One-Cycle Control and Its Applications in Distributed Generation

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Abstract—Distributed generation (DG) with renewable energy sources is a trend, and power electronics is the key enabling technology for the successful deployment of DG. One-Cycle Control(OCC) provides a universal method to control MOSFET, IGBT, or GTO modules to realize power electronic functions such as inverters, FACTS, APF, PFC, etc. for distributed generation. Due to its fast response speed, circuit simplicity, and universal adaptability, OCC promises excellent performance, lower cost, and high reliability. This paper demonstrates a few examples of One-Cycle Controlled power electronics for distributed generation applications.

I. Introduction

Energy is the vital force that powers our businesses, services, homes, manufacturing, transportation, and defense systems. In recent years, the demand for energy has been increasing rapidly due to the growth of world population and technologies, which has not only posted a serious threat to our future energy reserve, but also has been causing detrimental effects on our environment by releasing harmful pollutants. According to the Department of Energy[1], about 60% of the world's energy consumption in 2001 was from fossil fuel and resulted in the emission of 6.5 billion metric tons of CO_2 into the atmosphere. It has become a pressing issue how to reliably supply future energy needs without environmentally harmful pollution and global warming.

In the United States, about 40% of the total energy consumption is used to generate electricity. Typically, electric power is generated by inefficiently burning of fossil fuel in centralized power generation facilities and the electricity is then delivered to users thorough out the country via thousands of miles of transmission grid as shown in Figure 1 that introduce resistive energy losses. Furthermore, due to extensive use of electronic and motor loads, significant harmonic and reactive currents are drawn from the transmission lines that further decrease transmission efficiency and reduce the system capacity. Our present power system has been up, running, and serving America for about one hundred years while evolving from isolated systems to the interconnected grid. Although generation and transmission capacities have been continuously added to the system in response to the demand, the infrastructure itself and the technologies used have had insignificant changes over the last two decades.

It is quite clear that the margin between the energy supply and the peak demand has become dangerously small, particularly in light of the energy shortage that occurred two years ago in California. It is also clear, that the technologies for controlling and protecting the power system have been inadequate, as shown in the greatest blackout in US history that occurred on August 14, 2003. It is an urgent task to renovate our power system so that it uses more renewable energy sources, has better generation and transmission efficiency, and is more stable and reliable. More efficient energy use can extend the present energy supply to accommodate growing demand, while exploitation of renewable energy sources can expand the clean-energy supply and displace less desirable energy sources. California has mandated that its three investor-owned utilities obtain 20% of their power from renewable sources by 2017; almost double the present 11%. This push clearly dictates increasing the number of power sources and therefore the complexity of the delicate balance of the grid and its sensitivity to the destabilizing effects of power quality.

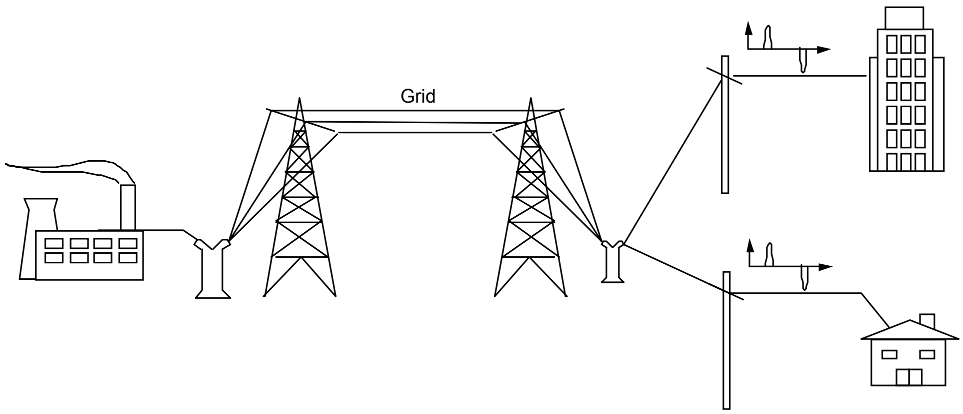

Figure 1. Present power system with centralized generation.

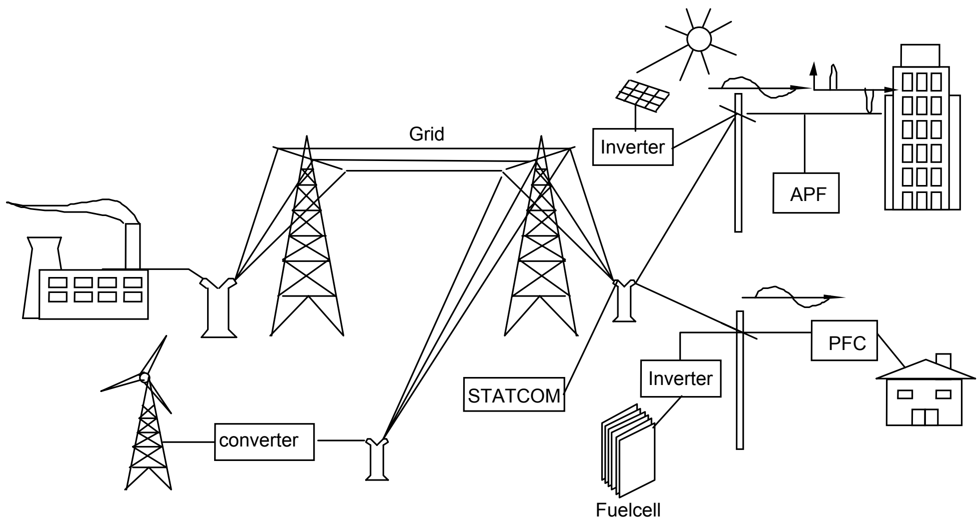

Figure 2. Future power system with centralized and distributed generation.

Most DG sources, both renewable (solar cells, wind power, etc.) and nonrenewable (fuel cells) generate electricity in a format that our present power transmission systems cannot accept; therefore, inverters and frequency converters must be used to convert the generated power. Furthermore, with many distributed power sources in the system, power electronic unified flow controllers are necessary to ensure the generated power flows through the grid to the point when and where it is needed. It is advantageous to use flexible ac transmission system (FACTS) components to damp and isolate the power system oscillations as well as swells/sags. In addition, near unity power factor (current in phase with voltage) and a zero harmonics environment must be maintained using active power filters (APF) and power factor corrected (PFC) rectifiers to ensure low transmission losses and safe operation of user equipment. In summary, power electronics is the key enabling technology for the successful commercialization of DG as shown in Figure 2. Industries are positioning for this new paradigm shift in energy; Darnell Group projects that the market for DG power electronics will increase by 25% to exceed \$5 billion annually by 2008[2].

Silicon has brought forth a complete revolution in the area of signal processing as shown by the blooming of computation and communication technologies. Silicon has also been extensively used for low power processing in the user side such as dc/dc, ac/ac converters. In comparison, the amount silicon used in the power system is pathetic. Silicon has proven advantages in speed, controllability, and power density; it is time for a silicon revolution in power systems. All of the necessary power electronics could potentially be realized in silicon, but the major roadblocks are cost and complexity, because there has not been a universal and simple power electronics method so custom designs are required for each application. In this paper, a universal controller—One-Cycle Control is described that can be used to configure IGBT modules into inverters, active power filters (APF), FACTS components, or power factor corrected (PFC) rectifiers as needed for distributed generation systems. Unification of these functions with a universal controller chip shall initiate and enable a new paradigm of siliconized power systems.

II. One-Cycle Control

Circuits for power processing are usually based on switching technology due to their efficiency advantage. A switching converter is commonly controlled by modulating the duty ratio of its switches, the ratio of the on time verses the switching period, according to a control function. Traditionally, feedback and/or feedforward signals are channeled through a controller to generate a modulation signal, then pulse-width modulation (PWM) is realized by comparing the modulation signal with a periodic sawtooth or triangular waveform; as a result, the generated triggering pulse has a duty ratio that is linearly related to the modulation signal, while the controlled variables usually have nonlinear relationships with the modulation signal due to the nonlinearity of the switching circuits. In this approach, the frequency spectrum of the modulation signal is much lower than the switching signal, e.g. ten times or more in engineering practice; therefore, the control speed is limited. Furthermore, since the control function is usually implemented by analog computation, the type of functions are limited, and so is the performance. In order to achieve more sophisticated control functions, the continuous feedback/forward signals are digitized, and then a digital signal processor (DSP) is used to program the control function. In this process, the control speed is further reduced by sampling and computation time. In a system with multiple loops, the inner loop must have a bandwidth much lower than the switching frequency, and the outer loop must be even slower than the inner one. As the consequence, one or more of the following can happen, the bandwidths of the loops are too close to one another to work properly. If sufficient clearance is placed between the two loops, the over response speed could be too slow to perform a job properly. Either of these cases could result in instability. The nonlinearity of the converter itself is also on the other side of the game table. It is not rare that researchers and designers spend years to figure out how to realize a control function for a particular application, which leads to high cost and nonstandard design. For some applications, such as three phase active power filters, only a few people in the world have sufficient extensive training to do the job.

In the low power area, Unitrod introduced some integrated circuit chips for dc/dc converters based on the traditional PWM approach and later a few more-advanced chips also appeared in the market, which has standardized the PWM design and reduced the design cycle dramatically. However, for high power applications, such as three phase PFC, APF, inverters, and FACTS components, the control functions are getting much more complicated by using the traditional PWM method. The published approaches are only case-by-case to solve some particular applications under certain operating conditions.

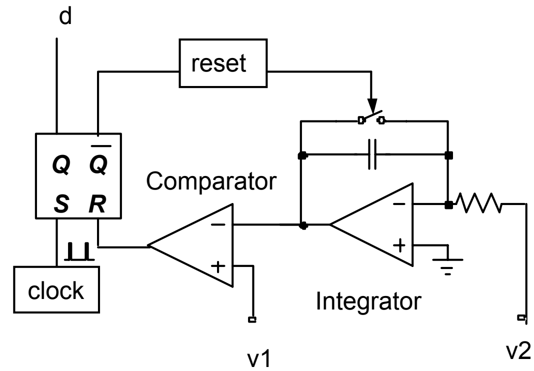

Figure 3. One-Cycle Control core

One-Cycle Control (OCC) is a nonlinear pulse-width modulation method. In contrast to the traditional PWM method, OCC control realizes PWM and a fast/nonlinear control in one go by modulating the slope of the sawtooth waveform. The implementation circuit is very simple and yet universal. In Figure 3, a basic control core is shown. A clock generates a periodic pulse train that sets the flop/flop at the beginning of the each switching cycle. Signal v2, at the input of the integrator, is integrated and the output value is compared to signal v1. When both signals at the two inputs of the comparator approach one another, the comparator changes its state, which in turn resets the flip/flop and the integrator to zero. This process repeats each switching cycle. With this OCC circuit, the duty ratio of the switch is controlled such that the chopped signal of v2 has an average in each switching cycle that is equal to or proportional to signal v1. Without loss of generality, if the integration constant is chosen to be the same as the switching period, the average of the chopped signal of v2 in each switching cycle is equal to signal v1. In other words, the duty ratio is modulated as

$V_2 d = V_1$ **--(1)**

Here a first order polynomial function of d is realized. Research at UCI [6,7,8,9,10,11,12,13] have demonstrated the control functions of most practical switching converters, inverters, rectifiers, active power filters, and FACTS components are first order polynomial equations. Therefore, the One-Cycle Control core can realize these pulse width modulation functions. A universal control chip is possible to control the listed DG power electronics equipment with much simpler circuit, could be several orders simpler, than previously proposed methods. With this One-Cycle Control chip, unified modular design of the DG equipment shall become reality. Following is a list of some examples of One-Cycle Control.

III. One Cycle Control of active power filters

Electronic loads using traditional diode and thyristor rectifiers draw pulsed current, motor-type loads draw reactive power from the ac main, and some low speed inverters and FACTS equipment also inject harmonics to the power lines causing significant reactive and harmonic current circulation in the transmission line that increase the transmission power losses and reduces the system capacity. Active power filters and power factor corrected rectifiers are some of the effective methods for harmonic and reactive current elimination.

Active power filters (APF), shunt or series, are devices that eliminate the reactive and harmonic components in the power line, so as to improve the power system transmission efficiency and capability. A shunt APF, for example, is in parallel with the nonlinear load and provides only the harmonic and reactive power to cancel the one generated by the nonlinear loads or sources. Active power filters can handle higher power so that they can be used in the user side or in the system side. A typical shunt APF is composed of a voltage source inverter (VSI) and control circuitry. Most previously reported control approaches need to sense the input voltage and the load current and then calculate the harmonics and reactive components in the load current in order to generate the reference for the VSI. In addition, dq conversion is needed in the control unit. Those control methods require fast real-time calculation so that a high-speed digital microprocessor and high performance A/D converters are necessary, which yields high complexity and cost. In contrast to previously proposed methods, the One-Cycle Control active power filter method developed at UCI has no need to calculate the harmonics of the load current in order to generate the reference for the control of the APF current. The control circuit is comprised of an integrator with reset, a clock, two comparators, and two flip/flops along with a few linear and digital components. It provides a low cost and high performance solution for power quality control. The three-phase APF with OCC control works in either symmetric or asymmetric power systems and with balanced or unbalanced loads.

A typical power stage of the APF uses a voltage source inverter, which is connected in parallel to the load as shown in Figure 1(a). A capacitor on the dc side is used to sink or source the harmonic and reactive current components. The capacitor voltage is constant in the steady state since there is no real power flow. Traditionally, the load currents are sensed to calculate the harmonic contents, which in turn is used as the reference to control the VSI to produce harmonics of equal amplitude but opposite direction that cancel the ones from the loads. For three phase system, there are two independent control variables, dq conversion is often used to control the six switches. The computations for the reference and the control are very intensive and require high speed A/D conversion and high speed DSP due to the real time requirement.

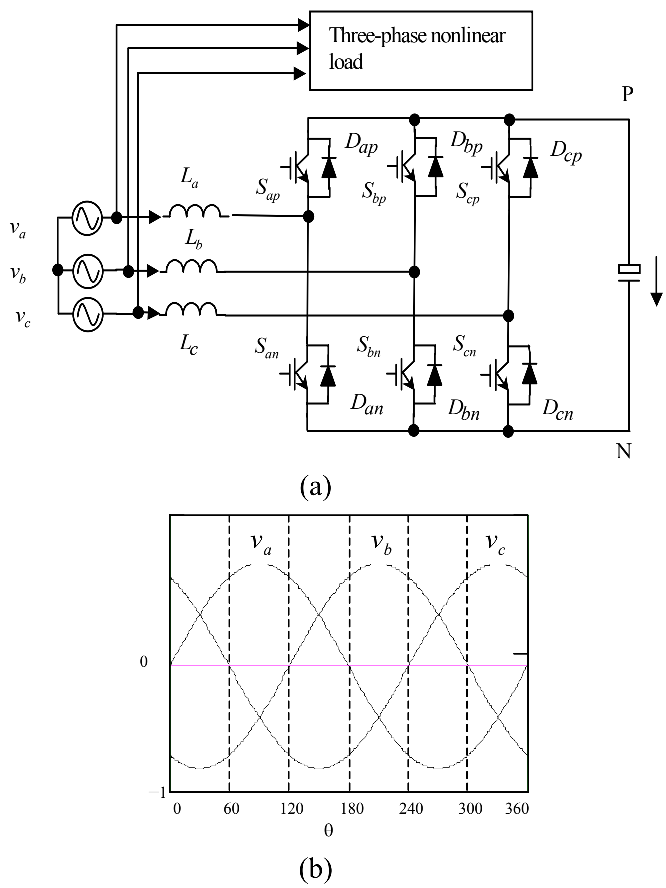

Figure 4. A voltage source inverter as the power stage of a shunt APF (a) and the normalized phase voltage waveforms of the power grid (b).

With OCC control, a three phase system is decomposed into a dual boost dc/dc converter by dividing the line period into six equal regions as shown in Figure 1(b). In the 0-60° region, the grid voltages of phase A and phase C are higher than phase B. The upper switch of phase B is kept off while the lower switches, on in the entire region so that the VSI is equivalent to a parallel connected dual boost converter with a conversion gain of

$$\begin{bmatrix} 1-d_{an} \\ 1-d_{cn} \end{bmatrix} = \begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix} \cdot \begin{bmatrix} \frac{V_a}{E} \\ \frac{V_c}{E} \end{bmatrix} \text{------------------------}(2)$$

In order to avoid the calculation of harmonic currents, the control goal is set as

$$\begin{bmatrix} \boldsymbol{v_a} \\ \boldsymbol{v_c} \end{bmatrix} = \boldsymbol{R_e} \cdot \begin{bmatrix} \boldsymbol{i_a} \\ \boldsymbol{i_c} \end{bmatrix} \text{--------------------------------}(3)$$

while $v_b = R_e i_b$ is automatically realized, since $i_a + i_b + i_c = 0$. Combining the control goal and the dual boost conversion ratio, a control key equation matrix is derived below,

$$\begin{cases} V_m \cdot \begin{bmatrix} 1-d_p \\ 1-d_n \end{bmatrix} = R_s \cdot \begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix} \cdot \begin{bmatrix} i_p \\ i_n \end{bmatrix} \\ d_t = 1 \end{cases} \text{------------}(4)$$

where Re is the emulated resistance that reflects the real power of the load, and *Rs* is the sensing resistance, $V_m = \frac{E \cdot R_s}{R_e}$, $d_p = d_{an}$, $d_n = d_{cn}$, $d_t = d_{bn}$, $i_p = i_a$, $i_n = i_c$. With a similar procedure, the control key equation matrix is found to be the same for the other five regions, where d_p, d_n, d_t, i_p, and i_n are given by TABLE I.

TABLE I: Cross-reference of i_p, i_n, d_p, d_n, d_t in all six regions of a line cycle.

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

Since the control key equation is a polynomial equation matrix of duty ratios d_{an} and d_{cn}, it can be

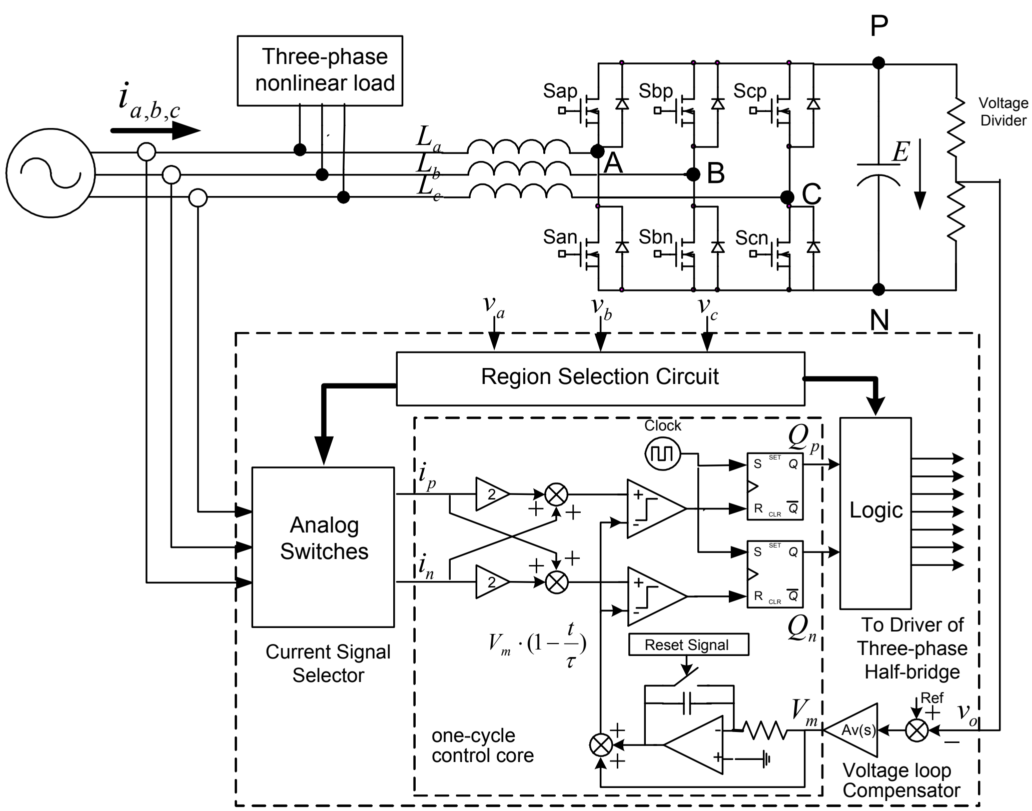

Figure 5. OCC-APF

realized by the One-Cycle Control core. Considering the fact that the sensed currents and the triggered switches are different for each region, the zero-crossing points of the phase voltages are sensed to generate a region signal, which is used to rotate a multiplexer to select the right current for a given region and to direct the duty ratio signals calculated by the OCC core to the right switches as shown in Figure 5.

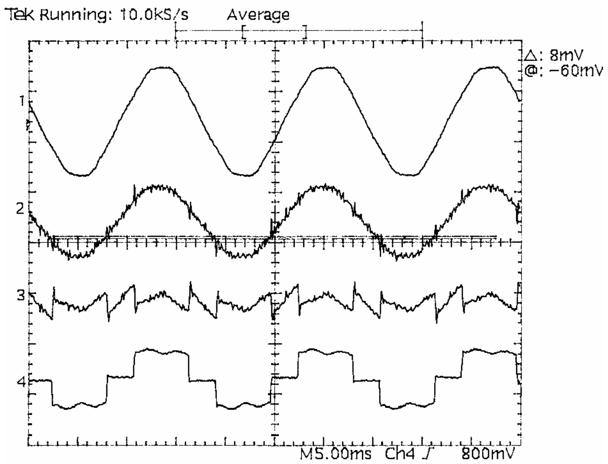

Figure 6. Experimental results for OCC-APF: curve 1 phase voltage at 10V/div, curve 2 line current, curve 3 the harmonic current generated by APF, and curve 4 the load current all for phase A. All currents are measured at 2A/div.

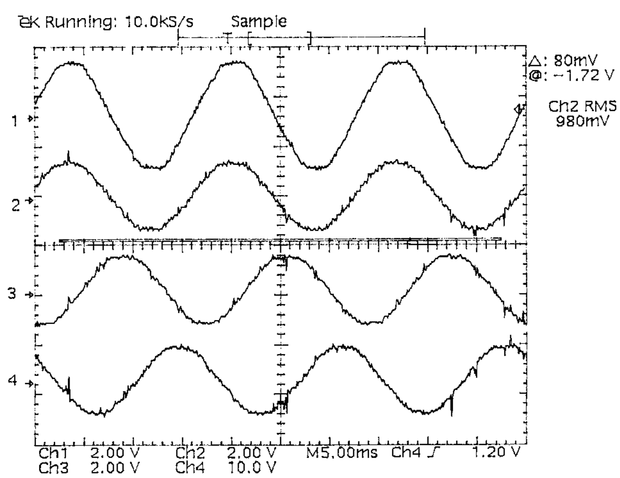

Figure 7. Experimental results for OCC-APF: curve 1, phave A voltage measured via a transformer, curve 2, 3, and 4 the line currents for all three phases at 2A/div.

Prototypes with 1kVA and 5kVA capacities were built at the UCI Power Electronics Laboratory for the verification of the concept. Figure 6 shows the experimental results for phase A voltage, line current, the APF current, and the load current. It is clear that the APF current effectively cancels the harmonics in the load, so the line current is sinusoidal with THD below 5%. Figure 7 shows that the line currents of all three phases are sinusoidal. Figure 8 shows the system performance when the line voltages are asymmetric. The experiments have demonstrated that the OCC-APF can eliminate the line current harmonics for symmetric or asymmetric power system, and for balanced or unbalanced loads.

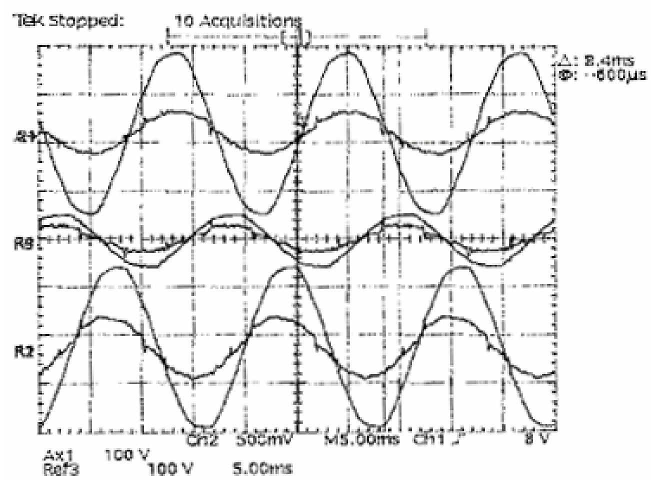

Figure 8. Experimatal results for OCC-APF: the ac main phase voltages and currents for all phases with asymmetric main where Va=120V, Vb=40V, and Vc=120V. All voltages are measured at 100V/div and all currents, 2A/div

IV. One Cycle Control of power factor corrected rectifiers

Articles [6,7,14] have shown numerous three-phase topologies for rectification. Those with a single capacitor output rail are suitable for high current operation while the others with split rails over two capacitors are suitable for high voltage operation. Unified control of these rectifiers was established based on the One-Cycle Control method[6.7]. In this paper, an example of a standard bridge rectifier is provided. Using the same procedure, a control key equation matrix is derived below,

$$\begin{cases} V_m \cdot \begin{bmatrix} 1-d_p \\ 1-d_n \end{bmatrix} = R_s \cdot \begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix} \cdot \begin{bmatrix} i_p \\ i_n \end{bmatrix} \\ d_t = 1 \end{cases} \text{--------------(5)}$$

where d_p, d_n, d_t, i_p, and i_n are given by TABLE I, $V_m = \dfrac{E \cdot R_s}{R_e}$, Re is the emulated resistance that reflects the real power of the load, and R_s is the sensing resistance. Although the principles of APF and PFC are different, the control key equations and

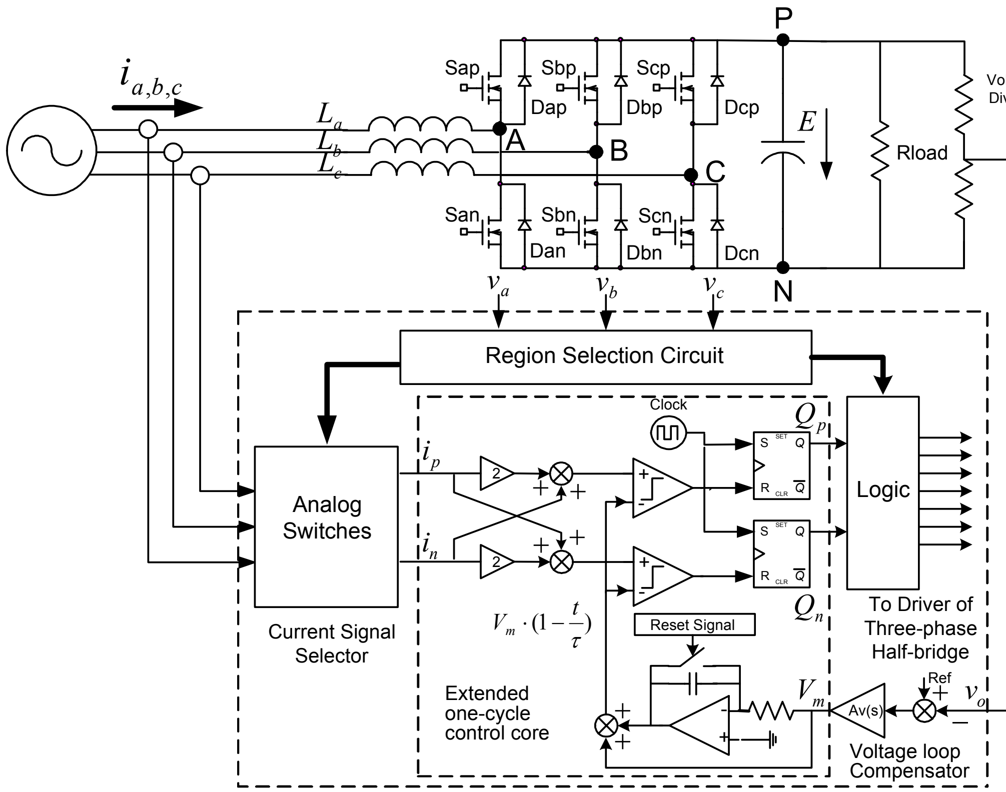

Figure 9. OCC-PFC

the control circuits are identical. The OCC-PFC circuit is shown in Figure 9.

V. One Cycle Control of inverters

Alternative energy sources such as fuel cells and photovoltaic are receiving overwhelm interest recently because they produce clean power. These power sources provide voltage in a variable dc form while the current power system takes ac current; therefore, grid-connected inverters are key elements in distributed power generation that convert variable dc to sinusoidal ac with high efficiency and low harmonics. By using the same procedures as shown for the APF, the control key equation in (0~60°) is generalized as

$$R_s \cdot \begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix} \cdot \begin{bmatrix} i_p \\ i_n \end{bmatrix} = \begin{bmatrix} K \cdot V_p - V_m \cdot d_p \\ K \cdot V_n - V_m \cdot d_n \end{bmatrix} \text{-----------(6)}$$

where R_s is the sensing resistance, where d_p, d_n, d_t, V_p, V_n, i_p, and i_n are given by TABLE II, $V_m = \frac{E \cdot R_s}{R_e}$, Re is the emulated resistance that reflects the real power of the load, and *Rs* is the sensing resistance. Since the control key equation is a polynomial equation matrix of duty ratios d_{an} and d_{cn}, it can be realized by the One-Cycle Control core[5]. Considering the fact that the sensed currents and the triggered switches are different for each region, the zero-crossing points of the phase voltages are sensed to generate a region signal, which is used to rotate a multiplexer to select the right current for a given region and to direct the duty ratio signals calculated by the OCC core to the right switches as shown in Figure 10.

Table II. Cross-reference of i_p, i_n, V_p, V_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_{ab}	V_{cb}	i_a	i_c	d_{ap}	d_{cp}	d_{bn}
60~120	V_{ab}	V_{ac}	$-i_b$	$-i_c$	d_{bn}	d_{cn}	d_{ap}
120~180	V_{bc}	V_{ac}	i_b	i_a	d_{bp}	d_{ap}	d_{cn}
180~240	V_{bc}	V_{ba}	$-i_c$	$-i_a$	d_{cn}	d_{an}	d_{bp}
240~300	V_{ca}	V_{ba}	i_c	i_b	d_{cp}	d_{ap}	d_{an}
300~360	V_{ca}	V_{cb}	$-i_a$	$-i_b$	d_{an}	d_{bn}	d_{cp}

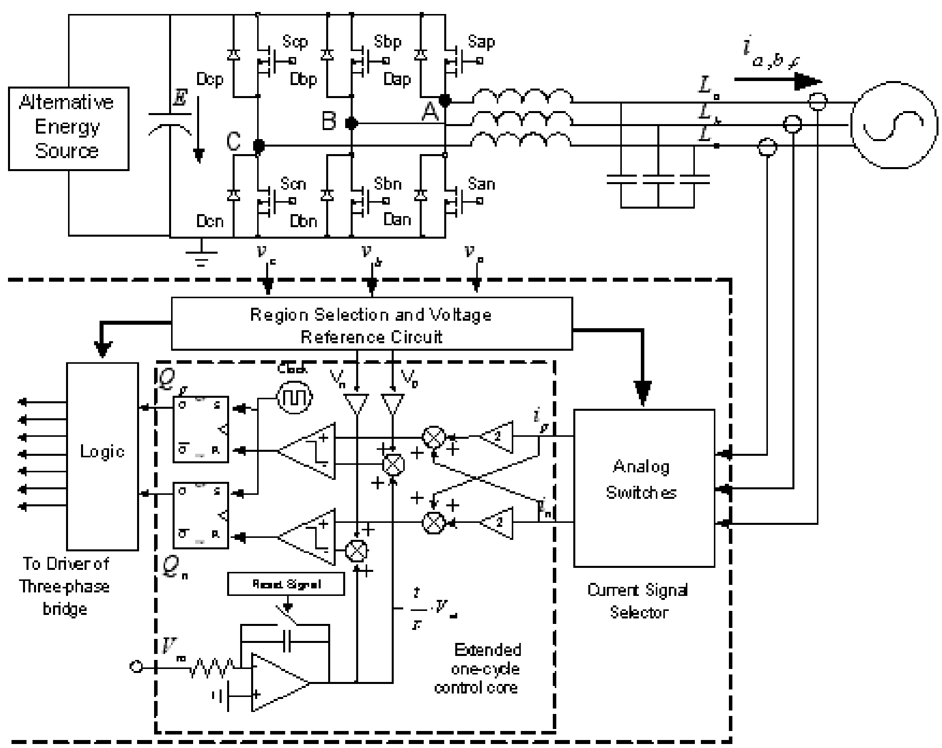

Figure 10. OCC-Inverter

VI. One-Cycle control of FACTS elements.

FACTS elements such as a Static Compensator (STATCOM), Distribution STATCOM (DSTATCOM), unified power flow controller (UPFC), unified power quality conditioners (UPQC), active power filters(APF), are some of the indispensable elements in Distributed Generation (DG) power system. The STATCOM can generate or absorb reactive power so as to control the power flow and damp power system oscillations; the DSTATCOM can perform load compensation, i.e. power factor correction, harmonic filtering, load balancing etc. when connected at the load terminal; the UPFC can be used for control of power flow when there are alternative paths with different ratings; the UPQC can perform both the functions of load compensation and voltage control at the same time; the APF can be used to eliminate the harmonic and reactive power flow in the feeder. In distributed generation systems, the power rating are on the order of MVAs and voltage is on the order of several kV, which create great opportunities for the use of IGBT-type devices. Researchers at the UCI Power Electronics Laboratory are working on various FACTS elements including STATCOM, UPQC, and UPFC. Here, a preview is given for a FACTS element APF-STATCOM[13] or DSTATCOM that produces reactive power and eliminates the harmonics. The schematic of the APF-STATCOM is shown in Figure 11.

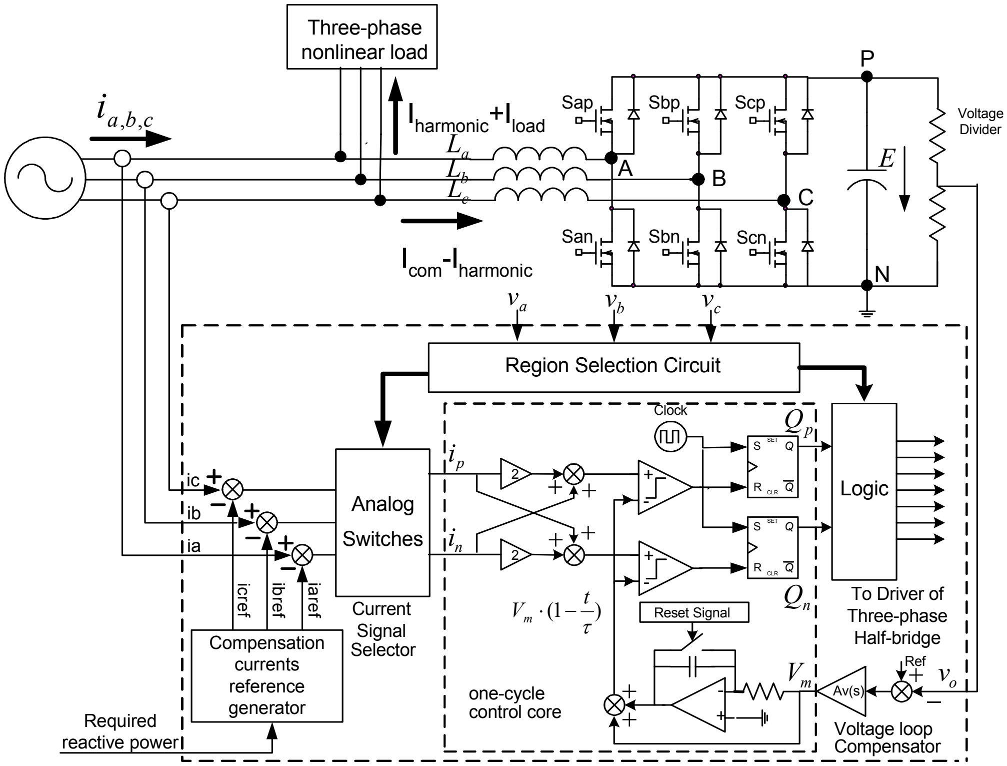

Figure 11. OCC-APF-STATCOM

VII. Summary

The recent great blackout in the Eastern US and Canada resulted in losses of several billions of dollars. It is an alarm for renovating our power systems. Distributed generation with more renewable sources, better power quality, and higher reliability is our future. This imposes a great challenge in front of us and a brand new opportunity for the blossoming of power electronics. In this paper, a simple, universal, reliable, and low cost solution, One-Cycle Control of power electronics equipment for distributed generation is presented. Several examples including APF, PFC, inverter, and STATCOM, are provided, however, the applications are not limited to those. In fact, research in UCI Power Electronics Laboratory has shown many other converter topologies can be controlled by OCC. Since One-Cycle Control serves as an analog computer for solving a polynomial equation of duty ratios and most problems in power electronics can be abstracted to such a polynomial function, OCC is universal. In addition, the implementation circuit is very simple. With One-Cycle Control, it is possible to build a universal control chip that can be configured to control MOSFET and IGBT modules to realize inverters, active power filters, power factor corrected rectifiers, and FACTS components; this will enable consolidation of the research and development cost that would otherwise be required for each specific applications. It is my prediction that a new paradigm "siliconized power system" is in the horizon.

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