International
IOR Rectifier

Bridgeless PFC Implementation Using One Cycle Control Technique

Bing Lu
Center for Power Electronics Systems
Virginia Polytechnic Institute and State University
674 Whittemore Hall
Blacksburg, VA 24061 USA

Ron Brown, Marco Soldano
AC-DC Applications Group
International Rectifier Corp.
101 N. Sepulveda Blvd
El Segundo, CA, 90245 USA

As presented at APEC ‘05

Abstract: Conventional boost PFC suffers from the high conduction loss in the input rectifier-bridge. Higher efficiency can be achieved by using the bridgeless boost topology. This new circuit has issues such as voltage sensing, current sensing and EMI noise. In this paper, one cycle control technique is used to solve the issues of the voltage sensing and current sensing. Experimental results show efficiency improvement and EMI performance.

I. INTRODUCTION

Single switch CCM PFC is the most widely used topology for the PFC applications because of its simplicity and smaller EMI filter size. Due to the high conduction loss and switching loss, this circuit has a low efficiency at low input line. With the development of super junction MOSFET and SiC Schottky diode, switching loss of the PFC circuit is dramatically improved [1]. Meanwhile, the circuit still suffers from forward voltage drop of the rectifier bridge caused high conduction loss, especially at low input line.

To reduce the rectifier bridge conduction loss, different topologies have been developed. Among these topologies, the bridgeless boost doesn’t require range switch, shows both the simplicity and high performance [2][3].

Without the input rectifier bridge, bridgeless PFC generates less conduction loss comparing with the conventional PFC. Although the circuit structure is simple, the location of the boost inductor on the AC side makes it difficult to sense the AC line voltage and inductor current.

At the same time, since the AC side inductor structure makes the output floating regarding the input line, the circuit suffers from high common mode noise.

Comparing with the average current mode control, one cycle control shows many benefits such as no multiplier requirement, no input voltage sensing requirement, and no inductor current sensing requirement. Therefore, one cycle control gives an attractive solution for the bridgeless PFC circuit [5][7][8].

In this paper, One Cycle Control technique is implemented in the bridgeless PFC. By using one cycle control both the voltage sensing and current sensing issues of the bridgeless PFC circuit can be solved. The experimental results show both the efficiency improvement and good power factor correction function. At the same time EMI results show that the circuit noise is controllable.

II. BRIDGELESS PFC CIRCUIT

The bridgeless PFC circuit is shown in Figure 1. The boost inductor is split and located at the AC side to construct the boost structure. The equivalent circuit of positive half line cycle is show in Figure 2. In this half line cycle, MOSFET S1 and boost diode D1, together with the boost inductor construct a boost DC/DC converter. Meanwhile, MOSFET S2 is operating as a simple diode. The input current is controlled by the boost converter and following the input voltage.

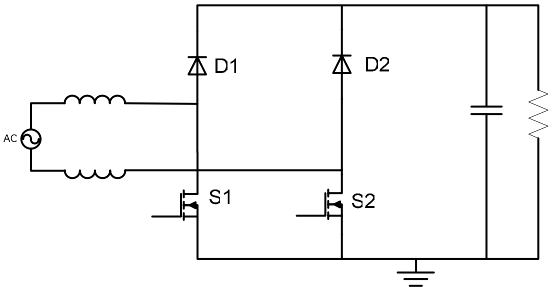

Figure 1 - Bridgeless PFC circuit

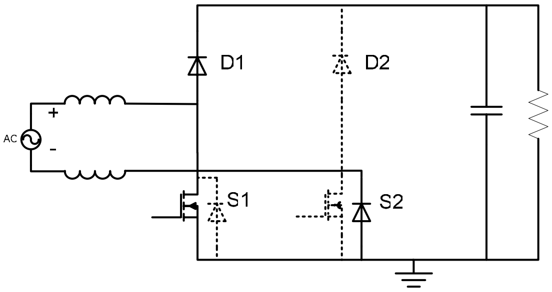

Figure 2 - Equivalent circuit of bridgeless PFC

During the other half line cycle, circuit operation as the same way. Thus, in each half line cycle, one of the MOSFET operates as active switch and the other one operates as a diode: both the MOSFETs can be driven by the same signal.

The difference between the bridgeless PFC and conventional PFC is summarized in Table 1. Comparing the conduction path of these two circuits, at every moment, bridgeless PFC inductor current only goes through two semiconductor devices, but inductor current goes through three semiconductor devices for the conventional PFC circuit.

As shown in Table 1, the bridgeless PFC uses one MOSFET body diode to replace the two slow diodes of the conventional PFC. Since both the circuits operating as a boost DC/DC converter, the switching loss should be the same.

Thus the efficiency improvement relies on the conduction loss difference between the two slow diodes and the body diode of the MOSFET. Besides, comparing with the conventional PFC, the bridgeless PFC not only reduces conduction loss, but also reduces the total components count.

Table 1 – Summary of differences between conventional PFC and bridgeless PFC

	Slow diode	Fast Diode	MOSFET	Conduction Path On/(Off)
Conventional PFC	4	1	1	2 slow diode, 1MOSFET/ (2 slow diode, 1 fast diode)
Bridgeless PFC	0	2	2	1 body diode, 1 MOSFET/ (1 MOSFET body diode, 1diode)

To estimate the efficiency improvement by using bridgeless PFC circuit, the loss comparison is performed based on theoretical analysis. The switch of choice is a super junction MOSFET rated at 22A, 600V and the diode bridge is chosen as GBPC2506W, rated at 25A, 600V. Curve fitting method is used to generate the conduction loss model of these devices. Based on the inductor current instantaneous current, the conduction losses generated by these two devices at 90V input and different output power are calculated as shown in Figure 3.

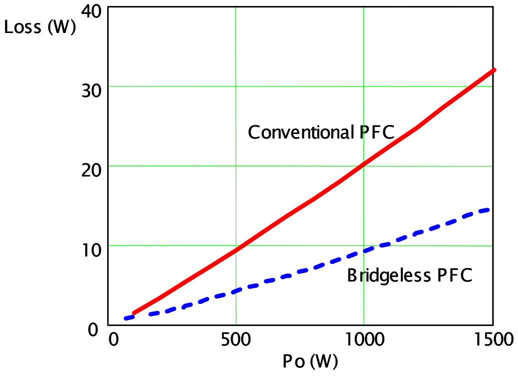

Figure 3 - Diode conduction loss comparison between conventional PFC and bridgeless PFC

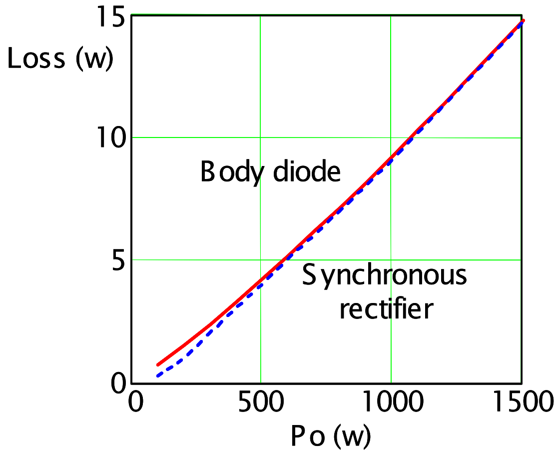

Figure 4 - MOSFET loss comparison between the body diode and synchronous rectifier at 25°C

For all the power level range, bridgeless PFC can improve the total efficiency at the full power level by around 1%. Considering small MOSFET on state resistance, turning on the MOSFET may further reduce the conduction loss by using synchronous rectifier. The conduction loss of the MOSFET is evaluated based on the lower voltage drop caused by the MOSFET body diode and on state resistance. The calculation results are shown in Figure 4. The power losses of these two cases are very similar.

Although the synchronous rectifier has slight improvement at low power cases, the improvement goes away when the MOSFET temperature rises up, since the on state resistance is higher with higher temperature. Considering the complexity of synchronous rectifier, it shouldn't be implemented.

III. CHALLENGES OF BRIDGELESS PFC CIRCUIT

As shown in Figure 1, the bridgeless PFC circuit doesn't have an input diode bridge and the boost inductor is located on the AC side. Since the output and input of the circuit have no direct connection, the bridgeless circuit has several issues of input voltage sensing, current sensing and EMI noise.

The voltage sensing and current sensing issues are related to the control of bridgeless PFC circuit. For the conventional PFC circuit, several kinds of different control methods have been developed [4], such as the average current mode control, peak current mode control, and one cycle control [7][8].

The average current mode control is the most popular control method because of its high performance and easy to understand: the controller multiplies input voltage signal with the voltage loop output voltage to generate the current reference while the current loop controls the inductor average current to follow the current reference.

As for the One Cycle Control, the controller uses the voltage loop output voltage and inductor peak current to calculate the duty cycle of each switching cycle. Since the duty cycle meets the requirement of the boost circuit input and output voltage relationship, the inductor current peak current automatically follows the input voltage shape. Thus the power factor correction function is achieved [7][8].

A. Input voltage sensing

For the conventional PFC, input voltage sensing is simple. Because of the existence of the rectifier bridge, the rectified input voltage can be directly sensed by using the voltage divider, as shown in Figure 5.

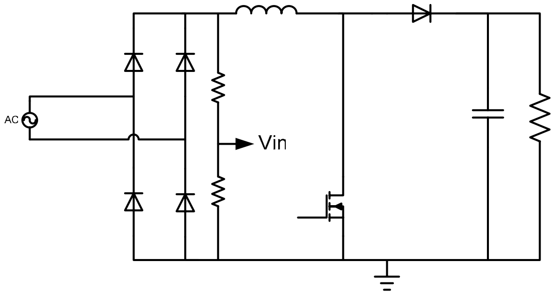

Figure 5 - Input voltage sensing for conventional PFC

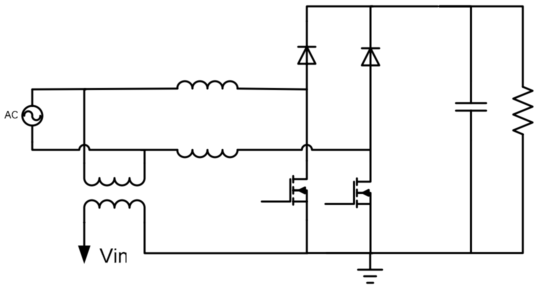

Figure 6 - Low frequency transformer for bridgeless PFC voltage sensing

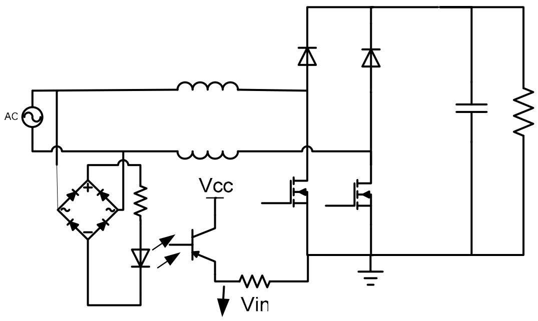

Figure 7 - Optical coupler for bridgeless PFC voltage sensing

For the bridgeless PFC, there is no rectifier bridge and no place to use the voltage divider to sense the input voltage. A line frequency transformer is a simple solution for the voltage sensing, as shown in Figure 6. Due to the larger size of low frequency transformer and the cost issue, it is generally unacceptable for an efficient design.

The optical coupler is also a good candidate for the voltage sensing, because it can easily achieve isolation, as shown in Figure 7. To achieve lower distortion of the voltage sensing, higher linearity optical coupler with wide operating range needs to be used, which is not practical and much more complex comparing with the conventional voltage divider sensing.

For the average current mode control, the inductor current reference is generated based on the sensed input voltage: the input voltage sensing is necessary and will cause higher cost or larger converter size.

When One Cycle Control is used all the necessary information is generated out of the peak inductor current working and the voltage loop output, making input voltage sensing unnecessary.

For the conventional PFC circuit, the voltage sensing is simple, which makes the benefit of the one cycle control less obvious. The complex input voltage sensing of bridgeless PFC makes the one cycle control a more attractive control method.

B. Current sensing

For the conventional PFC, inductor current sensing is quite simple. Simply putting a shunt resistor at the return path of the inductor current, the inductor current can be sensed and with the common ground of the control, as shown in Figure 8. There is no isolation requirement for the current sensing.

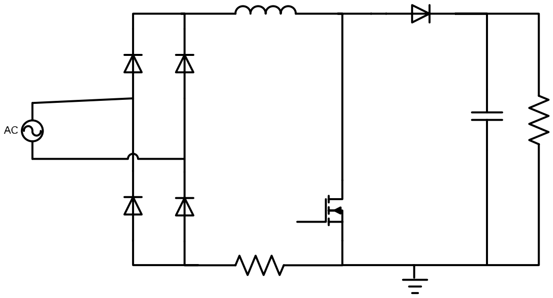

Figure 8 - Current sensing for conventional PFC

For the bridgeless PFC, the inductor return path doesn't share the same ground as the output. Therefore an isolated sensing method has to be used. Same as voltage sensing, a 60Hz current transformer will give a straightforward solution.

In general a low frequency transformer will introduce a non negligible phase delay on the current signal, causing a degradation of the power factor.

Another isolation method is to use the differential mode amplifier, as shown in Figure 9. Because the PFC circuit switching at high switching frequency and high output voltage, the high common mode voltage will cause extra noise in the current signal. Since the current sensing voltage is low to minimize the power loss, the power factor may be hurt by the current sensing noise. Besides, the differential amplifier cost is much higher comparing with the shunt resistor solution.

Alternatively, the inductor current can be reconstructed by the switch and diode current. Due to the different conduction path of the inductor current a total of three current transformers is required for the current sensing.

Figure 10 shows the position of the required current transformers. The input current I_{IN} can be reconstructed as the sum of the three sensed currents:

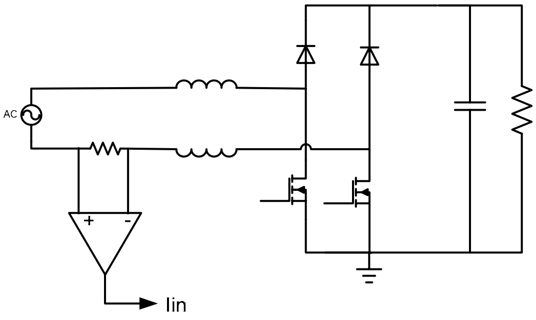

Figure 9 - Differential mode amplifier for bridgeless PFC current sensing

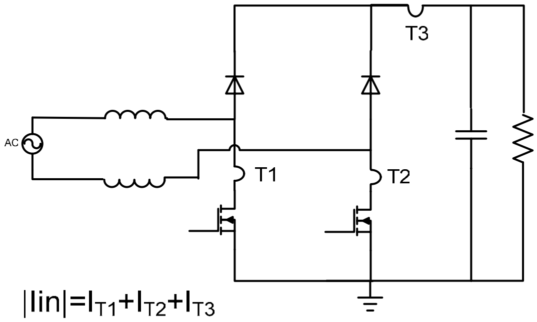

Figure 10 - Current transformer for bridgeless PFC current sensing

For average current mode control, inductor average current is required for the current loop. But for One Cycle Control only the inductor peak current is required for the control. Therefore, the current sensing can be simplified.

By using two current transformers in series with the switches, the inductor peak current can be easily sensed. At the same time the use of current transformer can further reduce the power loss caused by shunt resistor. Same as the voltage sensing, the simple current method for the conventional PFC circuit makes the one cycle control less attractive. For bridgeless PFC, the complexity of current sensing makes one cycle control the most attractive control method.

C. EMI Noise

EMI noise issues rely on the power stage structure. For the conventional PFC, the output voltage ground is always connected with the input line, through the rectifier bridge. Therefore, the only parasitic capacitor contributes to the common mode noise is the parasitic capacitance between the MOSFET drain to the earth ground, as shown in Figure 11.

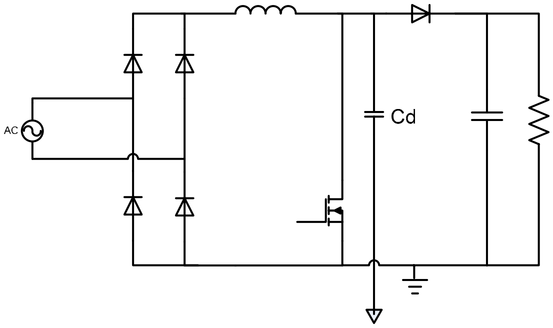

Figure 11 - Parasitic capacitance that contributes to common mode noise for conventional PFC

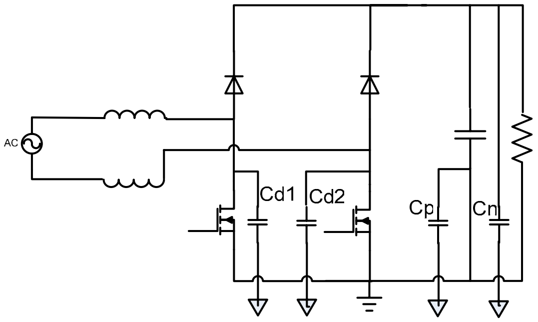

Figure 12 - Parasitic capacitances that contribute to common mode noise for bridgeless PFC

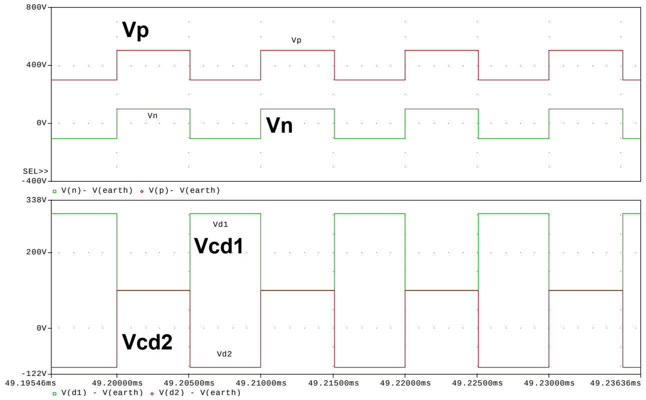

Figure 13 - Voltage on the parasitic capacitor of bridgeless PFC

For the bridgeless PFC the output voltage is always floating in regard of the input AC line. Thus, not only the parasitic capacitance between the MOSFET drains to the earth ground C_{d1} and C_{d2}, but also all the parasitic capacitances between the output terminals to the earth ground C_n and C_p contribute to the common mode noise, as shown in Figure 12.

The simulation results are shown in Figure 13. The dv/dt on the parasitic capacitors between the MOSFET drains to the earth ground V_{cd1} and V_{cd2} are reverse polarity.

By carefully designing the parasitic capacitances, noise cancellation can be achieved [9]. As the dv/dt of the parasitic capacitances between the output terminals to the earth ground, V_p and V_n, are the same, there is no way to achieve noise cancellation.

Considering these capacitors not only include the output of the PFC stage parasitics but also the input for the load, the common mode noise can be much worse comparing with the conventional PFC circuit.

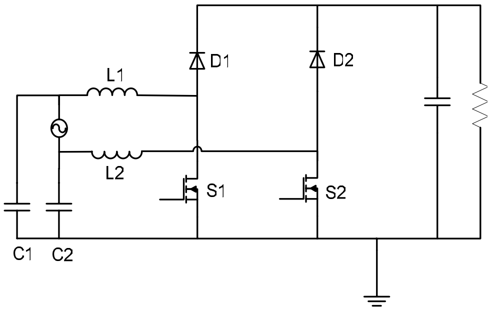

Figure 14 - An improved EMI performance bridgeless PFC circuit

To solve the EMI noise issue, a new EMI noise reduction circuit for the bridgeless PFC circuit is introduced. The circuit schematic is shown in Figure 14. Comparing with the original bridgeless PFC circuit, the circuit adds two capacitors in the circuit to create a high frequency path between the output voltage to the input AC line.

IV. EXPERIMENTAL IMPLEMENTATION

Based on the analysis above, the bridgeless PFC circuit can both simplify the circuit topology and improve the efficiency, while the One Cycle Control is the most attractive control method for the bridgeless PFC circuit.

One 500W, 100 kHz switching frequency, universal line input bridgeless PFC circuit is designed and implemented with One Cycle Control, using IR1150S controller.

Super Junction MOSFET 600V 22A and 600V 4A SiC diode are used in the prototype. Besides, the conventional PFC circuit using same devices is built to serve as the benchmark.

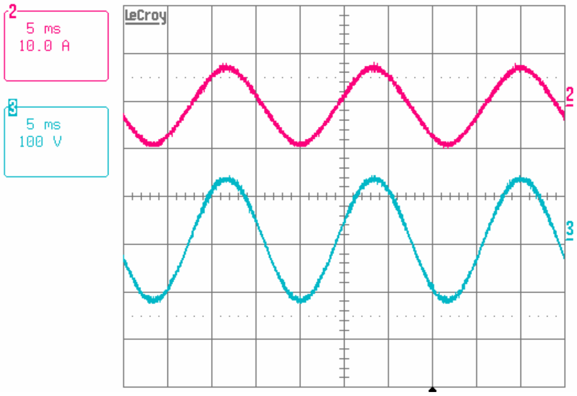

Figure 15 - Input voltage and current waveforms of the bridgeless PFC

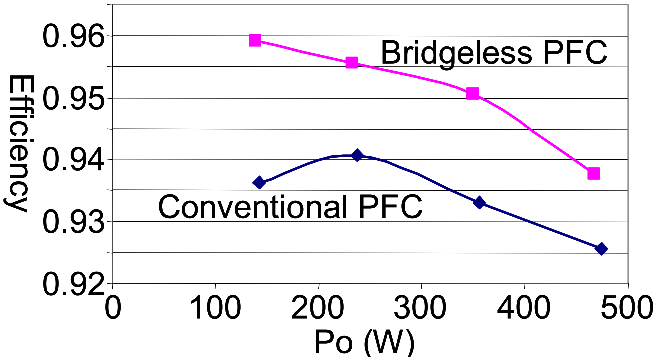

Figure 16 - Efficiency comparison between conventional PFC and bridgeless PFC

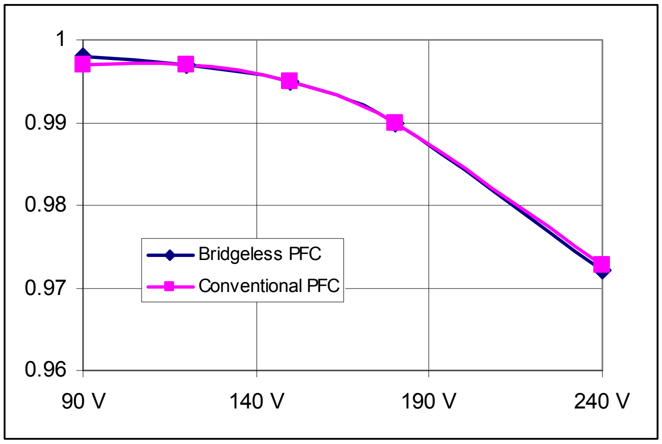

Figure 17 - PF comparison at different input line

The input voltage and current waveforms are shown in Figure 15. The input current perfectly follows the input voltage. Thus the power factor correction function is achieved by using one cycle controller. The efficiency comparison between these two circuits at 90V input line is shown in Figure 16.

For the whole power range, efficiency improvement is around 1%, which is quite coincident with the theoretical analysis. The power factor at full output power and different input line is shown in Figure 17. The high power factor is achieved by using the One Cycle Control for the whole input line range. EMI performances of the bridgeless PFC and the conventional PFC circuit are compared, and the results are shown in Figure 18 and Figure 19. From the experimental results, the bridgeless PFC noise is similar to the conventional PFC circuit noise at low frequency range. Although the noise is slightly higher at the high frequency range, the EMI noise of the bridgeless PFC circuit is controllable.

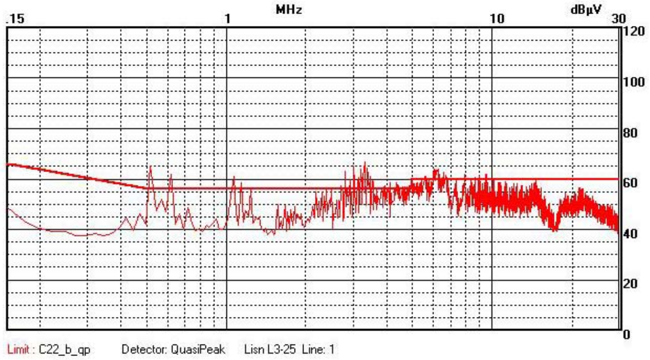

Figure 18 - EMI noise of the conventional PFC

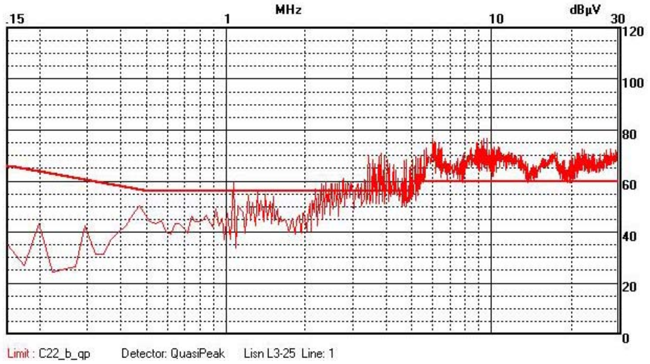

Figure 19 - EMI noise of bridgeless PFC

V. CONCLUSIONS

The bridgeless PFC topology removes the input rectifier conduction losses and is able to achieve higher efficiency. Based on the theoretical analysis, 1% efficiency improvement is expected from the circuit.

The efficiency improvement comes at the cost of increased complexity for input voltage and current sensing. At the same time additional EMI issues are present.

The One Cycle Control does not require input line sensing and can operate in peak current mode, providing a simple and high performance solution and overcoming the limitation of bridgeless topology with conventional control. The EMI issues can be also overcome by using a modified version of the bridgeless topology.

The experimental results show the simplicity of the One Cycle Control and high power factor, meanwhile, verify that the bridgeless PFC can improve 1% efficiency comparing with the conventional PFC circuit.

Although the bridgeless PFC circuit exhibits slightly higher EMI levels, the noise is controllable and similar to the conventional PFC circuit EMI.

REFERENCES

[1] Lu, B.; Dong, W.; Zhao, Q.; Lee, F.C.; “Performance evaluation of CoolMOSTM and SiC diode for single-phase power factor correction applications”, APEC '03. Pages:651 - 657 vol.2

[2] Liu J.; Chen W.; Zhang J.; Xu, D.; Lee, F.C.; “Evaluation of power losses in different CCM mode single-phase boost PFC converters via a simulation tool”, IAS’2001, Pages:2455 - 2459 vol.4

[3] Srinivasan, R.; Oruganti, R.; “A unity power factor converter using half-bridge boost topology”, IEEE Transactions on Power Electronics, Volume: 13 , Issue: 3 , May 1998, Pages:487 - 500

[4] Sebastian, J.; Jaureguizar, M.; Uceda, J.; “An overview of power factor correction in single-phase off-line power supply systems”, IECON '94, Pages:1688 - 1693 vol.3

[5] Lai Z.; Smedley, K.M.; “A family of continuous-conduction-mode power-factor-correction controllers based on the general pulse-width modulator”, IEEE Transactions on Power Electronics, Volume: 13 , Issue: 3 , May 1998, Pages:501 - 510

[6] Liu, Y.; Smedley, K.; “Control of a dual boost power factor corrector for high power applications”, IECON '03. Pages:2929 - 2932

[7] Smith, K.M., Jr.; Lai, Z.; Smedley, K.M.; “A new PWM controller with one-cycle response”, IEEE Transactions on Power Electronics, Volume: 14 , Issue: 1 , Jan. 1999, Pages:142 - 150

[8] Gegner, J.P.; Lee, C.Q.; “Linear peak current mode control: a simple active power factor correction control technique for continuous conduction mode”, PESC '96 Pages:196 - 202 vol.1

[9] Shoyama M., Tsumura T., and Ninomiya T., “Mechanism of Common-Mode Noise Reduction in Balanced Boost Switching Converter”, PESC’04, p1115~1120

[10] International Rectifier, IR1150S data sheet

[11] K. Smedley - US Patent 5,278,490 – California Institute of Technology