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Current Driven Synchronous Rectifier with Saturable Current Transformer and Dynamice Gate Voltage control for LLC Resonant Converter

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***Abstract*—This paper proposes an improved current driven synchronous rectifier with saturable current transformer and dynamic gate voltage control feature for LLC resonant converter efficiency improvement. A model of saturable current transformer is proposed. Compared with other voltage driven and current-driven synchronous rectifier, this current driven synchronous rectifier has several outstanding characteristics. This synchronous rectifier is completely self-contained. It needs no external signal or power supply. It is also insensitive to parasitic inductance. Inherent dynamic gate voltage control reduces gate loss in the MOSFET by saturable current transformer. A 300W 400V-12V converter is built to demonstrate the advantages of the proposed current driven synchronous rectifier. High efficiency at 98% can be achieved. There is more than 4% efficiency improvement compared with schottky diode.**

I. INTRODUCTION

There is ever-increasing demand in telecommunication system and computer equipment for low voltage, high current power supply. LLC resonant converter is a good topology because it has zero-voltage switching and operates at high switching frequencies [1]. On the secondary side, synchronous rectifier is a popular method to reduce rectification loss.

The design of driving circuit is the key of synchronous rectifier technique. A generic way to drive a synchronous rectifier makes use of an additional secondary winding in the main transformer. However, it does not work in resonant converter. This is because the switching waveform is not in phase with the required switching time of the synchronous rectifier [2]. Other methods use the signal within the synchronous rectifier to control itself [3]-[8] which are either voltage driven or current driven. Although a lot of research effort has been made on these methods [9]-[19], there are still weaknesses.

Voltage driven synchronous rectifier derives the driving signal form the drain sources voltage V_{DS} of a MOSFET [20]-[22]. However, the accuracy of the V_{DS} is highly dependent on the PCB layout and the MOSFET package. The operation is impaired by noise and a tailor made phase compensation network is needed in the power path [23]. This is because the sensed terminal drain source voltage of the MOSFET is actually the sum of the MOSFET resistive voltage drop and the package inductive voltage drop. Thus, it cannot be directly used to drive the synchronous rectifier. It increases the complexity of the circuit. Also, external power supply is needed for driving the MOSFET.

Current driven method obtains the driving signal form the MOSFET current [24]-[27]. The response of the current driven method is fast. No external power supply is needed for driving the MOSFET. However, the core used in this method needs several windings to clamp the driving voltage and reset the current transformer. It is desirable to reduce the number of windings in the core.

A very low turn on resistance MOSFET is widely used in synchronous rectifier technology. It reduces the conduction loss effectively. However, this type of MOSFET has a relative high input capacitance [28]. The gate loss becomes significant. It is desirable to reduce gate drive loss.

In this paper, a current driven synchronous rectifier with Saturable Current Transformer is presented. An improved dynamic gate voltage feature is inherent in this circuit. A current transformer model is proposed to explain the saturation mechanism. With the help of a saturable current transformer, the four winding current transformer is reduced to a two winding current transformer. Also, the inherent dynamic gate voltage control by saturable current transformer effectively reduces gate drive losses. A level trigger circuit is added in the current driven driver in order to reduce synchronous rectifier duty cycle loss. This current driven synchronous rectifier is a stand-alone system and no external power supply is needed. This synchronous rectifier circuit allows pin to pin replacement of the out rectifier diode. A 300W, 400V-12V converter is built to demonstrate the advantages of this proposed current driven synchronous rectifier. High efficiency at 98% is achieved which ismore

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than 4% efficiency improvement compared with schottky diode.

II. Current Driven Synchronous Rectifier for LLC Resonsnant Converter

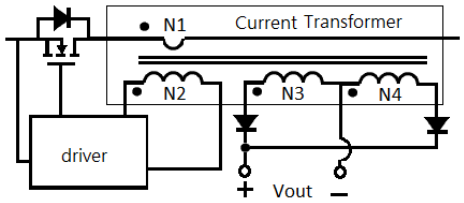

Fig. 1(a) Simplified scheme of current driven synchronous rectifier

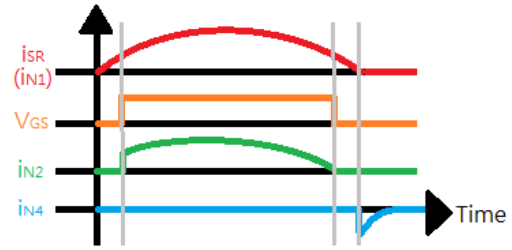

Fig. 1 (b) Waveforms of current driven synchronous rectifier

Fig. 1(a) shows the simplified functional scheme of current driven synchronous rectifier proposed earlier [24]-[26]. Fig. 1(b) shows the waveforms of the current driven synchronous rectifier. The current transformer has four windings. N_1 is the primary windings. Secondary winding N_2 develops the control signal for the driving circuit. Winding N_3 clamps the voltage for the MOSFET. Winding N_4 resets the current transformer after the duty cycle in each cycle. This current driven synchronous rectifier cannot replace the rectifier diode form pin to pin. It needs to connect the winding N_3 and N_4 to the output of the converter in order to clamp the driving voltage and recover the sensing energy. The driving voltage of the MOSFET is fixed.

III. Driving Scheme for Improved Current Driven Synchronous Rectifier and a Current Transformer Modeling

In this section, a scheme for improved current driven synchronous rectifier is proposed. A saturable current transformer model and operation mechanism is explained.

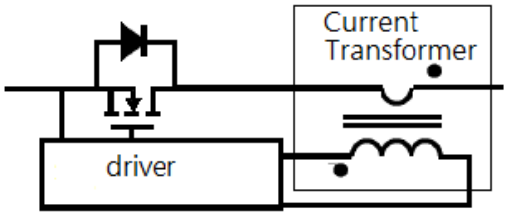

Fig. 2 Simplified scheme of proposed current driven synchronous rectifier

Fig 2 shows the simplified functional scheme for the proposed synchronous rectifier in this paper. A current transformer develops the signal for the MOSFET. A driving circuit filters out the noise and triggers the signal from current transformer. It is important to understand the mechanism of the current transformer especially the current transformer saturation mechanism in the synchronous rectifier.

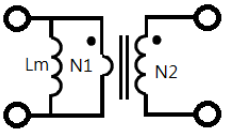

Fig. 3 Current transformer equivalent model

A typical equivalent circuit model for the current transformer is shown in Fig. 3. The magnetizing inductance L_M accounts for the finite permeability of the magnetic core. There is a maximum flux density B_{max} above which the core saturates. The saturation is caused by a transformer current above which the core saturation. This saturation current I_{sat} level can be worked out from the core material parameter.

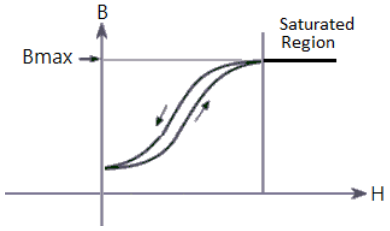

Fig. 4 Typical *B-H* curve

Fig. 4 shows a typical *B-H* curve of ferrite in DC mode. In the region before saturated,

$$B = \mu_0 \mu_r H \tag{1}$$

μ_0 is the permeability of vacuum and μ_r is the relative permeability.

In the saturated region,

$$B = B_{max} \tag{2}$$

B_{max} is the saturation flux density. By Ampere's Law

$$F = \int H\, dl = Ni \approx Hl \tag{3}$$

$$H \approx \frac{Ni}{l} \tag{4}$$

i is the current, N is the number of turns and l is the length of coil. The saturation current can be solved by combining equations (2), (3) and (4)

$$I_{sat} = \frac{l B_{max}}{N \mu_0 \mu_r} \tag{5}$$

By Faraday's Law

$$\frac{dBA_e}{dt} = \frac{V_{Lm}}{N}$$

$$\int V_{Lm} dt = NBA_e \tag{6}$$

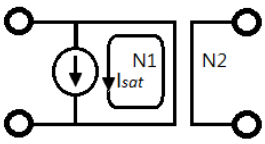

Fig. 5 Saturated current transformer model

Fig. 5 shows the equivalent model when the current transformer is saturated. The current transformer is saturated when the magnetic flux density reaches its maximum. The

magnetic flux current is represented by the constant current source which is equal to the saturation current I_{sat}. The coupling between the primary and secondary is lost. Both sides of the current transformer become short circuit.

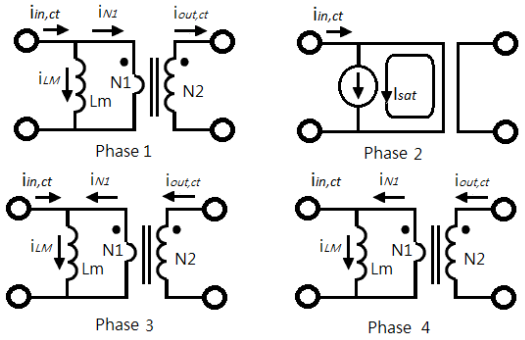

Fig.6 Operations of the saturable current transformer in synchronous rectifier

Fig. 6 shows the four operation phases of the current transformer with saturation in LLC resonant converter. Assume the magnetizing current is completely reset in each cycle.

In phase 1, the current transformer input current $i_{in,ct}$ starts to rise. The current transformer magnetizing current i_{LM} and output current $i_{out,ct}$ increases simultaneously. The current transformer is saturated when the i_{LM} reaches saturation current I_{sat}.

In phase 2, both primary and secondary side becomes short circuit as a result of the core saturation. The magnetizing current remain unchanged and equal to the saturation current I_{sat}. This phase ends when the input current $i_{in,ct}$ falls to saturation I_{sat} again.

In phase 3, the current transformer starts to reset when $i_{in,ct}$ falls below I_{sat}. The output current $i_{ct,out}$ is negative because the magnetizing current is greater than the input current $i_{ct,out}$. This phase ends when the primary current is equal to zero.

In phase 4, the output current $i_{ct,out}$ is negative. The current transformer is fully reset when the output current is equal to zero. It is ready for the next cycle.

IV. CURRENT DRIVEN SYNCHRONOUS RECTIFIER WITH SATURATION CORE FOR LLC RESONANT CONVERTER

A. *Proposed Current Driven Synchronous Rectifier circuit with Saturable Current Transformer*

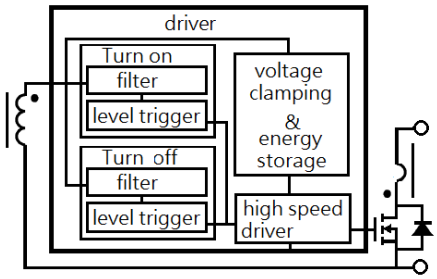

Fig. 7(a) Functional scheme for current driven synchronous rectifier

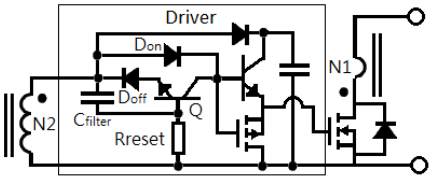

Fig. 7 (b) Improved current driven synchronous rectifier with saturable core circuit

Fig 7(a) shows the detail functional scheme for the current-driven synchronous rectifier used in this paper. Fig. 7(b) shows the circuit of the current driven synchronous rectifier with saturable current transformer. The turn on and turn off circuits are separated to fit the operation of mechanism of saturable current transformer. As mentioned, the output current of the current transformer increases form zero with the input current simultaneously. The trigger level should be set at zero. However, the output current of the current transformer become negative before the primary current become zero again. Thus, different level trigger is needed to control the time of turn on and turn off.

B. *Operation of Current Driven Synchronous Rectifier with Saturable Current Transformer*

A simplified circuit is used in order to understand the mechanism of the driver with saturable current transformer in fig. 8.

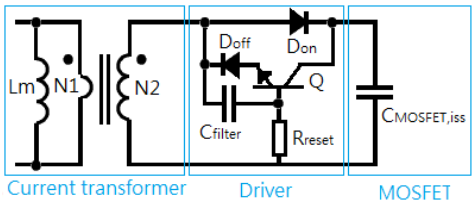

Fig. 8 Simplified circuit of proposed current driven synchronous rectifier

The current transformer model established is applied. Capacitor $C_{MOSFET,iss}$ represents the input capacitance of the MOSFET. Voltage $V_{CMOSFET,iss}$ is equal to the voltage of V_{GS}.

Fig. 9(a) shows the five operation phases of the current driven synchronous rectifier with saturable transformer. Fig. 9(b) shows the waveform of the current transformer.

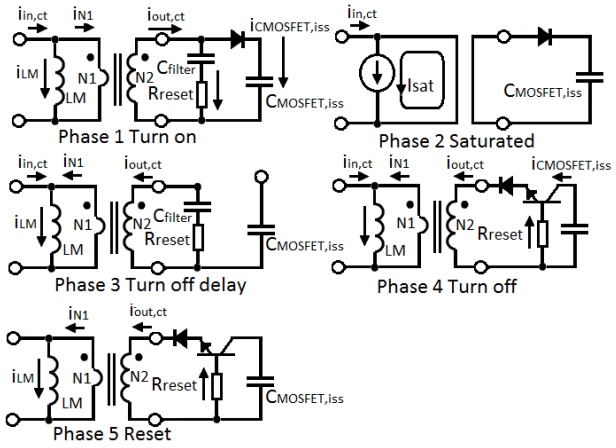

Fig. 9(a) Operation of proposed current driven synchronous rectifier

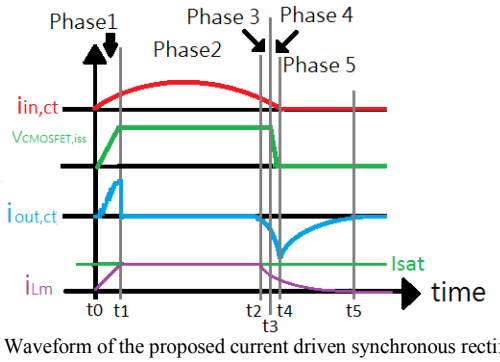

Fig. 9 (b) Waveform of the proposed current driven synchronous rectifier

Phase 1 [t_0- t_1] Turn on period

At $t = t_0$, current i_{LM} is zero. The current transformer input current $i_{in,ct}$ starts to rise. The magnetizing current i_{LM} and output current $i_{out,ct}$ increases simultaneously. Both capacitors $C_{MOSFET,iss}$ and C_{filter} are charged by the output current of the current transformer $i_{out,ct}$. This is the only period to charge up the capacitor $C_{MOSFET,iss}$. The MOSFET is turned on when capacitor $C_{MOSFET,iss}$ is charged up. This phase ends at $t = t_1$ when i_{LM} is equal to the saturation current, I_{sat}.

Phase 2 [t_1- t_2] Saturated period

At $t = t_1$, current i_{LM} has reached the saturation current I_{sat} and the current transformer is saturated. The primary side and secondary side of the current transformer becomes a short circuit. The magnetizing current becomes constant and equal to the saturation current I_{sat}. This phase ends at $t = t_2$ when $i_{in,ct}$ is equal to I_{sat} again.

Phase 3 [t_2- t_3] Turn off delay period

At $t = t_2$, current $i_{in,ct}$ is equal to I_{sat} and it is reducing. The output current of the current transformer become negative because the current transformer input current $i_{in,ct}$ is less than magnetizing current i_{LM}. The current transformer starts to reset through the capacitor C_{filter} and resister R_{reset}. The Voltage of the capacitor $C_{MOSFET,iss}$ remains unchanged until $V_{Cfilter}$ equal to the summation of $V_{d,off}$ and V_{BE}.

Phase 4 [t_3-t_4] Turn off period

At $t = t_3$, voltage $V_{Cfilter}$ equal to the summation of $V_{d,off}$ and V_{BE} and npn is conduct. Capacitor $C_{MOSFET,iss}$ is discharged through the npn. The MOSFET is turned off. This phase will end when the current transformer input current $i_{in,ct}$ is equal to zero.

Phase 5 [t_4- t_5] Reset period

At $t = t_4$, the current transformer input current $i_{in,ct}$ is zero. The current transformer is resetting. This phase will end at t=t_5 when the magnetizing current is equal to zero. The current transformer is fully reset and ready for next cycle.

V. Dynamic Gate Voltage Control in Current Driven Synchronous Rectifier with Saturable Current Transformer

A. Power dissipation of MOSFET in synchronous rectifier

In this section, power dissipation of MOSFET in the synchronous rectifier is discussed and the advantage of dynamic gate voltage control is shown. A very low turn on resistance MOSFET is widely used in synchronous rectifier technology. However, this type of MOSFET has a relative high input capacitance $C_{MOSFET,iss}$. The switching loss due to $C_{MOSFET,iss}$ becomes significant. For example, the maximum $R_{DS(on)max}$ of a very low turn on resistance MOSFET is 1.9m Ω when V_{GS} is 10V. The input capacitance $C_{MOSFET,iss}$ is 8800pF. The input capacitance of the MOSFET with same voltage rating and the maximum $R_{DS(on)max}$ of 17 mΩ is 880p [28]. The input capacitance is much higher in very low on-resistance MOSFET. From the data sheet [28], the $R_{DS(on)}$ is 2.5mΩ when the V_{GS} is 6V; the $R_{DS(on)}$ is 1.6mΩ when the V_{GS} is 10V. The switching loss for the gate drive and conduction loss of the MOSFET in each pair of synchronous rectifier is

$$\text{Total loss} = f_{sw} C_{iss} {V_{gs}}^2 + R_{DS(on)typ} {I_{out}}^2 \qquad (7)$$

Assume the switching frequency is 150KHz, the total loss against the loading current is shown as below.

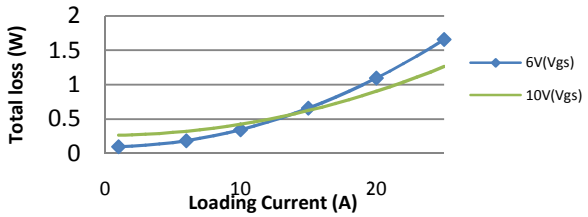

Fig. 10 Total loss against loading current (A)

Fig. 10 shows that the loss is lower when the gate voltage is lower at low load current. A dynamic gate voltage control with adjustable drive voltage can take advantage of this characteristic to reduce the loss.

B. Characteristics of current driven synchronous rectifier with saturable current transformer in gate voltage

In this section, the relationship between V_{GS} and N_2 is discussed. It shows that the characteristics of the proposed synchronous rectifier with saturable current transformer can achieve inherent dynamic gate voltage control. In pervious section, the operation mechanism of current driven synchronous rectifier clearly shows that the capacitor $C_{MOSFET,iss}$ is charged up only in the non-saturated period. Only the current at the beginning of each cycle affects the voltage of capacitor $C_{MOSFET,iss}$. In practice, the non-saturation period of the current transformer for this current driven synchronous rectifier is very short. It is normally around 500ns. The characteristics of the LLC resonant converter make the secondary current waveform of the power transformer a half sinusoid waveform. The current in this period can be linearized as

$$i_{in,ct}(t) = I_{in,ct@500ns} \frac{t}{500ns} \qquad (8)$$

The current $I_{in,ct@500ns}$ is the value of $i_{in,ct}$ at 500ns which is defined to indicate the different output current of LLC resonant converter. The current transformer input current $i_{in,ct}$ is the secondary current of the main transformer, which is the loading current of the converter. For the prototype used in this paper,

$$i_{in,ct@500ns} \approx \frac{1}{2} i_{load} \qquad (9)$$

Voltage of $C_{MOSFET,iss}$ can be solved by considering the energy transformer form the current transformer to the capacitor $C_{MOSFET,iss}$. Energy stored in the capacitor C_{filter} can be neglected because the value of C_{filter} is very small. Capacitor $C_{MOSFET,iss}$ voltage $V_{CMOSFET,iss}$ is equal to gate-source voltage V_{GS} of the MOSFET. Assume the energy loss in the totem pole is same as the energy loss in $C_{MOSFET,iss}$, then

$$(V_{N_2} - V_{D_{on}}) \int_0^{t_1} i_{out,ct} dt = C_{MOSFET,iss} {V_{C_{MOSFET,iss}}}^2 \quad (10)$$

Combine equation (8) and (10)

$$\frac{1}{2}(V_{GS}) i_{out,ct}(t_1) = C_{MOSFET,iss} {V_{gs}}^2 \quad (11)$$

At time t_1, the output current $i_{out,ct}$ has reach maximum,

$$i_{out,ct\,(t1)} = \frac{N_1}{N_2}\left(i_{in,ct@500ns} \frac{t_1}{500n} - I_{sat}\right) \quad (12)$$

Sub the saturation time in equation (6), then

$$V_{N2} t_1 = N_2 B_{max} A_e \quad (13)$$

Thus V_{GS} and t_1 can be calculated by specific N_2, B_{max} and A_e for different current load by equation (10), (12) and (13)

The relationship of V_{GS} and N_2 is plotted as follow.

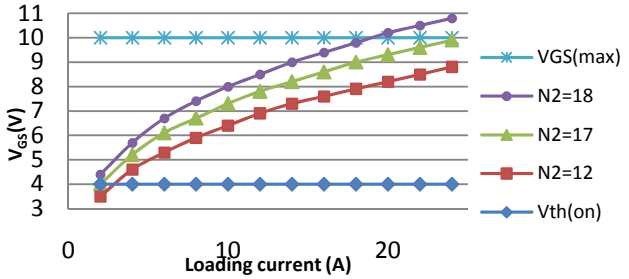

Fig. 11 V_{GS} of different N_2 against loading current (A)

Fig. 11 shows the relationship of V_{GS} and N_2 against different output current of LLC resonant converter. It shows that the characteristics of the current driven synchronous rectifier with saturable current transformer can provide inherent dynamic gate voltage. It is fits in the requirement to reduce gate loss.

Fig. 11 also shows that $V_{CMOSFET,iss}$ increases when the number of turn increases. If N_2 is too high, it will exceed the maximum V_{GS}. If N_2 is too low, the current driven synchronous rectifier will function only at a high output current of main transformer.

Compare the gate loss of $C_{MOSFET,iss}$ per pair of dynamic gate voltage control with Constant Gate Voltage control,

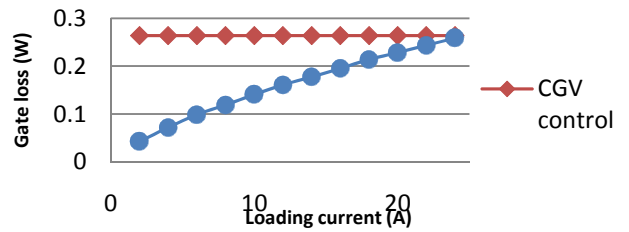

Fig. 12 Gate loss against loading current

Fig. 12 shows the energy loss in light load of dynamic gate voltage control is smaller than constant gate voltage control. At 2A, the gate loss of dynamic gate voltage control is 0.08W and the gate loss of constant gate voltage control is 0.51W. More than 84% loss is reduced. The gate loss at low current output in dynamic gate voltage control is significantly reduced.

VI. Current Driven Synchronous Rectifier with Saturable Current Transformer Design

In this section, a method to calculate the number of turns of current transformer N_2 is proposed. After choosing the type of MOSFET and current transformer, N_2 can be calculated to achieve the dynamic gate voltage control. Consider equations (10), (12) and (13), then

$$N_2 = \frac{V_{GS}\left(\frac{i_{in,ct@500ns} B_{max} A_e}{500n\left(V_{GS}+V_{D_{on}}\right)} - I_{sat}\right)}{2\left(C_{MOSFET,iss} {V_{GS}}^2\right)} \quad (14)$$

The MOSFET used in the prototype has a maximum V_{GS} of 20V and $V_{GS(th)}$ of 4V. However, the $R_{DS(ON)}$ is constant when V_{GS} is higher than 10V. Thus, 4V-10V is set as the boundaries of the V_{GS}. A toroidal ferrite core with one millimeter square cross section area is used as the current transformer. The loading range of the converter is 2A - 25A.

By equation (9) and (14), the range of N_2 is 15.3 to 17.3. Therefore, N_2=17 is chosen for the example. This design procedure produces the number of turns for the toroidal ferrite core chosen and gives good dynamic voltage for the gate drive.

VII. Experimental Result

A prototype is built to verify the design of the proposed current driven synchronous rectifier with saturable current transformer.

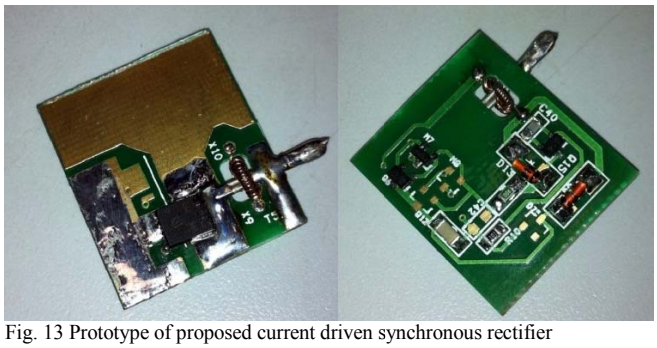

Fig. 13 Prototype of proposed current driven synchronous rectifier

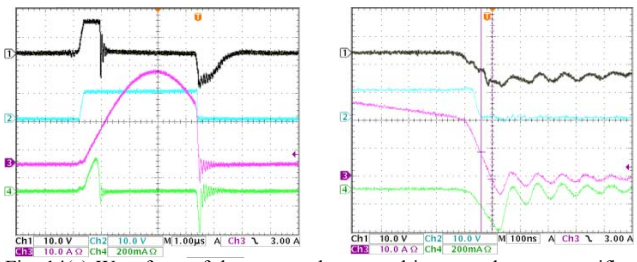

Fig. 14(a) Waveform of the proposed current driven synchronous rectifier in

CCM

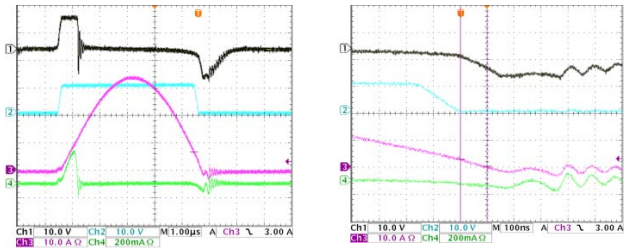

Fig. 14(b) Waveform of the proposed current driven synchronous rectifier in DCM

Ch1: Current transformer output voltage, Ch2: V_{GS}, Ch3: Loading current, Ch4: current transformer output current

Fig. 14 shows the waveform of the proposed current driven synchronous rectifier. The waveforms show that the MOSFET turns on when the output current of the main transformer starts to conduct. The gate voltage of the MOSFET is charged up by the output current of the current transformer. The MOSFET turns off when the output current of the main transformer tends to zero. The output current of the current transformer becomes negative before the output current of the main transformer become zero. As mentioned, it is because the current transformer starts to reset before the output current of the main transformer become zero. With the help of the turn off level trigger, the synchronous rectifier turn off at 38ns in CCM and 102ns in DCM before the output current become zero. The results show that the current driven synchronous rectifier is functioning as expected.

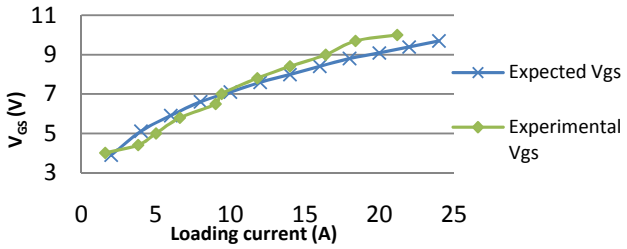

Fig. 15 Expected V_{GS} and experimental V_{GS}, N_2=16, A_e=1mm2

Fig. 15 shows the expected V_{GS} and experimental V_{GS} against output current based on the MOSFET chosen. The value of expected and experimental is very close. The gate voltage is increase when the output current is increase. The results show good agreement with expected characteristics of current driven synchronous rectifier with saturable current transformer.

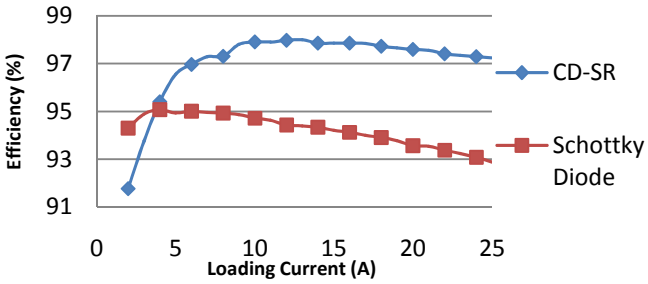

Fig. 16 Efficiency against loading current of LLC resonant converter with (a) proposed synchronous rectifier, (b) schottky diode

Fig 16 shows the efficiency of the 300W, 400V-12V LLC resonant converter using: (a) proposed current driven synchronous rectifier, (b) schottky diode. At half load, the efficiency with proposed current synchronous rectifier is 98% where the efficiency with schottky diode is 94.4%. The average efficiency from 20% to 100% load with proposed current driven synchronous rectifier is 97.6% where the efficiency with schottky diode is 94.1%. At full load, the efficiency with proposed current driven synchronous rectifier is 97.2 % where the efficiency with schottky is 92.9% only. The results show that using the proposed current driven synchronous rectifier has more than 4% efficiency improvement compared with schottky diode.

VIII. CONCLUSION

In this paper, an improved current driven synchronous rectifier with saturated current transformer for LLC resonant convert is presented. A saturable current transformer model is proposed to explain the saturation mechanism. This saturable current transformer makes the current driven synchronous rectifier to have inherent dynamic gate voltage control. The dynamic gate voltage control can reduce the gate loss significantly. This current driven synchronous rectifier is a stand-alone component. It replaces the output diode pin to pin i in LLC resonant converter.

A prototype of current driven synchronous rectifier for LLC resonant converter is built to verify the design of the proposed circuit and design. The prototype achieves high efficiency at 98%. The proposed current driven synchronous rectifier has more than 4% efficiency improvement compared with schottky diode.

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