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AN IMPLEMENTATION OF HIGH EFFICIENT-H-BRIDGE DC-TO-DC CONVERTER WITH HIGH PWM

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Abstract— This paper gives a hybrid-type complete-bridge dc/dc converter with high efficiency. Using a hybrid manipulate scheme with a simple circuit structure, the proposed dc/dc converter has a hybrid operation mode. Under a everyday input variety, the proposed converter operates as a segment-shift complete-bridge series resonant converter that provides excessive performance with the aid of making use of smooth switching on all switches and rectifier diodes and lowering conduction losses. When the input is lower than the normal input range, the converter operates as an active-clamp step-up converter that complements an operation variety. Due to the hybrid operation, the proposed converter operates with large segment shift value than the traditional converters underneath the ordinary input variety. Thus, the proposed converter is capable of being designed to offer high electricity conversion efficiency and its operation variety is prolonged. A 1kW prototype is implemented to verify the theoretical analysis and validity of the proposed converter.
Keywords:-Full-bridge circuit, phase-shift control, active clamp circuit.

I. INTRODUCTION

Now a days, demands on dc/dc converters with a excessive energy density, excessive efficiency, and coffee electromagnetic interference (EMI) had been elevated in diverse commercial fields. As the switching frequency increases to attain high power density, switching losses associated with the turn-on and turn-off of the switching gadgets growth. Because these losses limit the growth of the switching frequency, soft switching techniques are critical. Among preceding dc/dc converters, a phase-shift full-bridge (PSFB) converter is appealing because all primary switches are turned on with 0-voltage switching (ZVS) without additional auxiliary circuits [1]. However, the PSFB converter has some extreme issues including slender ZVS variety of lagging-leg switches, high power losses by circulating modern-day, and voltage ringing across rectifier diodes. Especially, with a requirement of wide input variety, the PSFB converter is designed to perform with small phase-shift price underneath the ordinary input variety; the design of the PSFB converter lengthens the freewheeling c programming language and reasons the excessive circulating modern which will increase conduction losses [2], [3].Recently, the numerous PSFB converters the use of

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auxiliary circuits had been brought [4]-[12]. The PSFB converters amplify ZVS range or lessen the circulating cutting-edge through utilizing additional passive or energetic auxiliary circuits. However, the additional circuits bring about complicated circuit configuration, complicated manipulate approach, and extra power losses [13]. In addition, a few PSFB converters nonetheless require the more snubber to prevent severe voltage ringing trouble throughout rectifier diodes. In [14], [15], the PSFB converters employing a series resonant converter had been introduced, namely, the PSFB collection-resonant converters; they have got many advantages which include soft switching techniques of all number one switches and rectifier diodes, removal of circulating modern, discount of voltage stress on rectifier diodes, and a easy circuit shape.However, whilst all aforementioned PSFB converters are required to guarantee a huge operation range, they nonetheless perform with the small section-shift cost underneath the regular input variety. The operation with the small segment-shift fee usually offers high conduction losses by way of excessive peak current; it outcomes in low energy performance. To reap excessive performance beneath the normal input variety and cover the wide enter range, the specific strategies are suggested. The converters in [16], [17] exchange the flip ratio of the transformer by using additional switching devices. Although the method achieves excessive efficiency and ensures the wide input range, these techniques provide circuit complexity and discount of the transformer utilization. Active-clamp circuits were usually used to take in surge strength saved in leakage inductance of a transformer.Moreover, the circuits offer a tender switching method [18], [19]. Some research have introduced dc/dc converters combining the active-clamp circuit and voltage doubler or multiplier rectifier [20], [21]. The circuit configuration lets in to attain a step-up feature like a lift converter. The voltage stresses of rectifier diodes also are clamped on the output voltage and no more snubber circuit is needed.In this paper, a unique hybrid-kind FB dc/dc converter with excessive efficiency is proposed; the converter is derived from a combination of a PSFB collection-resonant converter and an energetic-clamp step-up converter with a voltage doubler circuit. Using a hybrid control scheme with a easy circuit structure, the proposed converter has operation modes. Under the normal input variety, the proposed converter operates as a PSFB series-resonant converter. The proposed converter yields excessive efficiency by using making use of gentle switching techniques on all of the primary switches and rectifier diodes and with the aid of decreasing conduction losses. When the enter voltage is decrease than the ordinary enter range, the converter operates as an active-clamp step-up converter. In this mode, the proposed converter r affords a step- up function b y the usage of the energetic-clamp circuit at the primary side and the voltage doubler rectifier at the secondary side. Due to the hybrid operation, the proposed converter operates with larger phaseshift value than the conventional PSFB converters underneath the everyday enter range. Thus, the proposed converter has the subsequent blessings:

1) Under the ordinary input variety, the proposed converter may be designed to optimize electricity conversion performance.
2) When the enter is decrease than the everyday enter variety, the proposed converter performs a step-up characteristic, which complements the operation variety.
3) Without complex circuit systems, the converter has excessive performance below the ordinary input range and extends the operation variety.The precept operation of the proposed converter is represented in Section II. The relevant evaluation is given in Section III. Finally, a 1kW prototype of the proposed converter is carried out to confirm its theoretical analysis and validity.

II. PRINCIPLE OPERATION OF THE PROPOSED CONVERTER

Fig.1 indicates a circuit diagram of the proposed converter. On the number one aspect of the power transformer T, the proposed converter has a FB circuit with one blocking diode DB and one clamp capacitor Cc. On the secondary aspect, there is a voltage doubler rectifier. The operation of the proposed converter can be labeled into instances. The one is a PSFB collection-resonant converter mode and the alternative is an active-clamp step-up Converter mode.
To examine the steady-nation operation of the proposed converter, numerous assumptions are made.
1) All switches S1, S2, S3, and S4 are taken into consideration as best
switches except for his or her body diodes and output capacitors.
2) The clamp capacitor *Cc* and output capacitor *Co* are large enough, so the clamp capacitor voltage *Vc* and output voltage *V*o have no ripple voltage, respectively.
3) The transformer *T* is composed of an ideal transformer with the primary winding turns *Np*, the secondary winding turns *N*s, the magnetizing inductance *Lm*, and the leakage inductance *Llk*.
4) The capacitance of the resonant capacitors *Cr1* and *Cr2* is identical. Thus, *Cr1=Cr2*.

A. PSFB SERIES-RESONANT CONVERTER MODE

Under the normal input voltage range, the proposed converter is operated by phase-shift control. In this mode, *Vc* is the same as the input voltage *Vd* and *DB* is conducted. All switches are driven with a constant duty ratio 0.5 and short dead time. Fig. 2 and 3 show the operation waveforms and equivalent circuits, respectively. A detailed mode analysis is given as four modes.
Mode 1 [*t0, t1*]: Prior to *t0*, the switches *S1* and *S2* are in onstate and the secondary current *is* is zero. The primary current *ip* flows through *DB*, *S1*, *S2*, and *Lm*. During this mode, the primary voltage *vp* and secondary voltage *vs* of the transformer *T* are zero. Thus, the magnetizing current *i*m is constant and satisfies as follows:

$$i_m(t) = i_p(t) = i_m(t_0). \quad (1)$$

Mode 2 [*t1*, *t2*]: At *t*1, *S2* is turned off. Because *i*p flowing
through *S*2 is very low, *S2* is turned off with near zero-current. In this mode, *ip* charges *CS2* and discharges *CS4*.
Mode 3 [*t2*, *t3*]: At *t*2, the voltage across *S4* reaches zero. Atthe same time, *ip* flows through the body diode *DS4*. Thus, *S4* is turned on with zero-voltage while *DS4* is conducted. In this mode, *vs* is *nVd* where the turn ratio *n* of the transformer is given by *N*s/*N*p and the secondary current *is* begins to

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flow through *D1*. The state equation of this mode is written as follows:

$$L_{lk}\frac{di_s(t)}{dt} = nV_d - v_{cr1}(t) \quad (2)$$

$$i_s(t) = C_{r1}\frac{dv_{cr1}(t)}{dt} - C_{r2}\frac{dv_{cr2}(t)}{dt} \quad (3)$$

Where *vcr1* and *vcr2* are the voltages across *Cr1* and *Cr2*, respectively. Since *Vo* is constant, the secondary current *is* can be obtained as

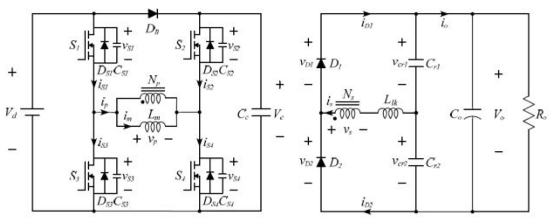

Fig. 1. Circuit diagram of the proposed hybrid-type full-bridge dc/dc converter.

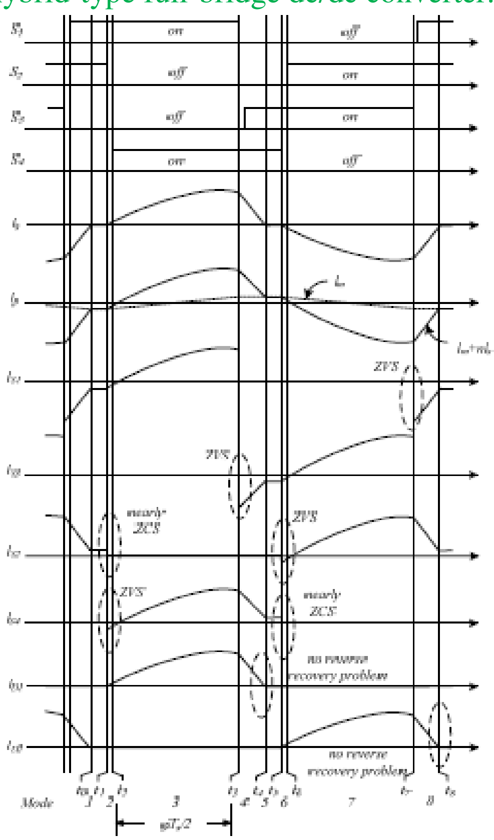

Fig. 2. Operation waveforms in the PSFB series-resonant converter mode.

$$i_s(t) = C_{r1}\frac{dv_{cr1}(t)}{dt} - C_{r2}\frac{d(V_o - v_{cr1}(t))}{dt} = C_r\frac{dv_{cr1}(t)}{dt} \quad (4)$$

where the equivalent resonant capacitance *Cr* is *Cr1+Cr2*. Using Eqns. (2) and (4), the secondary current *is* can be calculated as

$$i_s(t) = \frac{nV_d - v_{cr1}(t_2)}{Z_r}\sin\omega_r(t-t_2). \quad (5)$$

The angular frequency *ωr* and characteristic impedance *Zr* are given by

$$\omega_r = \frac{1}{\sqrt{L_{lk}C_r}}, \quad Z_r = \sqrt{\frac{L_{lk}}{C_r}}. \quad (6)$$

Meanwhile, the magnetizing current *i*m increases linearly as follows:

$$i_m(t) = i_m(t_2) + \frac{V_d}{L_m}(t-t_2). \quad (7)$$

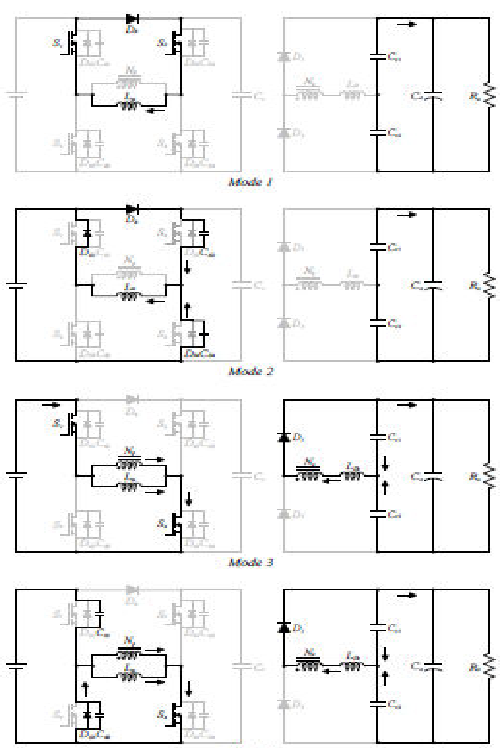

Fig. 3. Equivalent circuits during half period in the PSFB series-resonant converter mode.

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In this mode, power is transferred from the input to the output.

Mode 4 [*t3*, *t4*]: This mode begins when *S1* is turned off. The primary current *ip* charges *CS1* and discharges *CS3*. When the voltage across *S3* becomes zero, *ip* flows through the body diode *D*S3. Thus, *S3* is turned on with zero-voltage while *DS3* is conducted. When *vp* is zero, *D1* is still conducted and -*vcr1* is applied to *Llk*. Thus, the secondary current *is* goes to zero rapidly. End of this mode, since the secondary current is close to zero before *D1* is reverse bias, the losses by the reverse recovery problem are small as negligible.

Since operations during the next half switching period are similar with *Mode 1-4*, explanations of *Mode 5-8* are not presented

B. Active-clamp Step-up Converter Mode

As the input voltage decreases up to a certain minimum value of the normal input range, the phase-shift value *φ* increases up toits maximum value, 1. If the input voltage is

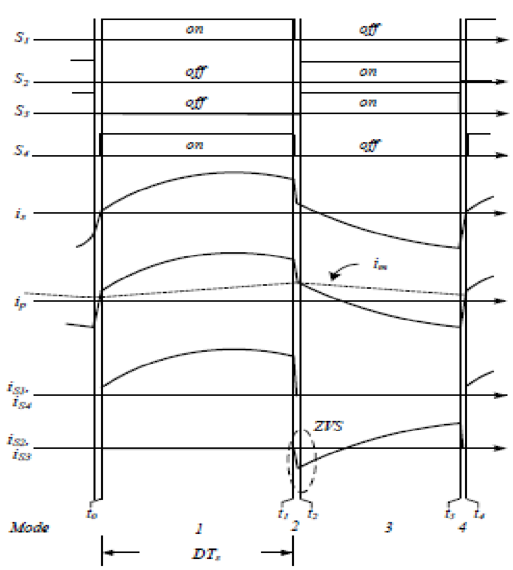

Fig. 4. Operation waveforms in the active-clamp step-up converter mode

lower than the minimum value of the normal input range, the proposed converter is operated by dual asymmetrical pulse width modulation (PWM) control. The switches (*S1*, *S4*) and (*S2*, *S3*) are treated as switch pairs and operated complementarily with short dead time. The duty *D* over 0.5 is based on (*S*1, *S*4) pair. In this situation, the clamp capacitor voltage *V*c is higher than *Vd*. Then, the blocking diode *DB* is reverse biased and the proposed converter operates as the active-clamp step-up converter. Fig. 4 and 5 show the operation waveforms and equivalent circuits in the active clamp step-up converter mode, respectively.

Mode 1 [*t0*, *t1*]: At *t0*, *S1* and *S4* are turned on. Since *Vd* is

applied to *Lm*, the magnetizing current *im* is linearly increased and is expressed as

$$i_m(t) = i_m(t_0) + \frac{V_d}{L_m}(t - t_0). \qquad (8)$$

D1 is conducted and the secondary current *is* begins to resonate by *Llk*, *Cr1*, and *Cr2*. In this mode, the state equation is written as follows:

$$L_{lk}\frac{di_s(t)}{dt} = nV_d - v_{cr1}(t) \qquad (9)$$

$$i_s(t) = C_{r1}\frac{dv_{cr1}(t)}{dt} - C_{r2}\frac{dv_{cr2}(t)}{dt} = C_r\frac{dv_{cr1}(t)}{dt}. \qquad (10)$$

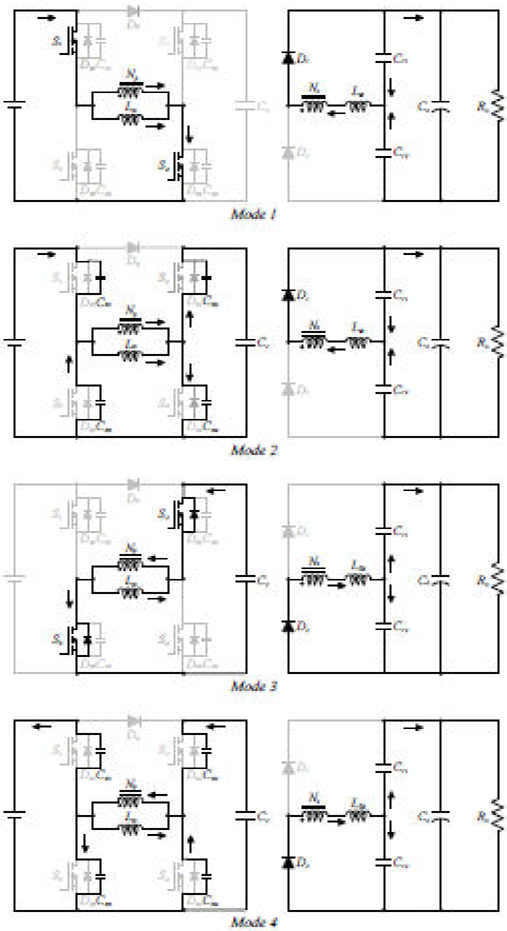

Fig. 5. Equivalent circuits during a switching period in the active-clamp step-up converter mode.

From Eqns. (9) and (10), the secondary current *is* can be calculated as

$$i_s(t) = i_s(t_3)\cos\omega_r(t-t_3) - \frac{nV_c - v_{cr2}(t_3)}{Z_r}\sin\omega_r(t-t_3). \quad (11)$$

In this mode, power is transferred from the input to the output.

Mode 2 [*t1*, *t2*]: At *t*1, *S1* and *S4* are turned off. The primary current *i*p charges and discharges the output capacitors of the switches during very short time.

Mode 3 [*t2*, *t3*]: This mode begins when the voltages across *S2* and *S3* are zero. At the same time, *i*p flows through *DS2* and *DS3*. Thus, *S2* and *S3* are turned on with zero-voltage. Since the negative voltage -*Vc* is applied to *Lm*, the magnetizing current *i*m decreases linearly as

$$i_m(t) = i_m(t_3) - \frac{V_c}{L_m}(t-t_3). \quad (12)$$

In this mode, the secondary current *is* begins to second resonance and the state equation is written as follows:

$$L_{lk}\frac{di_s}{dt} = v_{cr2}(t) - nV_c \quad (13)$$

$$i_s(t) = C_{r1}\frac{dv_{cr1}(t)}{dt} - C_{r2}\frac{dv_{cr2}(t)}{dt} = -C_r\frac{dv_{cr2}(t)}{dt}. \quad (14)$$

Using Eqns. (13) and (14), the secondary current is given by

$$i_s(t) = i_s(t_3)\cos\omega_r(t-t_3) - \frac{nV_c - v_{cr2}(t_3)}{Z_r}\sin\omega_r(t-t_3). \quad (15)$$

Mode 4 [*t3, t4*]: At *t3*, *S2* and *S3* are turned off. The primary current *i*p charges *CS2*, *CS3* and discharges *CS1*, *CS4* during very short time.

III. ANALYSIS OF THE PROPOSED CONVERTER

In the PSFB series-resonant converter mode, *Mode 4* is neglected since the duration of *Mode 4* is relatively very short.

During *Mode 3*, the secondary current *is* in Eqn. (5) flows through *D*1; the current is the same as sum of the current charging *Cr1* and current discharging *Cr2*. As shown in Fig.3, during the half switching period *T*s/2, *Cr2* is discharged as much as the load current *io* while *Cr1* is charged. Thus, the average value of the current flowing through *D*1 is the same as twice the load current during *T*s/2. Due to the symmetric operation, the average value of the current flowing through *D2*is also twice the load current during the next half switching period. Both average values of *vcr1* and *vcr2* are *V*o/2 and *vcr1*(*t*2) in Eqn. (5) is obtained from the ripple voltage □*vcr1* of *Cr1* as

$$v_{cr1}(t_2) = \frac{V_o}{2} - \frac{\Delta v_{cr1}}{2} = \frac{V_o}{2} - \frac{1}{2C_{r1}}\int i_{cr1}(\tau)d\tau = \frac{V_o}{2}\left(1 - \frac{T_s}{2C_{r1}R_o}\right) = \frac{V_o}{2}\left(1 - \frac{\pi Q}{2F}\right) \quad (16)$$

where the frequency ratio F and quality factor Q are given by

$$F = \frac{f_s}{f_r}, \quad Q = \frac{4\omega_r L_{lk}}{R_o} = \frac{4}{\omega_r C_r R_o}. \quad (17)$$

Because the average value of the current flowing through *D1*during *Ts*/2 is the same as 2*io* and is zero during next half switching period, the average value of the current flowing through *D1* during *Ts* is equal to *io*. Thus, the load current *io* can be derived as

$$i_o = \frac{V_o}{R_o} = \frac{1}{T_s}\left[\int_{t_2}^{t_2+\varphi T_s/2} \frac{nV_d - v_{cr1}(t_2)}{Z_r}\sin\omega_r(\tau - t_2)d\tau\right] = F\left[\frac{nV_d - v_{cr1}(t_2)}{2\pi Z_r}\left(1 - \cos\frac{\pi\varphi}{F}\right)\right]. \quad (18)$$

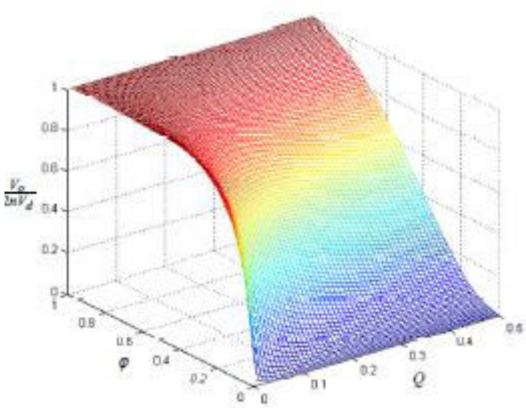

Fig. 6. Normalized voltage gain at *F*=1.05 in the PSFB series-resonant converter mode.

From Eqns. (16) and (18), the voltage gain in the PSFB series resonant converter mode can be derived as follows:

$$\frac{V_o}{V_d} = \frac{2n}{\dfrac{\pi Q}{F\left(1 - \cos\dfrac{\pi\varphi}{F}\right)} + \left(1 - \dfrac{\pi Q}{2F}\right)}. \quad (19)$$

Fig. 6 shows the normalized voltage gain in the PSFB series resonant converter mode.

In the active-clamp step-up converter mode, the average
voltage *V*c for *D* > 0.5 is obtained as

$$V_c = \frac{D}{1-D}V_d. \quad (20)$$

By the volt-second balance law for the magnetizing inductance *L*m, the following equations are derived as

$$nV_d DT_s = \frac{n^2 L_m}{n^2 L_m + L_{lk}} V_{cr2}(1-D)T_s \quad (21)$$

$$\frac{n^2 L_m}{n^2 L_m + L_{lk}} V_{cr1} DT_s = nV_c(1-D)T_s \quad (22)$$

where *Vcr1* and *Vcr2* are the average values of the voltages across *Ccr1* and *Ccr2*, respectively. The sum of *Vcr1* and *Vcr2* is *V*o. From Eqns. (21) and (22), the average values *Vcr1* and *Vcr2* are obtained as

$$V_{cr1} = \frac{n^2 L_m + L_{lk}}{nL_m} V_d = (1-D)V_o \quad (23)$$

$$V_{cr2} = \frac{n^2 L_m + L_{lk}}{nL_m} \frac{D}{1-D} V_d = DV_o. \quad (24)$$

Assuming *Llk* is much smaller than *Lm*, the voltage gain in the active-clamp step-up converter mode can be derived as follows:

$$\frac{V_o}{V_d} = \frac{n}{1-D}. \quad (25)$$

The voltage gain becomes that of an isolated boost converter.It means that the proposed converter performs step-up function in the active-clamp step-up converter mode. In the PSFB series-resonant converter, the leading-leg switches *S1* and *S3* can be easily turned on with zero-voltage by the reflected secondary current. However, when the state of the lagging-leg switches *S2* and *S4* are

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changed, the secondary current is zero. Thus, only the energy stored in *Lm* is involved in ZVS of the lagging-leg switches condition; it is obtained as

$$\frac{1}{2}L_m(\frac{\Delta i_m}{2})^2 = \frac{1}{2}L_m(\frac{\varphi V_d}{4L_m f_s})^2 > \frac{4}{3}C_m V_d^2 \qquad (26)$$

where *Cm* is the output capacitance of the MOSFET switches. From Eqn. (26), the magnetizing inductance *L*m can be decided as

$$L_m < \frac{3\varphi_{\min}^2}{128 C_m f_s^2} \qquad (27)$$

the lagging-leg switches is related to the frequency ratio. As *F* increases, the ZCS range decreases [15]. Therefore, to guarantee both ZVS of all primary switches and ZCS of the lagging-leg switches, *F* should be selected to be slightly more than one. In the active-clamp step-up converter mode, *S2* and *S3* can achieve ZVS turn-on naturally from the asymmetrical PWM operation.As shown in Fig.2, in the PSFB series-resonant converter mode, *Llk* performs as the output inductor and all energy stored in *Llk* is delivered to the load until the secondary current is zero. Then, only small magnetizing current flows on the primary side. In the active-clamp step-up converter, the proposed converter is operated by dual asymmetrical PWM control scheme. In the PWM scheme, there is no circulating current [22]. Thus, the proposed converter eliminates the conduction loss by the circulating current in the entire operation range.

IV. IMPLEMENTATION AND EXPERIMENTS

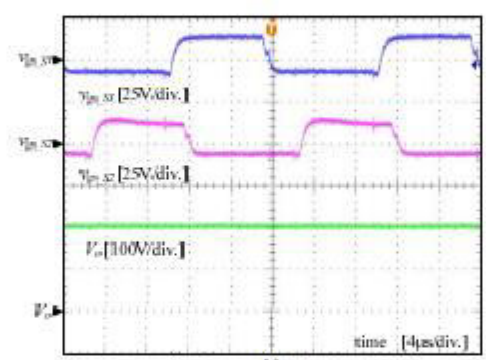
To evaluate a feasibility of the proposed converter, a 1kW proto type was built and tested. The operation range of the proposed converter is from 250V to 350V. The output voltage is designated as 200V and the normal input range is set up from 320V to 350V.

A. Implementation of The Prototype

Considering power conversion efficiency under the normal input range, the proposed converter is designed. To obtain ZVS turn-on of the switches, the switching frequency *fs* should be higher than the resonant frequency *fr*. By the design rule proved in [15], the frequency ratio *F* (*fs/fr*) is selected to be

TABLE I
PARAMETERS OF THE PROTOTYPE

Parameters	Symbols	Value
Input voltage	V_d	250-350V
Output voltage	V_o	200V
Switching frequency	f_s	50kHz
Primary winding turns	N_p	24turns
Secondary winding turns	N_s	8turns
Magnetizing inductance	L_m	695μH
Leakage inductance	L_{lk}	8.3μH
Clamp capacitor	C_c	11μF
Resonant capacitors	C_{r1}, C_{r2}	680nF
Output capacitor	C_o	680μF
Switches	S_1, S_2, S_3, S_4	STW26NM60
Blocking diode	D_B	FFAF40U60DN
Output diodes	D_1, D_2	FFPF15U40S



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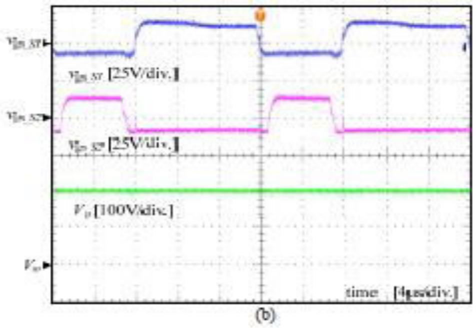

Fig. 7. Experimental waveforms for the gate signals and output voltage according to the operation mode. (a) PSFB series-resonant converter mode when *Vd* =350V. (b) Active-clamp step-up converter when *Vd* =250V

slightly more than one. The quality factor *Q* is decided by Eqn. (17). If *Q* is too small, the proposed converter is operated with small *φ* under the normal input range. Thus, *Llk* is selected as 8.3µH. From the normal input range, the turn ratio *n* is decided by Eqn. (19) and Fig. 6. All switch stresses are determined by

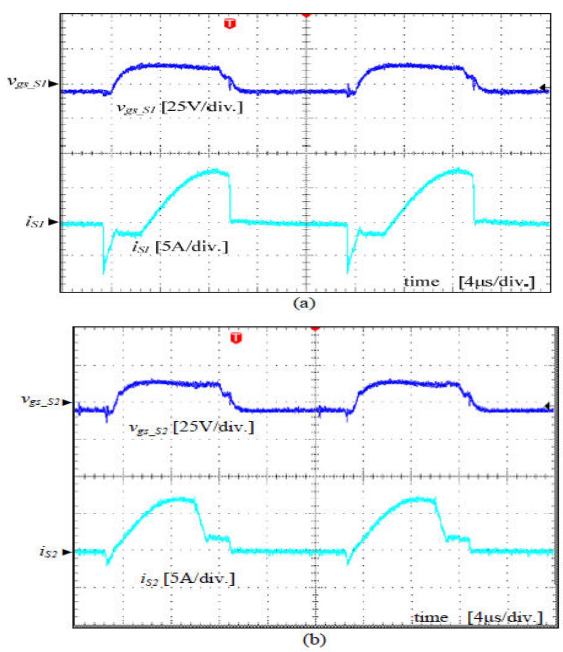

Fig. 8. Experimental waveforms for soft switching in the PSFB series resonant converter mode. (a) ZVS turn-on of *S*1. (b) ZVS turn-on and ZCS turn-off of *S*2.

the input voltage in the PSFB series-resonant converter mode. On the other hand, in the active-clamp step-up converter mode, the voltage stress of the switches *S1* and *S2* are the same as the input voltage and those of *S*3 and *S*4 are determined by Eqn. (20). In both the operation modes, voltage stresses of the rectifier diodes are clamped at the output voltage *Vo*. The major experimental parameters are presented in Table I. The prototype is implemented using a single DSP chip, dsPIC33EP512GM604 (Microchip) which provides both phase-shift and asymmetrical PWM control.

B. EXPERIMENTAL RESULTS

Fig. 7 shows waveforms for the gate signals and output voltage in the proposed converter according to the operation mode. *vgs_S1* and *vgs_S2* are each gate signal for *S*1 and *S*2, respectively. When the input voltage is 350V, the proposed converter is operated by phase-shift control with the constant duty 0.5. On the other hand, when the input voltage is 250V, the proposed converter is operated by the asymmetrical PWM control with the duty 0.61. In both operation modes, the proposed converter regulates *vo*. Fig. 8 (a) and (b) show waveforms for the gate signals and currents of *S1* and *S2* at full load condition when *Vd* = 350V. When the switches are turned on, the currents flow through the body diode of each switch. It is clear that all switches are turned on with zero-voltage. Furthermore, as shown in Fig. 8 (b), *S2* is turned off with near

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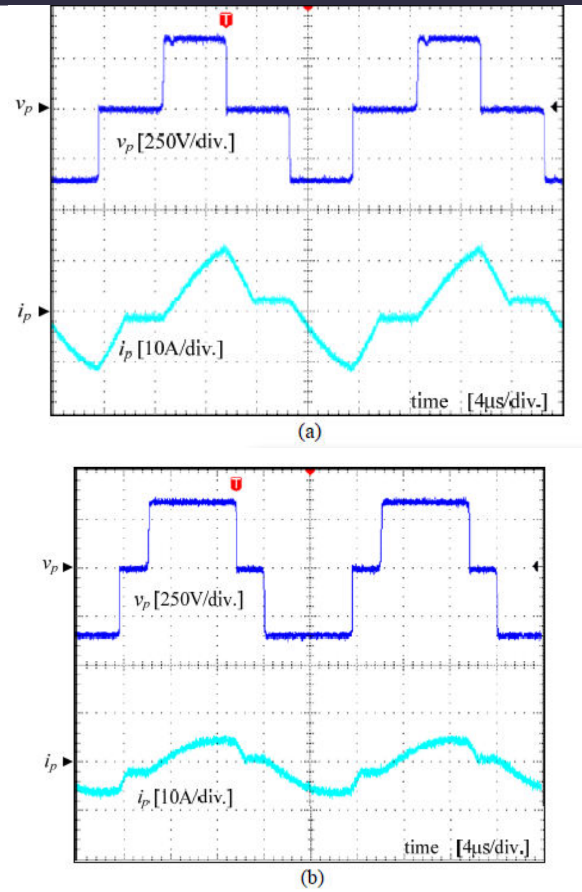

Fig. 9. Experimental waveforms for the current stress when Vd =350V. (a)Conventional PSFB series-resonant converter. (b) Proposed converter.

zero current as the theoretical analysis. Fig. 9 show waveforms for the primary voltage vp and current ip of the conventional PSFB series-resonant converter and the proposed converter at full-load condition under the normal input range. In the conventional PSFB series-resonant converter, to guarantee the designated operation range, higher turn ratio n (=0.417) is required than the proposed converter. Other parameters are shown in Table I. When the input voltage Vd is 350V, the conventional converter operates with small φ (=0.5). On the other hand, the proposed converter is operated with larger φ .

V. CONCLUSION

The novel hybrid-kind complete-bridge dc/dc converter with excessive performance has been brought and proven by using the analysis and experimental effects. By the usage of the hybrid control scheme with the easy circuit structure, the proposed converter has both the step-down and step-up functions, which ensure to cover the huge enter range. Under the everyday input range, the proposed converter achieves high performance through presenting soft switching method to all of the switches and rectifier diodes, and lowering the modern-day stress. When the input is decrease than the ordinary input range, the proposed converter gives the step-up feature by way of the use of the energetic-clamp circuit and voltage doubler, which extends the operation range. To confirm the validity of the proposed converter, 1kW prototype changed into built and tested. Under the regular input range, the conversion performance is over 96% at full-load circumstance, and the enter range from 250V to 350V is guaranteed. Thus, the proposed converter has many benefits which includes high efficiency and huge enter variety.

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