DR. SLOBODAN CUK,
President, TESLAco

Part 2

Bridgeless PFC Converter Achieves 98% Efficiency, 0.999 Power Factor

A Bridgeless PFC converter based on a novel switching method eliminates full-bridge rectifiers and helps to reduce the size and cost of switching power supplies.

Last month, we described a patent-pending Bridgeless PFC converter based on a novel hybrid-switching method that eliminates the full-bridge rectifier altogether. The true single-stage power processing results in many advantages over conventional two-stage PFC converters with front-end full-bridge rectifiers, including efficiency over 98% achievable with appropriate switching devices, 0.999 Power Factor, reduced cost, size and weight, single low cost magnetics, and 100% utilization of all components for either positive or negative half-cycles of input line voltage. The Three-Phase Bridgeless PFC converter extension provides unity power factor operation, low total harmonic distortion, and eliminates the large output DC storage capacitor, yet results in small output ripple voltage. The bridgeless PFC converter of *Fig. 1a* operates directly of the AC line voltage, since the front-end full-bridge rectifier associated with conventional PFC converters is eliminated.

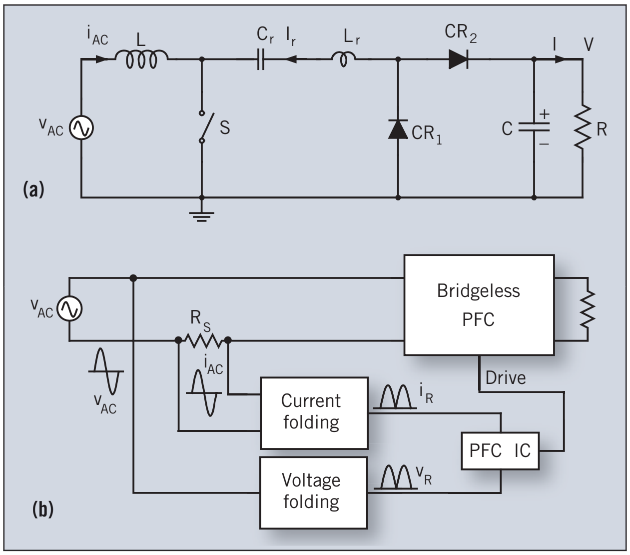

Fig. 1. Bridgeless PFC Converter

(a) Converter topology with one controllable switch S. (b) Control implementation using standard PFC IC controller and additional current folding and voltage folding signal-processing circuits for current sense and voltage sense inputs to PFC IC controller.

In Part 1, it was shown that this converter is capable of providing the dc voltage step-up for either polarity of the input voltage. Furthermore, it was also shown that the DC conversion ratio is the same for either polarity of the input voltage and equal to:

$$\frac{V}{Vg}=\frac{1}{(1-D)} \qquad (1)$$

Thus, the equality of the step-up dc conversion gains as a function of duty ratio D of the controlling switch S for either polarity (1) is one important pre-requisite for a converter to operate as a Single-Stage AC-DC (Bridgeless) converter with PFC function.

In a clear departure from the previous attempts at bridgeless PFC conversion, all components, all three switches, input inductor L, resonant inductor Lr, and resonant capacitor Cr are 100% utilized as they take part in PFC operation for both

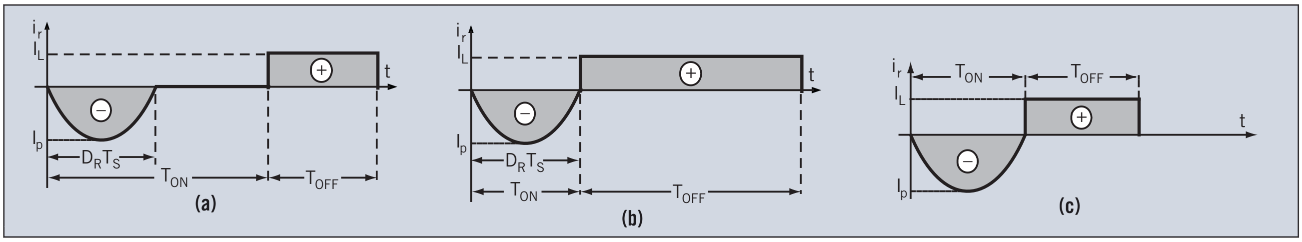

Fig. 2. Resonant inductor current waveforms: (a) Variable ON-time and constant switching frequency resulting in a coasting zero current interval. (b) Constant ON-time and variable OFF-time eliminates zero current coasting interval. (c) Constant ON-time and variable switching frequency result in effective duty ratio control.

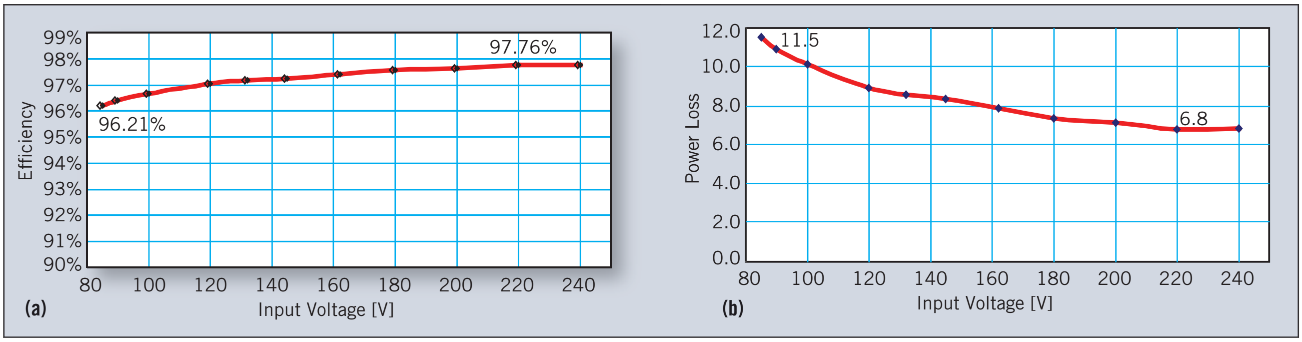

Fig. 3. Experimental measurements on a 300W prototype of a Bridgeless PFC converter: (a) Efficiency measurements at a 300W level over the wide input ac voltage range from 85 to 240 Vac (b) Power loss measurements over the same wide input voltage range.

positive as well as negative part of input line ac voltage so that there are never any idle components as is the case in conventional PFC converters.

PFC CONTROL MECHANISM

The Power Factor Correction is based on forcing the input line current iAC of the converter in *Fig. 1b* to become proportional and in phase to the input ac line voltage by use of the appropriate control circuit. One circuit, which can be utilized, comprises the conventional PFC IC controller to which current folding and voltage folding signal processing circuits are added externally, as illustrated in the block diagram of *Fig. 1b*.

The duty ratio modulation is used to control the average input current of the ac-dc switching converter of Fig, 1b; hence the bandwidth of this current feedback loop must be wide enough to force the average input current to be proportional to ac input voltage with minimal or no distortion. This is achieved by use of the switching frequency 1000 time higher than 60Hz, such as 60kHz.

On the other hand, a second voltage control loop should have a low bandwidth (lower than 60Hz) in order not to introduce the distortion in the input current and yet regulate the output voltage. Thus, the output dc voltage will be regulated although with a low bandwidth and will have a small ripple voltage provided an appropriate large size output storage capacitor C is used. Such a large output capacitor is needed in a single-phase AC line PFC converter to fill in for the difference in the pulsating input power and constant output DC power. This large output capacitor C requirement is completely removed when the Three-phase Bridgeless PFC converter is applied to a balanced three-phase ac line input.

ALTERNATIVE PFC CONTROL METHODS

The forcing of input line current to be proportional to input line voltage is accomplished by controlling the duty ratio D of the controlling switch S in one of two ways:

1. Duty ratio modulation with constant switching frequency.
2. Constant ON-time and variable OFF time and therefore, variable switching frequency.

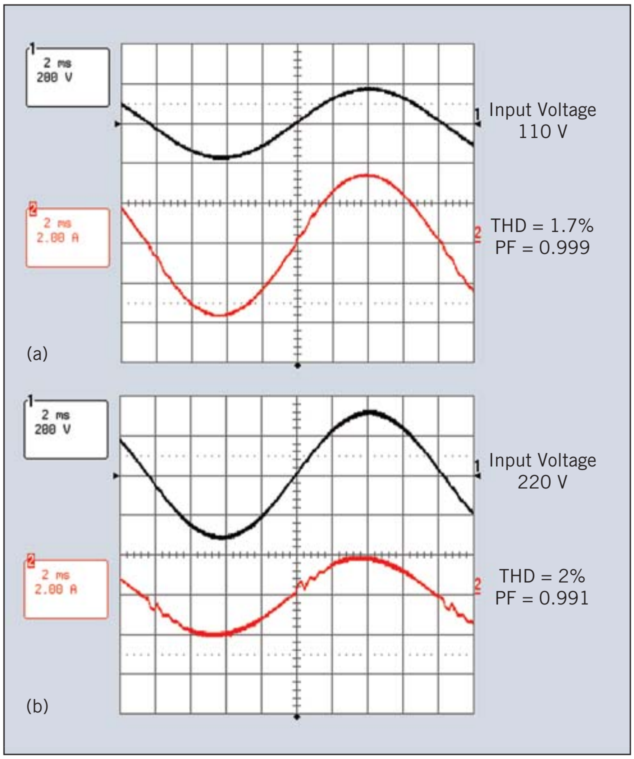

Fig. 4. Line voltage and line current measurements when line voltage is provided by a laboratory sine-wave generator: (a) Line voltage (top trace) and ac line current (bottom trace) at 110Vac, 60Hz input voltage. (b) Line voltage (top trace) and ac line current (bottom trace) at 220Vac and 60Hz.

The ON-time interval starts at zero level. Since the two rectifiers limit the current flow to only one direction the resonant capacitor discharge interval is effectively limited to exactly one-half of the resonant period, that is:

$$D_R T_S = Tr/2 \qquad (2)$$

$$T_r = 1/f_r \qquad (3)$$

We have also introduced here a notion of the resonant

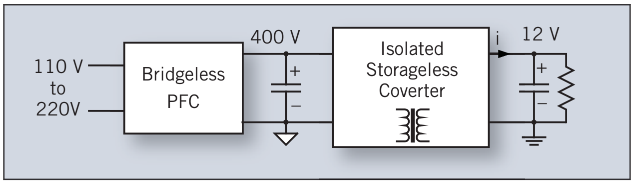

Fig. 5. Computer server power supply using a Bridgeless PFC Converter and an Isolated Storageless Converter.

duty ratio, D_R. The resonant circuit is therefore formed by the loop consisting of two resonant components, C_r and L_r, switch S and respective current rectifiers (one for positive and one for negative input voltage) connected in series as shown earlier, hence limiting discharge current to only one direction.

In this case, the resonant interval D_RT_S is smaller than ON time interval (*Fig. 2a*) or equal to on-time interval (*Fig. 2b*). Note that the duty ratio D higher than resonant duty ratio D_R results in a coasting interval shown by zero current level of resonant current since rectifier CR_1 is turned-OFF (*Fig. 2a*).

If one wants to completely eliminate this zero-current coasting interval, a variable OFF-time control, hence variable switching frequency control, should be used.

CONSTANT ON-TIME AND VARIABLE OFF-TIME CONTROL

For highest efficiency and best performance, zero current coasting intervals described above should be eliminated. The best mode of operation is then to keep the ON-time constant as per:

$$T_{ON} = DT_s = T_r/2 = \text{constant} \qquad (4)$$

so that duty ratio is proportional to switching frequency, or:

$$D = f_S/2f_r \qquad (5)$$

Thus, voltage regulation is obtained by use of the variable switching frequency f_S and corresponding duty ratio D as per Equation (5). Note that all DC quantities, such as DC conversion ratio, Equation (1), DC voltages on capacitors and dc currents of inductors are still a function of duty ratio D only, as in the case of constant-switching frequency operation, since the switching frequency (whether constant or variable) is effectively removed from all the steady-state conditions.

Note that this is one of the key differences between the hybrid-switching method and all other conventional resonant methods, in which the steady-state conditions are not only the function of duty ratio D, but also of load current, resonant frequency and other circuit parameters and conditions. In hybrid switching, despite the presence of the resonance, the same simplicity of the conventional PWM control is retained: the voltage conversion ratio and other steady state conditions depend on the duty ratio D alone.

The waveforms of *Fig. 2b* and *Fig. 2c* show the constant ON-time (interval DT_s) displayed first to emphasize the variable OFF-time and variable switching frequency as well as the elimination of zero coasting intervals of constant switching frequency operation.

The single-stage ac-dc PFC converter is verified on an experimental 300W prototype, which converts 110V AC line voltage and 220V ac line voltage into a 400V output DC voltage with very high efficiency over the wide input voltage range. *Fig. 3a* shows efficiency measurements at a 300W level over the input ac voltage range from 85Vac to 240Vac and Fig. 3b shows power loss measurements.

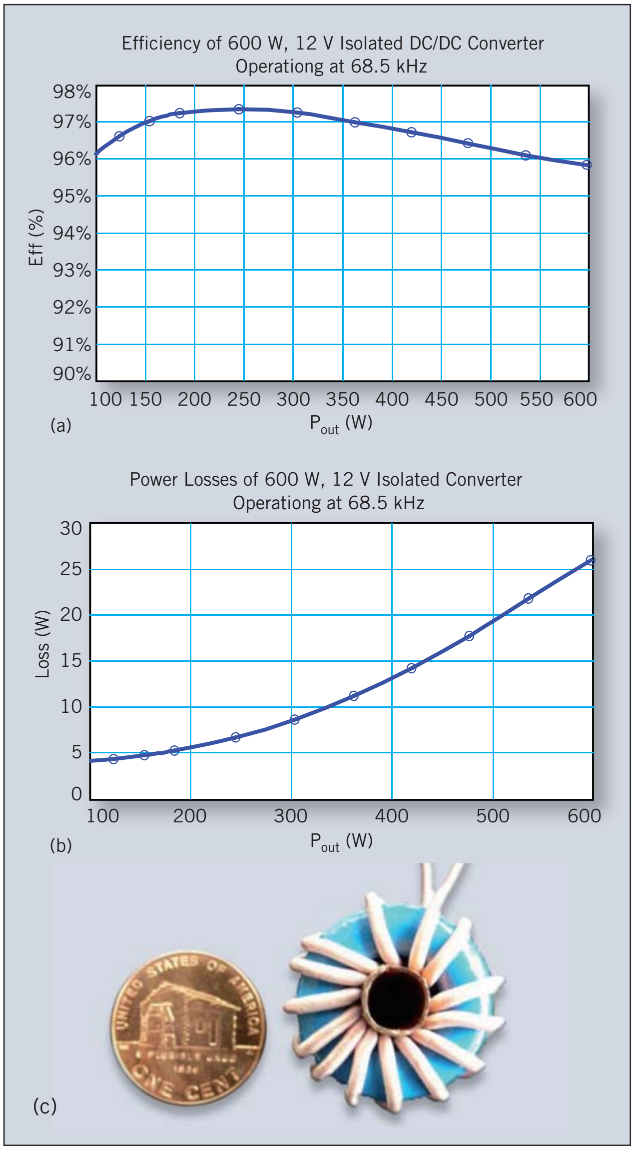

Fig. 6. Efficiency measurements on a 600W prototype of an Isolated Storageless Converter providing 12V output at 50A load current and operating at 68.5kHz:
a) Efficiency measurements over load current range.
b) Power loss measurement over the load current range.
c) Isolation transformer used in the 600W prototype.

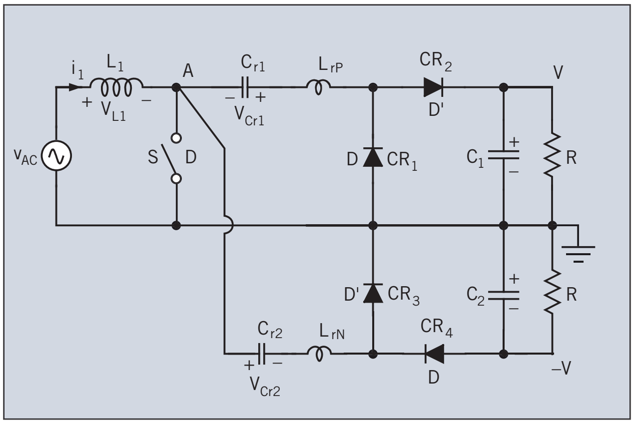

Fig. 7. Bridgeless PFC converter with two outputs: positive and negative and a common inductor L and common controlling switch to reduce the size, weight and cost and improve the efficiency.

Very high efficiency of over 97% was measured over the wide input ac voltage range. Note the very high efficiency at the low ac line voltage of 85Vac as shown in Fig. 3a while the low total losses are shown in *Fig. 3b*. This clearly indicates the absence of the bridge rectifier on the front. The conventional PFC converters have a significant efficiency drop at the low 85V ac line due to the two-diode voltage drops of the bridge rectifier.

Fig. 4a shows the line voltage (top trace) and ac line current (bottom trace) at 110V 60Hz input voltage. The Power Factor was measured at 300W load to be 0.999 and total harmonic distortion (THD) of 1.7% was measured.

Fig. 4b shows the line voltage (top trace) and ac line current (bottom trace) at 220V AC and 60Hz. The power factor was measured at 300W load to be 0.991 and THD 2%.

The measurements of harmonic currents are displayed in *Table 1* for 110V and *Table 2* for 220Vac for both 60Hz and 50Hz.

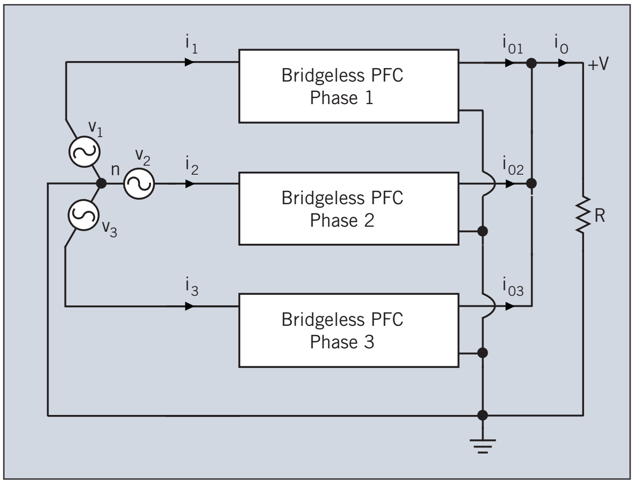

Fig. 8. Three-phase Bridgeless PFC converter eliminates the need for large output capacitor C.


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COMPUTER SERVERS, PC POWER SUPPLIES

Out of many applications required by industry regulations to use the PFC control, perhaps most widespread is the use in computer servers and personal computers. The block diagram of such a system application is shown in *Fig. 5*, in which the front-end Bridgeless PFC converter generates intermediate high dc voltage for energy storage at 400V for the 20 msec hold-up time requirement.

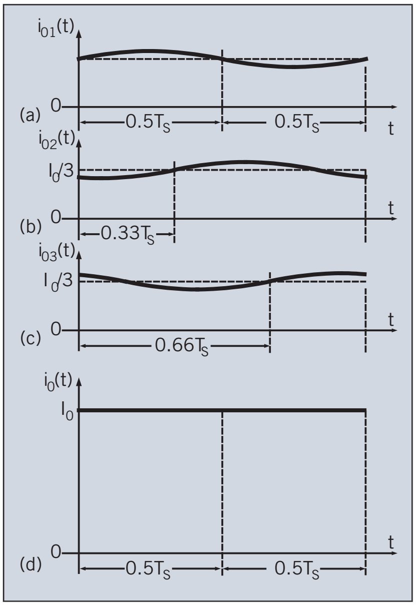

Fig. 9. The DC load current components for the converter in Fig. 9: (a) Load current due to phase 1 input current (b) Load current due to phase 2 input current (c) Load current due to phase 3 input current (d) Total load current is sum of the load currents due to each of the input phase currents The DC components add together to DC load current I0, while the ac components add up to zero due to their three-phase relationships.

For such applications, TESLAco has developed a very high efficiency, ultra small size Isolated Storageless Converter™ based on its Storageless Conversion Method. The efficiency measurements data for a prototype of a 600W, 12V output storageless voltage converters are shown in *Fig. 6a* and loss measurements in *Fig. 6b*. The only magnetic component in the converter is the isolation transformer depicted in *Fig. 6c*. This transformer is built using two stacked ferrite toroidal cores, each having a 33mm^2 cross-section for a rather small total cross-section of only 66mm^2 despite the low operating switching frequency of 68.5kHz. The core type is EPCOSR20x10x7 in N87 material 14/2/3.

Another unique feature is a use of only one-turn secondary for a 12V output DC voltage, revealing a much lower flux excitation of the transformer in this storageless converter as compared to conventional converters requiring at least 3 turns secondary windings for an effective 4V/turn flux excursion and a much bigger ferrite cores at such low operating switching frequency. Clearly, the toroidal structure of the core suggests no DC bias in the transformer, hence no saturation with any DC load current and high overload current capability of two or more times over the nominal load current limited by short term thermal considerations.

TWO OUTPUT BRIDGELESS PFC CONVERTER

The early DC transmission system proposed by Edison was a three-wire system with a neutral wire carrying no DC current. For DC transmissions, this results in doubling the transmitted power for the same amount of copper used compared to straightforward two-wire DC transmission system and is therefore the preferred method.

The Bridgeless PFC converter can generate either positive or negative polarity output DC voltage, so as to lead to direct implementation of a three-wire DC transmission system. This is easily seen in the converter of *Fig. 1a*, in which the change of direction of both current rectifiers CR_1 and CR_2 will result in the negative output DC voltage. Further size and weight savings and efficiency improvements can be made when two such separate converters are integrated into one single converter with two outputs, having a single inductor L and one active switch S, as illustrated in the converter of *Fig. 7*.

BRIDGELESS PFC ADVANTAGES OVER BRIDGE-TYPE PFC CONVERTERS

The new Bridgeless PFC converter is based on a novel hybrid-switching method that eliminates the full-bridge rectifier altogether. Therefore, the present invention results in many fundamental advantages over conventional bridge-type PFC converters:

- Highest efficiency with over 98% achievable with appropriate single active switching device for switch S.
- Reduction of the cost, size and weight.
- High power quality with low total harmonic distortion
- Full utilization of all the components for both positive and negative part of the input ac cycle as there are no idle components in either line cycle.
- Small size and low cost resonant capacitor and resonant inductors.
- Bridgeless PFC converter together with Isolated Storageless Converter form a very efficient and ultra-small size conversion system for data center servers and personal computers. Two-output extension of the Bridgeless PFC converter with positive and negative output DC voltages
- Three-Phase Bridgeless PFC converter eliminates large output storage capacitor and yet results in low output ripple voltages.
- Three-phase Bridgeless PFC converter provides the most efficient connection between three-phase ac transmission line and the local DC transmission system.
- Efficient and direct connection between long distance three-phase ac transmission system and long distance DC transmission system.

THREE-PHASE BRIDGELESS PFC CONVERTER

The three-phase alternating current system of Nikola Tesla has replaced the Edison DC transmission system as a much more efficient alternative for long distance electrical power transmission, due to a use of three-phase transformer to raise the transmission voltage to 400kV and correspondingly reduce the transmission current and copper losses. Tesla's three-phase transmission system, however, has among others, one unique property: despite the fact that each 120 degrees shifted phase has a sinusoidal voltage and current, and therefore a time varying instantaneous power, the sum of the instantaneous input powers of a balanced three-phase transmission system is constant and independent of time:

$$i_1 v_1 (t) + i_2 v_2 (t) + i_3 v_3 (t) = P = \text{constant} \qquad (6)$$

This feature of the three-phase transmission system is used to a great advantage in the three-phase Bridgeless PFC converter shown in *Fig. 8*. Each of the three Bridgeless PFC converters of *Fig. 1a* is connected to a respective phase of the three-phase star-connected input, while their outputs are connected to a common output voltage, so that the output DC ground terminal is connected to the neutral of the four-wire, three-phase star connected ac input voltage.

The output dc power is a product of the output DC voltage and output DC current and by definition is not fluctuating in time and should be equal to (6) as ac transmission does not store dc energy. This comes as a direct result that, although each phase of the three output currents of the respective individual Single-phase Bridgeless PFC converters, designated as $i_{01}(t)$, $i_{02}(t)$, and $i_{03}(t)$ in *Fig. 8* are by themselves time-varying as depicted in the waveforms of *Fig. 9 a,b, c*, their sum, due to the phase shift of 120 degrees, results in the constant load current I0 and constant power P given by (6) even without a need for any output capacitor C due to following relationship:

$$i_{01}(t) + i_{01}(t) + i_{01}(t) = I_0 \qquad (7)$$

Note that in the conventional three-phase rectification using six current rectifiers, the resulting rectified dc voltage ripple would require a proportionally large output capacitor C. Although the direct rectification of the three-phase line would result in a relatively good power factor, the harmonic

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Table 1. 110Vac input, 60 Hz, THD = 1.7%, Power Factor =0.999				
Harmonic No.	**mA/W**	**Max.**	**Limit (mA) For 300 W**	**Test (mA) 60 Hz**
3	3.4	2300	1020	38
5	1.9	1140	570	14
7	1.0	770	300	7
9	0.5	400	150	5.8
11	0.35	330	105	3.5
13	0.30	210	89	2.5
15	0.26	150	77	3.4
17	0.23	132	68	4.5
19	0.20	118	61	7.2
21	0.18	107	55	5.7
23	0.17	98	50	9.3
25	0.15	90	46	9.5
27	0.14	83	43	9.8
29	0.13	78	40	10.0
31	0.12	73	37	4.8
33	0.12	68	35	2.9
35	0.11	64	33	0.8
37	0.10	61	31	0.7
39	0.10	58	30	0.8

Table 2. 220Vac input, 60 Hz, THD = 2.0%, PF @ 60Hz = 0.991, THD = 6.3, PF50Hz=0.98					
Harmonic No.	**mA/W**	**Max.**	**LIMIT (mA) FOR 300 W**	**Test (mA) 60 Hz**	**Test (mA) 50 Hz**
3	3.4	2300	1020	20.5	21.5
5	1.9	1140	570	10.7	7.5
7	1.0	770	300	12.5	8.0
9	0.5	400	150	10.8	8.1
11	0.35	330	105	7.6	6.5
13	0.30	210	89	7.5	4.8
15	0.26	150	77	10.5	7.0
17	0.23	132	68	15.0	10.5
19	0.20	118	61	14.2	10.5
21	0.18	107	55	12.3	9.2
23	0.17	98	50	13.5	7.8
25	0.15	90	46	18.0	10.0
27	0.14	83	43	21.0	12.7
29	0.13	78	40	20.0	14.0
31	0.12	73	37	16.7	13.5
33	0.12	68	35	11.3	12.5
35	0.11	64	33	6.3	11.5
37	0.10	61	31	3.3	11.0
39	0.10	58	30	2.0	10.5

Tables: Total harmonic distortion (THD) measured with 300W load (1) For 110Vac, 60Hz input voltage (2) 220 Vac, 60Hz and 50Hz input voltage.

distortion present in each phase will not meet regulation requirements and would therefore require active or passive PFC control for reduction of harmonic currents.

CONNECTION TO A FUTURE DC TRANSMISSION SYSTEM

Solar generation is starting to provide increased power to complement the power generated by traditional sources, such as coal, oil, nuclear and hydropower. Solar sources generate a DC power leading to the planning of a future DC transmission lines at high DC voltages. Clearly, such DC transmission lines would be most effective as a three-wire DC transmission system with neutral or ground and positive and negative DC voltages available for long distance transmission.

The Three-phase Bridgeless PFC converter shown in Fig. 8 would be an ideal link between the three-phase AC transmission system and a future DC transmission system. Note that the Three-phase Bridgeless PFC converter can take the same advantage as the single-phase, Bridgeless PFC implementation of *Fig. 7* and convert its power to a three-wire DC transmission system.

SECOND "IMPOSSIBLE" CONVERTER SOLUTION

The bridgeless PFC converter will find its way into other applications as design engineers seek to take advantage of the circuit's size and performance attributes. The second in the series of "impossible" converter solutions, *"Single-Stage Isolated Bridgeless PFC Converter"* , will be published in the September issue of Power Electronics Technology. This isolated Bridgeless PFC converter, shown in *Fig. 10*, provides both PFC and isolation in a single-stage power processing consisting of an active switch S on primary side and two current rectifiers on the secondary side and one magnetic core. The design achieves an ultra-high conversion efficiency of over 97%.

Editorial Note: For questions regarding this article and for contact information to the author,readers are directed to TESLAco's web site at http;//www.teslaco.com.

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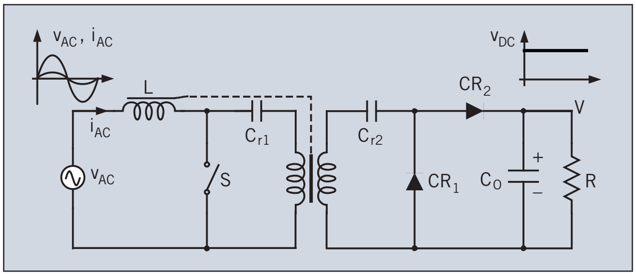

Fig. 10. Single-stage Isolated Bridgeless PFC Converter.