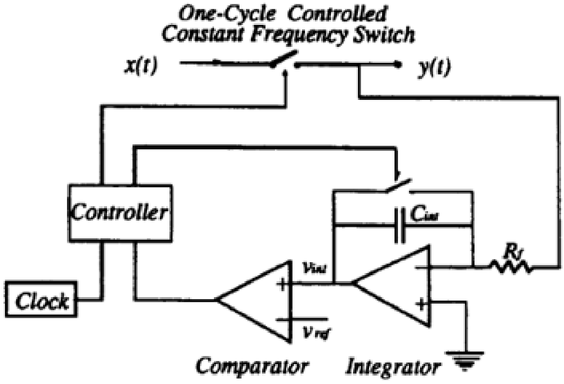

Fig 2.One cycle controlled constant frequency switch

Then the average value of the switched variable at the switch output is exactly equal to control reference in each cycle, since the switching period is constant. Therefore, the average of the switched variable is instantaneously controlled within one cycle [32].

$y(t) = 1/T_s \int x(t)\,dt = 1/Ts \int V_{ref}(t)\,dt = V_{ref}$ (10)

The technique to control switches according to this concept is defined as the One-Cycle Control technique. With One-Cycle Control, the effective output signal of the switch is

$y(t) = V_{ref}$ (11)

The switch fully rejects the input signal and linearly all-passes the control reference V_{ref}; therefore, the One-Cycle Control technique turns a non-linear switch into a linear path. The implementation circuit for One-Cycle Controlled constant-frequency switch is shown in Fig. 2. The key component of the One-Cycle Control technique is the integrator and the resetter. The integration starts the moment when the switch is turned on by the fixed frequency clock pulse [33]. The integration value,

$Vi_{nt} = k \int x(t)\,dt$ (12)

is compared with the control reference v_{ref} (t) instantaneously, where k is a constant. At the instant when the integration value V_{int} reaches the control reference v_{ref} (t),the controller sends a command to switch to change it from the on state to the off state. At the same time, the controller resets the integrator to zero. The duty ratio d of the present cycle is determined by the following equation

$k \int x(t)\,dt = V_{ref}(t)$ (13)

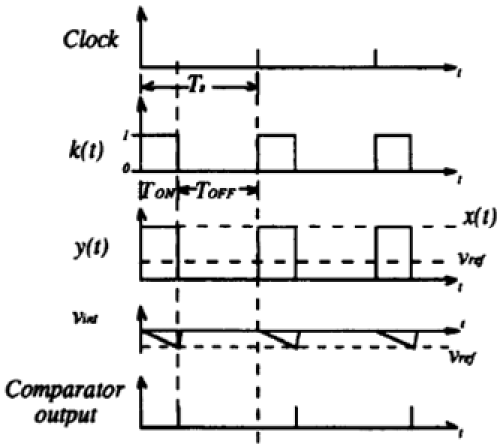

Fig.3 Waveform of one cycle controlled constant frequency switch

Since the switch period Ts is constant and K $1/T_s$ is a constant, the average value of the switched variables at the switch output y(t) is guaranteed to be $y(t) = 1/T_s \int x(t)\,dt = K\,V_{ref}$ in each cycle. Figure 4 shows the operating waveforms of the circuit when V_{ref}=constant

One Cycle Control for Double Input Buck Converter

OCC in Operating Mode I

In operating mode I, two duty cycles of the DIBC are used to regulate the input current of source 1 I_{in1} and the output voltage vo . According to (2), $i$in1 can only be controlled by $d_{y\,1}$.

So, $d_{y\,2}$ is assigned to regulate the output voltage. The control circuits of the OCC controllers are shown in Fig. 4, and the key waveforms are shown in Fig. 5.

OCC Controller of iin1:

As shown in Fig. 5(a), the OCC controller of iin1 consists of an integrator, an inverter, a comparator, a RS flip-flop, and a reset switch, where iin1 f is the sensed input current of the source 1 and the senor gain is k_{if} . A constant frequency clock turns ON Q_1 at the beginning of each switching cycle and activates the integrator simultaneously [34]. Thus, iin1 is integrated, i.e.,

$$i_{int}(t) = 1/(R_{int1}C_{int1}) \int k_{if}\, i_L(t)\, dt. \qquad (14)$$

The integral value i_{int} grows from zero, and when it reaches the control reference i_{ref} , the comparator changes its state and resets the RS flip-flop, and turns Q1 OFF. S_{r1} is turned on at the same time, and the integrator is reset to zero. $S_{r\,1}$ is kept ON until the next clock comes. The average value of iin1 in one switching cycle is

$$(i_{in1})Ts = 1/Ts \int i_L(t)\, dt = k_i\, i_{ref} \qquad (15)$$

where ki = $R_{int1}C_{int1}$ /(k_{if} Ts), and Ts is the switching period. Equation (15) indicates that the average value of iin1 exactly follows its control reference in a switching cycle. This means that OCC not only rejects perturbations from its own input source, but also totally rejects all the perturbations of the other input source, load current, and duty cycle $d_{y\,2}$. Moreover, no current regulator is required. It is noted that the input current reference i_{ref} is obtained from the MPPT controller.

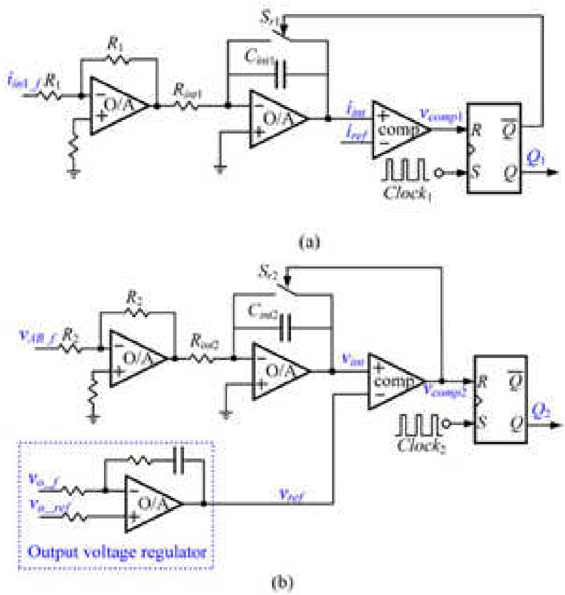

Fig. 4. Control circuit of OCC controllers in operating mode I. (a) OCC controller of *i*in1. (b) OCC controller of v_{AB}

OCC Controller of vAB :

As seen in Fig. 1, the average value of the voltage across points A and B v_{AB} is equal to the output voltage if the voltage drop of the filter inductor is neglected,so v_{AB} is chosen as the controlled variable to regulate the output voltage indirectly. As v_{AB} is determined both by dy 1 and dy 2, if v_{AB} is only integrated when the switch Q2 is conducting, the integral value does not represent the average value of v_{AB} . For the integrality of integration of v_{AB}, it is necessary to activate the integration immediately after the integrator being reset at the turn-OFF of Q2 . The circuit of OCC controller of v_{AB} is shown in Fig. 5(b), where v_{AB} f is the sensed signal of v_{AB} , and the sensor gain is k_{vf} . Unlike the OCC controller of ii_{n1} , the reset signal of the integrator is the output of the comparator, which is a narrow pulse signal. The constant frequency clock turns ON Q2 at the beginning of each switching cycle. The integrator for v_{AB} is activated at the turn OFF instant of Q2 in the last switching cycle. Thus, v_{AB} is integrated, i.e.,

$v_{int}(t) = 1/(R_{int2}C_{int2})\int k_{vf}\, v_{AB}(t)\, dt.$ (16)

When the integral value v_{int} reaches the control reference vr_{ef} , the comparator changes its state and turns Q2 OFF, and the integrator is reset to zero at the same time. Because the reset signal is a pulse with very short width, the reset time is very short, and the integration is activated immediately after there setting. Thus, we have

$(v_{AB})Ts = 1/Ts \int v_{AB}(t)\, dt = k_v v_{ref}$ (17)

where $k_v = R_{int2}C_{int2} / (k_{vf}\, Ts)$.

Equation (17) indicates that the average value of v_{AB} exactly follows its control reference in a switching cycle. Specifically, not only does it rejects perturbations from its own input sources, but also totally rejects all the perturbations of the other input source, load current, and the duty cycle of dy 1 . The output voltage v_o is not the actual average value of v_{AB} due to the voltage drop across the filter inductor, so a voltage regulator is necessary to guarantee well-regulated output voltage. The voltage reference of this regulator is v_o ref and its output v_{ref} serves as the reference for the OCC controller of v_{AB} .

OCC in Operating Mode II

In operating mode II, the output power is only provided by input source 1, and input source 2 is shut down. In other words, Q2 is turned OFF, $d_{y\,2}$ is equal to zero, and the OCC controller of v_{AB} takes over the control of the switch Q1 instead of the OCC controller of i_{in1} in operating mode I. The circuit of the OCC controller in operating mode II and the key waveforms are shown in Fig. 6, which is similar to the OCC controller of v_{AB} in operating mode I, and the only difference is that the output of the controller is used to control $d_{y\,1}$.

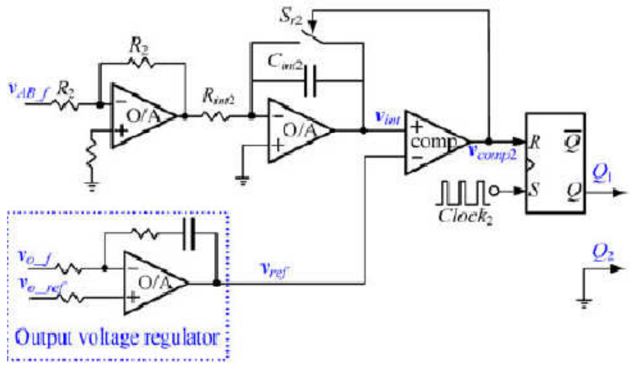

Fig 5 Control circuit in operating mode 11

A. **Mode Transitions**

As can be seen in Figs. 5 and 6, the two switches are controlled by different OCC controllers in different operating modes, so the mode transition circuit is required. The simplest method is to add a multiplexer, as shown in Fig. 7.When the enable signal of the multiplexer EN is low, Ao = AX, Bo = BX, so the switch Q1 is controlled by the OCC controller of iin1 and the switch Q2 is controlled by the OCC controller of v_{AB} . When the enable signal EN goes high, Ao = AY, Bo = BY; at this time, the switch *Q*1 is controlled by the OCC controller of v_{AB} and the switch *Q*2 is shut down completely. The key issue is how to select the appropriate control signal to change the state of EN to realize seamless mode transition, according to the available renewable energy and the output power. Because the output voltage of the DIBC is kept constant, v_{ref} , the output of the voltage regulator at the steady state is the same in different operating modes. When *P*1max < *Po*, the DIBC is operated in operating mode I If the available power of the input source 1 increases or the load current reduces suddenly, which leads to *P*1max > *Po* , the output voltage will increase, and thus, the output of the voltage regulator v_{ref} will keep on reducing until the DIBC is switched to operating mode II.

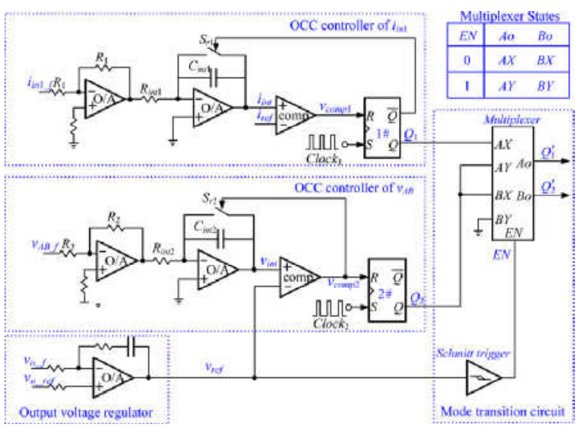

Fig 6 OCC circuit with multiple operating modes

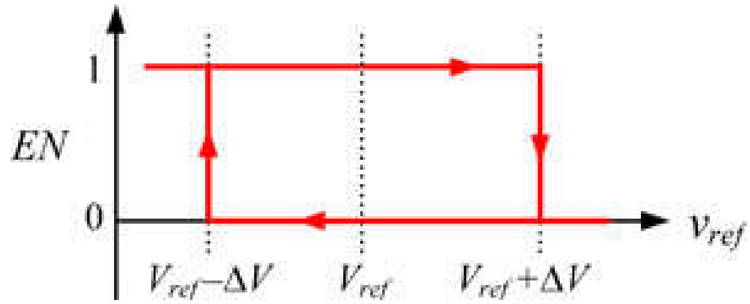

Fig 7 Characteristics of Schmitt trigger

Then the output voltage is regulated to reduce to the reference, and v_{ref} also restores to its steady-state value V_{ref} , which is proportional to the output voltage. Similarly, when $P_{1max} > P_o$, the DIBC is operated in operating mode II, if the available power of the input source 1 falls or the load current increases, which makes $P_{1max} < P_o$, the output voltage will keep on reducing, and thus, the output of the voltage regulator v_{ref} will keep on increasing, until the DIBC is switched to operating mode I. Then the output voltage is regulated to increase to the reference, and v_{ref} also restores to its steady-state value V_{ref} . From the aforementioned analysis, it is known that the output of the voltage regulator v_{ref} will experience a very short downward pulse when the DIBC changes from operating mode I to operating mode II. On the contrary, v_{ref} will experience a very short upward pulse when the DIBC changes from operating mode II to operating mode I. According to this, the enable signal EN can be obtained by sending v_{ref} to a Schmitt trigger, as shown in Fig. 8. The center and width of the hysteresis are set at V_{ref} and ΔV, respectively, as shown in Fig. 8. After adopting the Schmitt trigger, EN remains low in operating mode I and high in operating mode II at steady state due to setting of the hysteresis width ΔV. During the mode transition, v_{ref} will keep on changing until it reaches the threshold that is determined by ΔV, and this transient behavior helps to change the state of EN, as shown in Fig. 10. It can be seen that this transient behavior is not sensitive to the value of ΔV. In other words, v_{ref} can always touch the threshold no matter how much the value of ΔV is.

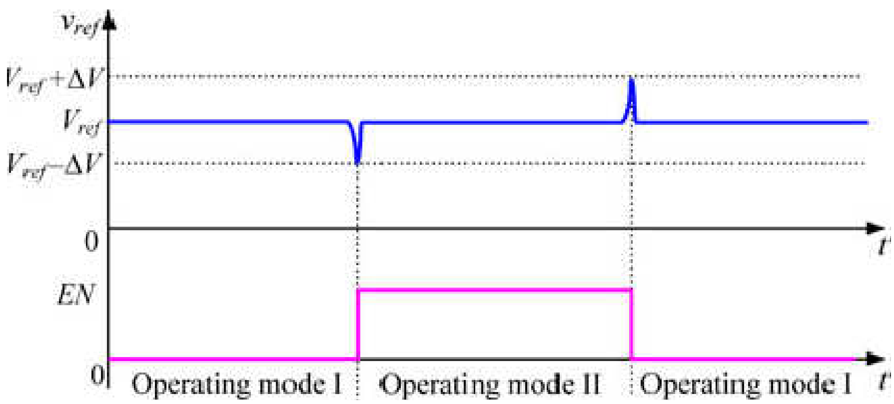

Fig 8 Transient of V_{ref} during the mode transition

Experimental Setup and Results

An 800-W prototype of the DIBC has been built to verify the effectiveness of the proposed OCC method and the design of the output voltage regulator. PV arrays and the rectified commercial grid serve as the main power source and the backup power source, respectively. The block diagram of the whole experimental system is shown in Fig. 9. The specifications of the prototype are listed as follows.

1) Input source 1: PV arrays formed by eight series connected SUNTECH solar panel switch rated short-circuit current 5 A, open-circuit voltage 350V, and maximum output power 950W. The input voltage Vin1 =200–350 VDC.

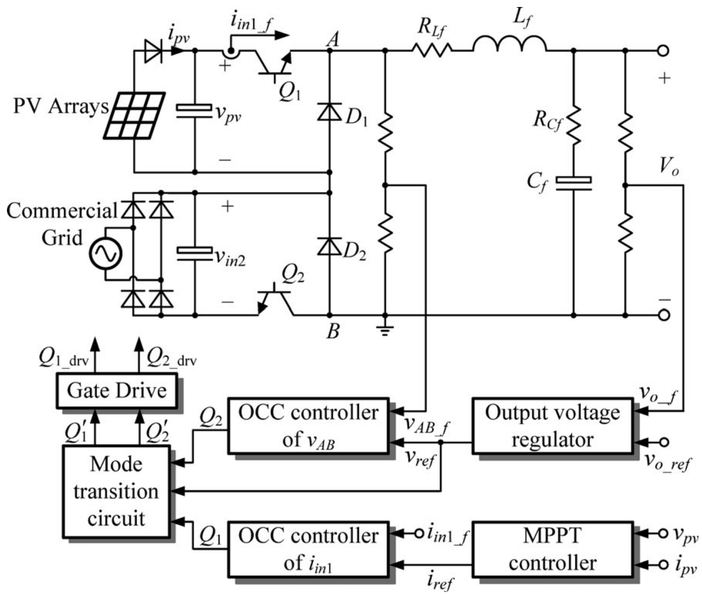

Fig. 9 Block diagram of the whole experimental system

2) Input source 2: Rectified 220 VAC/50Hz commercial grid with +/-10% voltage variations. The input voltage Vin2 =311 VDC +/-10%.
3) Output voltage: Vo = 180 VDC.
4) Output power: Po = 800W.
5) Switching frequency: fs = 100 kHz.

The key power components and the parameters of OCC controllers are listed as follows.

1) Output filter inductor: Lf = 1.38 mH with RLf = 0.2 Ω.
2) filter capacitor: Cf = 220 μF with RCf = 0.29 Ω.
3) Integration factor of OCC controller of vAB : kv = 70.
4) Integration factor of OCC controller of $i$in1 : ki = 1.
5) Sensor gain of output voltage: kf = 0.03.

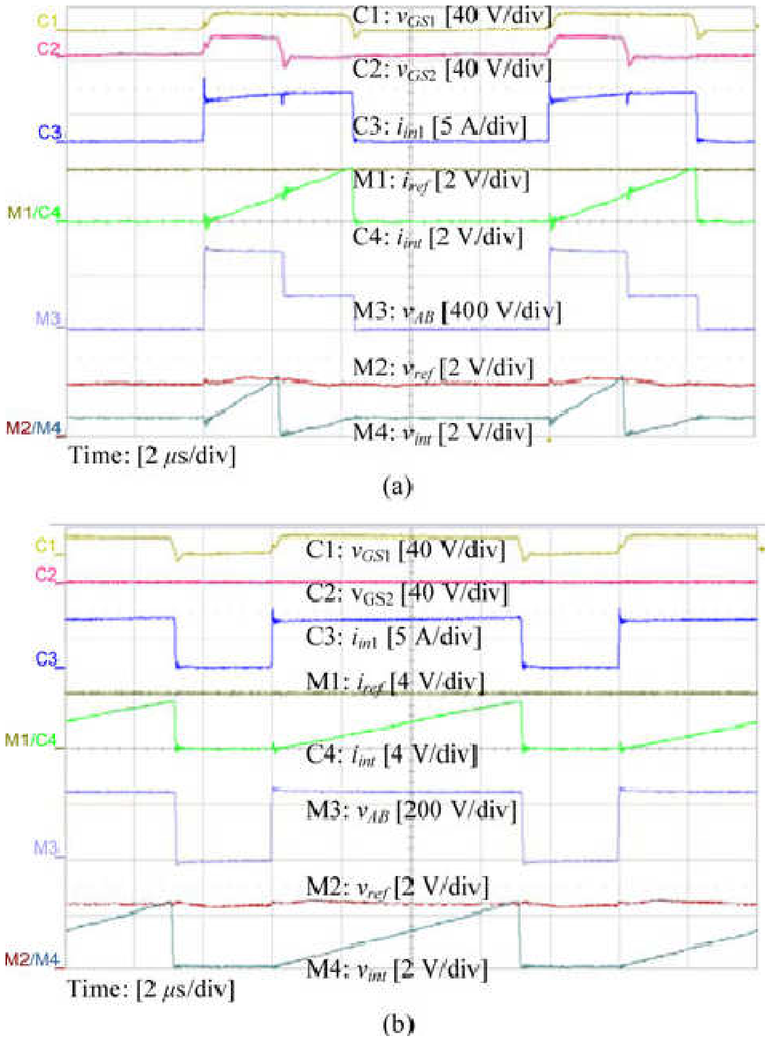

Fig 10 Experimental result under (a) mode 1 and (b) mode 11

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