One-Cycle Controller for renewable energy conversion systems

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The One-Cycle Control (OCC) technique [1,2] developed in the UCI Power Electronics Laboratory is a simple and powerful method for renewable power conversion. OCC performs pulse-width modulation and sawtooth slope modulation in one go, which results in accurate, fast, and stable control of nonlinear switching dynamics.

As shown in Figure 1 for a basic OCC core, the clock generates a periodic pulse train that sets the flop/flop at the beginning of the each switching cycle, and signal v_2 at the input of the integrator is integrated and the output value is compared to signal v_1, where the bandwidth of v_1 and v_2 are far below the switching frequency. When signals at the two inputs of the comparator meet, it changes its state, which in turn resets the flip/flop and the integrator. This operation can be expressed below:

$$-\frac{1}{RC}\int_0^{dT} v_2 dt = v_1 \qquad (1)$$

where "T" is the switching period and "d" is the duty ratio (the on time of the switch versus the switching period), R and C are the value of the resistor and capacitor of the integrator respectively. This process repeats cycle by cycle adjusting the duty ratio of the switch such that the chopped signal of v_2 has an average equal to or proportional to signal v_1. Without loss of generality, if the integration constant is chosen the same as the switching period, the switching cycle average of the chopped signal of v_2 equals signal v_1. In other words, the duty ratio is modulated as

$$-v_2 d = v_1 \qquad (2)$$

Equation (2) establishes a solution for the first-order polynomial function of duty ratio d. Researchers at UCI [3-] revealed that the control functions of most switching converters, such as inverters, PFC rectifiers, active power filters, and VAR generators, are all first order polynomial equations; this discovery thus opened up a wide range of applications for OCC. In fact, all these applications can be generalized into real "P" and reactive "Q" power flow in forward or backward direction; therefore, an OCC controller with four-quadrant P and Q capability can provide universal control of converters for all these applications. In the following context, several examples for renewable energy conversion are highlighted.

Renewable energy generated from solar panels and wind turbines is wild in nature. A dc/ac or ac /ac converter is required to convert the solar power or wind power respectively to that acceptable to the power grid, where the ac/ac converter can be realized by ac/dc and dc/ac back-to-back combo. In both cases, maximum power point tracking (MPPT) is desirable to maximize the power extraction.

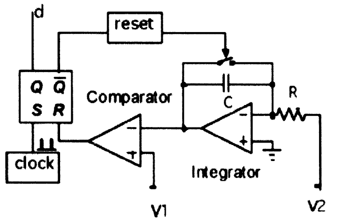
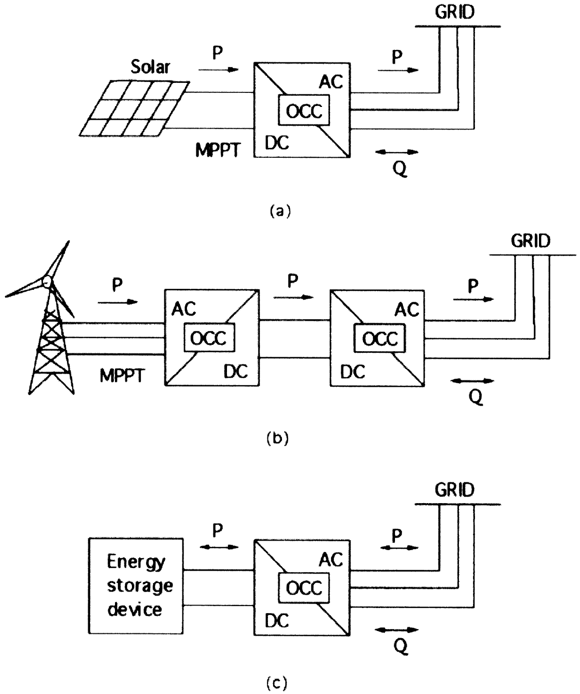


Figure 1. One-Cycle Control core

Considering the future power grid with high percentage of renewable power injection, additional reactive power (VAR) generation capability is necessary for power flow control, voltage support, and grid stabilization. Furthermore, energy storage is needed for balancing the supply and demand. With all these features in mind for modern grid applications, OCC provides a powerful solution as illustrated in Figure 2.

Fig. 2(a) and (b) show power flow from the solar panel and wind generator respectively via the OCC converters to the power grid with MPPT energy extraction and dynamic VAR generation, while Fig. 2(c), bidirectional power between the grid and the energy storage device with dynamic VAR as well. Although shown in the examples is a three-phase power grid, experimental results have been recorded for single-phase system as well at UCI[8,14].



(a)

(b)

(c)

Figure 2. Examples of One-Cycle Control renewable power converters.

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Article [14] presents an example of 600W single-phase solar inverter. An H-bridge is used as the power stage. Without getting into the details of the derivation, the control equation is rewritten below:

$$\begin{cases} R_S \cdot i_o - K \cdot V_o = -(V_c - K_g V_g) \cdot d_a \\ d_b = 1 \end{cases} \tag{3}$$

where, V_g and V_o are the input dc and the output of ac voltages, K and K_g are constants, d_a and d_b are duty ratios for designated switches as given by Table I, and V_c is the control reference.

TABLE I: CROSS-REFERENCE OF D_A AND D_B IN THE TWO REGIONS OF A LINE CYCLE.

Region	d_a	d_b
0~180	d_1	d_3
180-360	d_2	d_4

This control equation guarantees MPPT at the dc side and unity power factor current injection at the ac side. Since the control equation is a first order polynomial, it can be implemented by OCC as shown in Fig. 3. Experiments in the laboratory have yielded satisfactory result for solar power conversion as shown in Fig. 4. Due to the mounting angle of the solar panel, the peak power did not occur at noon. The extracted power is very close to the maximum power with 5% error near the peak.

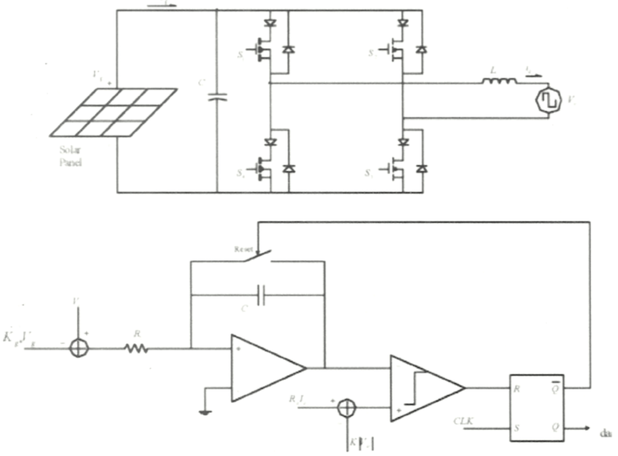

Figure 3. Circuit diagram of single-phase solar inverter with MPPT input and unity power factor output.

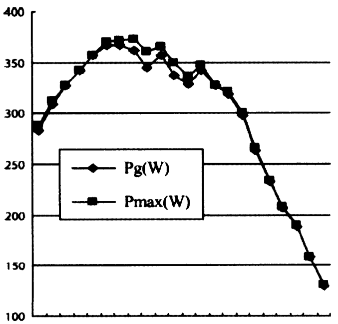

Figure 4. Experimental result of MPPT.

Fig. 5. Shows another example of three-phase inverter with dynamic VAR generation capability. A six-switch bridge is employed as the power stage. The control equation matrix was derived in [11], which is rewritten below:

$$\begin{cases} V_m \begin{bmatrix} 1-d_p \\ 1-d_n \end{bmatrix} = \begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix} \cdot \left(\begin{bmatrix} R_s \cdot i_p \\ R_s \cdot i_n \end{bmatrix} + ke^{j\theta} \begin{bmatrix} v_p \\ v_n \end{bmatrix} \right) \\ d_t = 1 \end{cases} \tag{4}$$

where d_p, d_n, d_t, V_p, V_n, i_p, and i_n are given by Table II, $\theta \in (\frac{\pi}{2}, \frac{3\pi}{2})$, k and V_m are constant, and Rs is the sensing resistance.

The control equation matrix is in the format of first order polynomial, thus the OCC method is also applicable. The circuit diagram of the grid-tied inverter with VAR is shown in Fig. 5. In addition to injecting active current to the grid, it can also provide VAR on demand. A 5kVA prototype shown in Fig. 6 was developed by One-Cycle Control, Inc. under the sponsorship of US Department of Energy, which has demonstrated the dynamic P and Q generation capability, as shown in Figure 7. It is clear from the waveforms that the phase currents have a phase shift from the associated phase voltages. This phase shift can be accurately controlled in the range of $\frac{\pi}{2}$ to $\frac{3\pi}{2}$ to respond to the demand of the power grid. Furthermore, Accurate and fast dynamic VAR generation is measured as shown in Fig. 8.

TABLE II:
CROSS-REFERENCE OF v_p, v_n, i_p, i_n, d_p, d_n, d_t IN ALL SIX REGIONS OF A LINE CYCLE.

Region	v_p	v_n	i_p	i_n	d_p	d_n	d_t
0~60	v_a	v_c	i_a	i_c	d_{an}	d_{cn}	d_{bn}
60~120	$-v_b$	$-v_c$	$-i_b$	$-i_c$	d_{bp}	d_{cp}	d_{ap}
120~180	v_b	v_a	i_b	i_a	d_{bn}	d_{an}	d_{cn}
180~240	$-v_c$	$-v_a$	$-i_c$	$-i_a$	d_{cp}	d_{ap}	d_{bp}
240~300	v_c	v_b	i_c	i_b	d_{cn}	d_{an}	d_{an}
300~360	$-v_a$	$-v_b$	$-i_a$	$-i_b$	d_{ap}	d_{bp}	d_{cp}

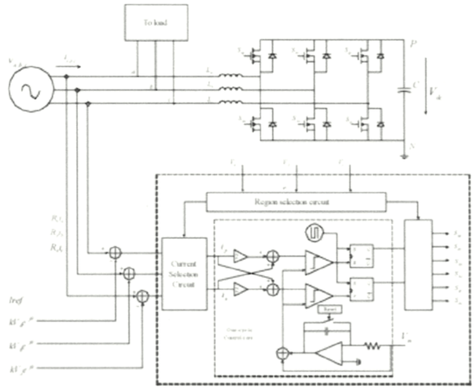

Figure 5. Circuit diagram of OCC-enabled grid-tied inverter with dynamic VAR generation.

Figure 6. Grid-tied inverter with VAR generation (5kVA), courtesy of One-Cycle Control, Inc.

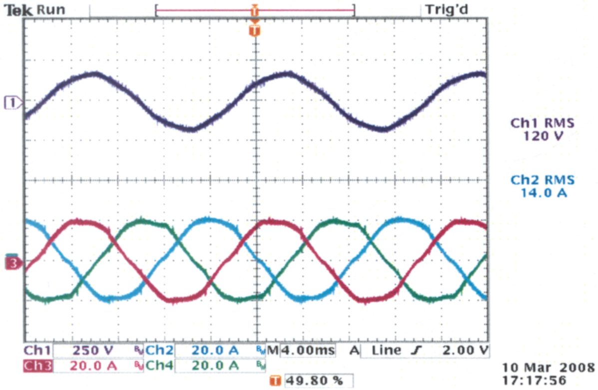

Figure 7. The measured phase A voltage and phase A, B, C currents with combined P and Q at 250V and 20A/div, courtesy of One-Cycle Control, Inc.

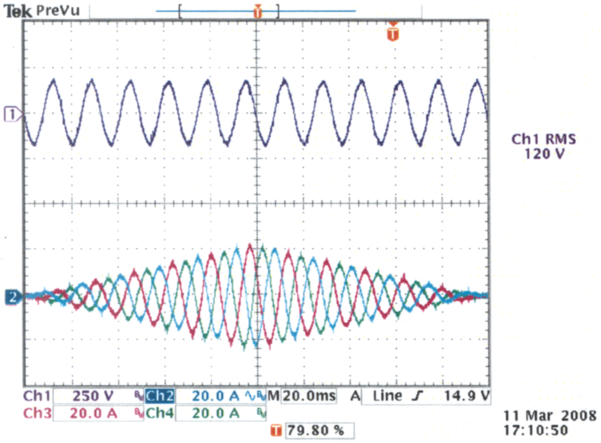

Figure 8. The measured phase A voltage and phase A, B, C currents featuring dynamic Q at 250V and 20A/div, Courtesy of One-Cycle Control, Inc.

OCC method is universal and implementation is simple. From the studies of UCI power electronics laboratory, it is evident that OCC has following capabilities. (1) Simple circuitry composed of an integrator with reset along with a few linear and logic components to realize the control. Thus no DSP and software is required in the control loop. If desire, a micro controller can be used for supervisory control. (2) Fast dynamic response because the inner current control loop is embedded in the PWM modulator so as to have a dynamic response in the speed of a switching cycle. Consequently, power conversion at wide line frequency range 0-1kHz is achievable with low total harmonic distortion in the line current. This feature is very desirable for airplane, space, and ship applications, where high frequency power grid is used. (3) Control of two and three level converters as well as Hexagram converters [20] to handle low voltage (200V, 480V) and medium voltage (2.3kV, 4.6kV) applications. (4) Robust and stable operation with solid global convergence to ensure dynamic stability and smooth transient. (5) Operation under balanced or unbalanced grid voltage and load conditions. (6) Universal control of PFC rectifier, active power filter, VAR generator, grid-tied inverter, and non-grid-tied inverter applications. As the direct benefit, combination of two, three, four, even five functions in one converter is made possible. For example, a bidirectional PFC rectifier for energy storage conversion could also have VAR generation and line harmonic cancellation capabilities (4 functions). This feature provides ultimate flexibility and enables previously unimaginable converters for modern grid applications.

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