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Analysis and Implementation of a Phase-Shift Pulse-Width Modulation Converter with Auxiliary Winding Turns

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Abstract: A phase-shift pulse-width modulation converter is studied and investigated for railway vehicle or solar cell power converter applications with wide voltage operation. For railway vehicle applications, input voltage range of dc converters is requested to have 30–40% voltage variation of the nominal input voltage. The nominal input voltages of dc converters on railway vehicles applications may be 37.5 V, 48 V, 72 V, 96 V and 110 V. Therefore, a new dc converter with wide input voltage operation from 25 to 150 V is presented to withstand different nominal input voltage levels such as 37.5–110 V on railway power units. To realize wide input voltage operation, an auxiliary switch and auxiliary transformer windings are used on output side of conventional full-bridge converter to have different voltage gains under different input voltage values. Phase-shift pulse-width modulation is adopted in the developed dc converter to accomplish soft switching operation on power switches. To confirm and validate the practicability of the presented converter, experiments based on a 300 W prototype were provided in this paper.

Keywords: PS-PWM (Phase-shift pulse-width modulation); power converter; full-bridge converter

1. Introduction

High efficiency power converters have been developed in renewable energy power conversion. However, the output voltage of solar panel varies widely and the voltage value is related to solar intensity. Thus, dc converters with wide voltage operation are demanded to convert solar energy to electric power. The dc-dc converters are required on railway vehicles for communication systems, braking systems, electric door systems and solid state lighting systems. However, the nominal input voltages of these control systems are different. The normal input voltages for the different applications are 110 V, 72 V, 48 V and 37.5 V. The international standard EN50155 demands a minimum $\pm 30\%$ voltage variation of the nominal input voltage for dc-dc converters in railway applications. Therefore, high efficiency dc-dc converters with wide input voltage operation from 37.5 V to 110 V with $\pm 30\%$ voltage variation are necessary for railway systems. Two-stage converters [1–3] are normally employed to realize wide voltage operation. The buck, buck-boost or boost circuit topology can be used in the first stage and full-bridge, half-bridge, forward or flyback circuit topology can be used in the second stage. However, the drawbacks of two stage converters are low circuit efficiency and more circuit components. The dc converters with series/parallel connection to achieve wide input voltage operation have been presented in [4–7]. Full-bridge or half-bridge converters with phase-shift pulse-width modulation (PS-PWM) on the secondary side have been discussed in [8–11] to realize soft switching and wide voltage operation. Series resonant converters or PS-PWM converters with wide voltage operation have been proposed in [12–19]. However, the input or output voltage range proposed in circuit topologies [4–19] is less than 4:1, i.e. $V_{in,max} \leq 4V_{in,min}$. For solar power conversion or

railway vehicle power converters, the input voltage range of dc converters may be greater than 6:1, i.e. $V_{in,max} \geq 6V_{in,min}$.

A single-stage dc converter is investigated to accomplish the wider voltage range (6:1 input voltage range, 150–25 V) and less switching loss. Full-bridge converter with two secondary windings and an auxiliary switch is used to achieve wide voltage range operation capability. For the low input voltage range, the auxiliary switch on output side is conducting. Thus, the high turns-ratio between the secondary-side and primary-side of transformer is employed to generate high voltage gain. On the other hand, the auxiliary switching is off and low transformer turns-ratio is adopted to obtain low voltage gain under high input voltage operation. Therefore, the wide voltage range operation is achieved in the presented circuit. Since the PS-PWM scheme is used to control full-bridge converter, active devices on the studied converter are worked at zero-voltage switching so that the switching losses can be decreased. Compared to conventional two-stage dc converters, the proposed converter has less power conversion stage and better circuit efficiency. Compared to conventional single-stage dc converters with 2:1 or 4:1 voltage range, the proposed converter has much wider input voltage operation range with 6:1 voltage range. Finally, the performance of the developed circuit is investigated by the measured waveforms from a laboratory circuit.

2. Circuit Structure

The proposed circuit with wide voltage operation is shown in Figure 1a. The basic structure of the studied circuit is a full-bridge circuit, $Q_1 \sim Q_4$, L_{lk} , and T , on input side and a center-tapped rectifier with two sets of secondary windings N_{s1} and N_{s2} and an auxiliary switch S on output side.

Figure 1. Proposed 6:1 wide voltage range converter (a) circuit diagram (b) low voltage range operation (c) high voltage range operation.

In relation to input voltage value, the studied circuit has two voltage operation ranges, low input voltage range and high input voltage range. When V_{in} is at low voltage range $V_{in} = V_{in,min} \sim 3V_{in,min}$ (3:1 operation range), the auxiliary switch S is in the on-state (Figure 1b). D_2 and D_3 are reverse biased. The secondary winding turns $N_{s1} + N_{s2}$ are connected to output side. The turn-ratio of transformer T is $N_p/(N_{s1} + N_{s2})$ and the converter has higher dc voltage gain for low input voltage operation. The effective duty cycle of full-bridge converter is depended on input voltage value to maintain output voltage constant. PS-PWM scheme is used to control phase-shift angle between the lagging-leg and leading-leg. Therefore, the soft switching characteristics of power switches on full-bridge converter can be achieved. If V_{in} is at high voltage range $V_{in} = 2V_{in,min} \sim 6V_{in,min}$ (3:1 operation range), auxiliary switch S is in the off-state and D_1 and D_4 are off as shown in Figure 1c. The secondary turns N_{s1} are connected to output side and the transformer turn-ratio is N_p/N_{s1} . Thus, the presented circuit has lower dc voltage gain in high input voltage operation. Based on the on/off states of auxiliary switch S and winding turns $N_{s1} + N_{s2}$ or N_{s1} connected to output load, a soft switching full-bridge converter with 6:1 ($V_{in,max}/V_{in,min} = 6$) wide input voltage range is accomplished in the studied circuit.

3. Operation Principle

The duty cycle control is used to generate the proper switching signals and provide a stable output voltage against the variation of V_{in} and I_o . According to input voltage value, auxiliary switch S is controlled at on-state or off-state for low voltage range operation or high voltage range operation. In the studied converter, it is assumed that $L_m \gg L_{lk}$, $C_{Q1} = \dots = C_{Q4} = C_{oss}$ and $N_{s1} = N_{s2} = N_s$. The proposed circuit has two input voltage ranges, $V_{in,min} \sim 3V_{in,min}$ and $2V_{in,min} \sim 6V_{in,min}$. The pulse-width modulation waveforms and the equivalent circuits for two input voltage ranges are provided in Figures 2 and 3. For each input voltage range, the proposed circuit has ten modes in every switching cycle.

3.1. Low Voltage Range (S on)

When $V_{in,min} < V_{in} < 3V_{in,min}$, auxiliary switch S is turned on. The effective duty cycle d_{eff} of full-bridge circuit is related to input voltage. The transformer turn-ratio in low voltage range is $n_L = N_p/(N_{s1} + N_{s2})$. The dc voltage gain is expressed as $G_L = V_o/V_{in,L} = 2d_{eff}/n_L$ where $V_{in,L}$ denotes V_{in} in low input voltage range. The pulse-width modulation waveforms are given in Figure 2a and the ten equivalent circuits for low voltage range operation are provided in Figure 2b–k.

Mode 1 [t_0, t_1]: In mode 1, Q_1 and Q_4 are on and $v_{Lm} \approx V_{in}$ due to $L_m \gg L_{lk}$. The power flow from input source to output load is through L_{lk} , T , D_1 , L_o and C_o . The output inductor voltage $v_{L_o} \approx V_{in}/n_L - V_o > 0$ and i_{L_o} increases.

Mode 2 [t_1, t_2]: Q_1 is off at time t_1 . Because of $i_p(t_1) > 0$, C_{Q2} (C_{Q1}) is discharged (charged). Due to C_{Q1} and C_{Q2} are low capacitances, i_p and i_{D1} are almost constant. At time t_2 , $v_{CQ2} = 0$ and the time duration in mode 2 is calculated as $\Delta t_{mode\ 2} \approx 2V_{in}C_{oss}n_L/i_{L_o}(t_1)$.

Mode 3 [t_2, t_3]: Since $i_p(t_2) > 0$ and $v_{CQ2}(t_2) = 0$, D_{Q2} conducts and Q_2 turns on after t_2 to have zero-voltage switching characteristic. In order to have soft switching operation, the dead time t_d between Q_1 and Q_2 is needed and expressed as $t_d > \Delta t_{mode\ 2} = 2V_{in}C_{oss}n_L/i_{L_o}(t_1)$. Since $L_{lk} \ll L_m$ and $R_{on,sw}$ (turn-on resistance of switches Q_1 and Q_2) is about hundreds of milliohm, the transformer primary voltage v_{Lm} and the secondary voltages $v_{s,N1}$ and $v_{s,N2}$ approximate zero voltage. D_1 and D_4 are forward biased. Then the inductor voltage $v_{L_o} = -V_o$ and i_{L_o} decreases. The primary current $i_p(t) \approx i_p(t_2) - V_{Q24,drop}/r_{lk}$ where r_{lk} is the equivalent resistance on L_{lk} and $V_{Q24,drop}$ is voltage drop on Q_2 and Q_4 .

Mode 4 [t_3, t_4]: At time t_3 , S_4 is off. Because of $i_p(t_3) > 0$, C_{S3} (C_{S4}) is discharged (charged). Due to C_{S3} and C_{S4} are low capacitances, i_p , i_{D1} and i_{D4} are constant. At time t_4 , $v_{CQ3} = 0$. The time duration in mode 4 is calculated as $\Delta t_{mode\ 4} \approx 2V_{in}C_{oss}/i_p(t_3)$.

Mode 5 [t_4, t_5]: Because of $i_p(t_4) > 0$ and $v_{CQ3}(t_4) = 0$, D_{Q3} is forward biased and S_3 turns on after t_4 to have zero-voltage switching operation. Due to both D_1 and D_4 are conducting, the primary

magnetizing voltage v_{Lm} is clamped at zero voltage. Thus, the leakage inductor voltage $v_{Llk} = -V_{in}$ and i_p is decreased. In this mode, i_{D1} (i_{D4}) is decreased (increased) to 0 (i_{Lo}) at time t_5 . The time duration in mode 5 is expressed as:

$$\Delta t_{\text{mode } 5} = (i_p(t_4) - i_p(t_5))L_{lk}/V_{in} \approx 2I_oL_{lk}/(n_LV_{in}) \quad (1)$$

The duty loss in Mode 5 is calculated in (2):

$$d_{\text{loss},5} \approx 2I_oL_{lk}f_{sw}/(n_LV_{in}) \quad (2)$$

The waveforms in modes 6–10 are symmetry to waveforms in modes 1–5. Therefore, the analysis and discussion of modes 6–10 are neglected in this section.

Figure 2. Cont.

(d)

(e)

(f)

(g)

(h)

Figure 2. Cont.

Figure 2. Proposed converter for low input voltage range (a) pulse-width modulation waveforms (b) mode 1 circuit (c) mode 2 circuit (d) mode 3 circuit (e) mode 4 circuit (f) mode 5 circuit (g) mode 6 circuit (h) mode 7 circuit (i) mode 8 circuit (j) mode 9 circuit (k) mode 10 circuit.

3.2. High Voltage Range (S off)

When $2V_{in,min} < V_{in} \leq 6V_{in,min}$, S is off and D_1 and D_4 are reverse biased as shown in Figure 1c. Only the secondary turns N_{s1} are connected to output load and the turn-ratio of transformer in high voltage range is $n_H = N_p/N_{s1}$. The effective duty cycle d_{eff} depends on V_{in} and I_o . The dc voltage gain in high voltage range operation is given as $G_H = V_o/V_{in,H} = 2d_{eff}/n_H$ where $V_{in,H}$ denotes V_{in} in high input voltage range. Since turn-ratio $n_H = 2n_L$ due to $N_{s1} = N_{s2}$, it can obtain $G_H = G_L/2$ under the same effective duty cycle d_{eff} . That means the proposed converter has high voltage gain in low input voltage range and low voltage gain in high input voltage range. The circuit waveforms in high voltage range operation are provided in Figure 3a and the ten equivalent circuits for high voltage range operation are illustrated in Figure 3b–k. The circuit operation in Figure 3b–k with the secondary winding turns N_{s1} in high voltage range are similar to the circuit operations in low voltage range presented in previous section. Therefore, the circuit analysis of the presented circuit operated at high voltage range are ignored in this section.

Figure 3. Cont.

(e)

(f)

(g)

(h)

(i)

Figure 3. Cont.

Figure 3. Proposed converter for high input voltage range (a) pulse-width modulation waveforms (b) mode 1 circuit (c) mode 2 circuit (d) mode 3 circuit (e) mode 4 circuit (f) mode 5 circuit (g) mode 6 circuit (h) mode 7 circuit (i) mode 8 circuit (j) mode 9 circuit (k) mode 10 circuit.

4. Circuit Characteristics and Design Example

Full-bridge PS-PWM converter with auxiliary secondary turns is adopted in the studied circuit to accomplish wide input voltage range operation. The effective duty cycle between the lagging-leg and leading leg is regulated under the different input voltage value and load current. For low (high) input voltage range, switch S is on (off) and the winding turns $N_{s1} + N_{s2}$ (N_{s1}) are connected to output terminal. The output voltage can be derived in (3) from flux balance theory on L_o :

$$V_o = \begin{cases} \frac{2V_{in,L}}{n_L} \left(d - \frac{2L_{lk}I_o f_{sw}}{n_L V_{in,L}} \right), & S \text{ on} \\ \frac{2V_{in,H}}{n_H} \left(d - \frac{2L_{lk}I_o f_{sw}}{n_H V_{in,H}} \right), & S \text{ off} \end{cases} \quad (3)$$

where d is duty cycle of leg voltage v_{ab} and $d = d_{eff} - d_{loss,5}$. The average value of output inductor current i_{L_o} equals I_o . The voltage ratings of active switches Q_1 – Q_4 equal $V_{in,max}$. The voltage ratings of D_1 – D_4 and S are functions of $V_{in,max}$, n_L and n_H .

$$V_{D1, rating} = V_{D4, rating} \approx 2V_{in,max}/n_L \quad (4)$$

$$V_{D2, rating} = V_{D3, rating} \approx 2V_{in,max}/n_H \quad (5)$$

$$V_{S, rating} \approx V_{in,max}/n_H \quad (6)$$

The average values of diode currents are $I_{D1} = \dots = I_{D4} = I_o/2$ and $I_{S,av} = I_o$. The output inductance L_o approximates:

$$L_o \approx \frac{(V_{in,max}/n_H - V_o)d_{eff,min}}{\Delta i_{L_o} f_{sw}} \quad (7)$$

The duty loss in Mode 5 is related to the leakage inductance L_{lk} . If the maximum duty loss is defined, then the leakage inductance L_{lk} is calculated in (8):

$$L_{lk} = \frac{n_L d_{loss,5} V_{in,min}}{2I_o f_{sw}} \quad (8)$$

The proposed converter is designed with the following parameters: $V_{in} = 150\text{--}25\text{ V}$ (6:1 ratio), $V_o = 12\text{ V}$, $I_{o, rated} = 25\text{ A}$, $P_o = 300\text{ W}$ and $f_{sw} = 100\text{ kHz}$. When $V_{in} = 25\text{--}75\text{ V}$ (low input voltage range), auxiliary switch S is on to obtain a high voltage gain due to the secondary turns $N_{s1} + N_{s2}$ are connected to output side. If V_{in} is increased and equal to 75 V , then switch S turns off and the converter is operated in high voltage range. The winding turns N_{s1} are connected to output side. If the input voltage is decreased from 150 V to 50 V , then switch S turns on and the circuit is operated in low voltage range. Thus, the proposed converter works in high voltage range when $V_{in} = 150\text{--}50\text{ V}$. It is assumed the proposed converter has 85% efficiency at $V_{in, min} = 25\text{ V}$ and 100% power under low voltage range. The maximum duty cycle of leg voltage v_{ab} at $V_{in, min} = 25\text{ V}$ is assumed 0.45 and the assumed duty cycle loss $d_{loss, 5} = 0.08$:

$$d_{loss, 5} = 2I_o L_{lk} f_{sw} / n_L V_{in, min} = 0.04 \quad (9)$$

From (3) and (9), the leakage inductance approximates:

$$L_{lk} = \frac{\eta d_{loss, 5} d_{max} V_{in, min}^2}{P_o f_{sw}} \approx 0.6375\text{ }\mu\text{H} \quad (10)$$

From (3), the turn-ratio n_L can be derived in (11):

$$n_L \approx \frac{d_{max} V_{in, min} + \sqrt{(d_{max} V_{in, min})^2 - 4V_o L_{lk} I_o f_{sw}}}{V_o} \approx 1.5 \quad (11)$$

In the prototype circuit, transformer T is implemented using TDK (Tokyo Electric Chemical Industry Co., Ltd.) EER-42 ferrite core with winding turns $N_p = 12$ and $N_{s1} = N_{s2} = 4$ and $L_m = 400\text{ }\mu\text{H}$. The minimum effective duty cycle $d_{eff, min}$ at $V_{in, L, max} = 75\text{ V}$ is derived in (12):

$$d_{eff, min} = \frac{d_{eff, max} V_{in, L, min}}{V_{in, L, max}} = \frac{(0.45 - 0.08) \times 25}{75} \approx 0.123 \quad (12)$$

The maximum ripple current Δi_{L_o} at $V_{in, L, max} = 75\text{ V}$ (low input voltage range) is assumed 30% of load current. From (7), the inductance L_o is expressed as:

$$L_o \approx \frac{(V_{in, L, max} / n_L - V_o) d_{eff, min}}{\Delta i_{L_o} f_{sw}} \approx 6.23\text{ }\mu\text{H} \quad (13)$$

The $L_o = 8\text{ }\mu\text{H}$ is used in the prototype circuit. The *rms* (root-mean-square) currents of $Q_1\text{--}Q_4$ are approximately calculated as:

$$i_{Q1, rms} = \dots = i_{Q4, rms} = \frac{I_{o, rated}}{n_L \eta \sqrt{2}} \approx 13.9\text{ A} \quad (14)$$

The maximum voltage on $Q_1\text{--}Q_4$ is the maximum input voltage $V_{in, max} = 150\text{ V}$. The average diode currents $I_{D1}\text{--}I_{D4}$ are 12.5 A . The voltage ratings of $D_1\text{--}D_4$ are given in (15) and (16):

$$V_{D1, rating} = V_{D4, rating} \approx 2V_{in, max} / n_L = 200\text{ V} \quad (15)$$

$$V_{D2, rating} = V_{D3, rating} \approx 2V_{in, max} / n_H = 100\text{ V} \quad (16)$$

MOSFETs (metal–oxide–semiconductor field-effect transistor) IRFB4229 with $250\text{ V}/46\text{ A}$ ratings are adopted for active switch $Q_1\text{--}Q_4$ and IRF3145 with $150\text{ V}/30\text{ A}$ ratings is adopted for auxiliary switch S . Fast recovery diodes APT30DQ60BG with $600\text{ V}/30\text{ A}$ ratings are selected for $D_1\text{--}D_4$ and the output capacitance $C_o = 2000\text{ }\mu\text{F}$.

5. Simulated and Experimental Results

Figure 4a shows the control block of the signals $Q_1 \sim Q_4$ and S . Schmitt trigger comparator is adopted to generate the signal S in order to select the correct range of input voltage. The PWM signals are generated by phase-shift PWM integrated circuit UCC3895. The output voltage is controlled by the voltage regulator TL431 and PC817. Figure 4b provides the photograph of the prototype. Figure 5 demonstrates the simulated results of the primary-side and the secondary-side voltages and currents at full load under low input voltage range for both $V_{in} = 25$ V and 75 V. One can observe that the effective duty cycle of v_{ab} at $V_{in} = 25$ V is larger than the duty cycle at $V_{in} = 75$ V. Therefore, the current ripple Δi_{Lo} at $V_{in} = 25$ V is less than current ripple Δi_{Lo} at $V_{in} = 75$ V. Similarly, the simulated results of the presented circuit operated at high input voltage range are provided in Figure 6 for both $V_{in} = 150$ V and 50 V. The lower input voltage ($V_{in} = 50$ V) has the larger duty cycle to reduce the output ripple current Δi_{Lo} compared to the condition at $V_{in} = 150$ V case. Experiments from a prototype with circuit components derived from previous section are provided to demonstrate the converter performance. The proposed circuit is operated at low input voltage range when V_{in} is increased from 25 V to 75 V. Then, the circuit goes to the high input voltage mode. If the input voltage is decreased from 150 V to 50 V, then the circuit operation goes to low input voltage range. Based on the input voltage operation range. Figures 7–9 gives the test results when input voltage is in low voltage range. Under low input voltage range, auxiliary switch S is on. Thus, the rectifier diodes D_2 and D_3 are reverse biased and off. Figure 7a,b show the experimental waveforms of the gate voltages, leg voltage v_{ab} and the primary current i_p at $V_{in} = 25$ V and 75 V and the rated output. It is clear that the converter has less phase-shift between Q_1 and Q_4 and larger duty cycle on leg voltage v_{ab} at $V_{in} = 25$ V input. Figure 7c,d provides the test waveforms of i_{D1} , i_{D4} and i_{Lo} at $V_{in} = 25$ V and 75 V and the rated power. Due the converter at $V_{in} = 25$ V input has large duty cycle, i_{Lo} has less current ripple at $V_{in} = 25$ V input compared to $V_{in} = 75$ V input. Figure 8a,b provides the experimental waveforms of switch Q_1 in leading-leg at 20% and 100% loads under $V_{in} = 25$ V input. It is clear the soft switching operation of Q_1 is achieved from 20% load under 25 V input case. In the same manner, test waveforms of Q_1 at 20% and 100% loads under 75 V input are given in Figure 8c,d. It can observe that Q_1 is also turned on at zero-voltage switching from 20% load at $V_{in} = 75$ V input case. Switches Q_1 and Q_2 have the same turn-on/off characteristics in the leading-leg. Therefore, the soft switching operation of switches Q_1 and Q_2 at leading-leg can be accomplished from 20% load in low input voltage range operation. Figure 9a,b show the test waveforms of the switch Q_3 at lagging-leg for 20% and 100% loads under 25 V input. It is clear that Q_3 is also turned on at zero voltage switching from 20% load. Figure 9c,d provide the measured waveforms of Q_3 at 75 V input. It can observe that Q_3 is hard switching at 75 V input case for both 20% and 100% loads. The soft switching condition of power switches at lagging-leg (leading-leg) is related to the leakage inductor (output inductor). Normally, the leakage inductance is much less than the output inductance. Therefore, power switches at leading-leg have wide zero-voltage switching range compared to the lagging-leg switches. The test results shown in Figures 8 and 9 agree with these statements. Figures 10–12 gives the experimental waveforms of the proposed converter for high input voltage range operation at 150 V and 50 V input. The test waveforms of $v_{Q1,g}$, $v_{Q4,g}$, v_{ab} and i_p at $V_{in} = 150$ V and 50 V under rated power are provided in Figure 10a,b. Compared to 150 V input case, the proposed converter has less phase-shift between Q_1 and Q_4 and larger duty cycle on leg voltage v_{ab} at $V_{in} = 50$ V input. The test results of i_{D1} , i_{D4} and i_{Lo} at 100% load under 150 V and 50 V input are shown in Figure 10c,d. Figure 11 provides the experimental waveforms of leading-leg switch Q_1 at various load power and input voltage values in high voltage range operation. It is clear that the soft switching operation of Q_1 is accomplished from 20% load for both 150 V and 50 V input. Similarly, the test waveforms of lagging-leg switch Q_3 at various load power and input voltage values are demonstrated in Figure 12. It can be observed that Q_3 has soft switching operation only at 50 V input under 100% load and hard switching operation for the other conditions. Figure 13 provides the test results of the circuit efficiencies. For both low and high voltage range operation, the lower input voltage has larger effective duty cycle and less conduction losses on power switches compared

to the higher input voltage. Thus, the circuit efficiency at 25 V input is better than 75 V input in low input voltage range. Similarly, the circuit efficiency at 50 V is better than 150 V input in high voltage range operation.

Figure 4. Prototype circuit (a) control block of the signals S and $Q_1 \sim Q_4$ (b) picture of the prototype.

Figure 5. Simulated results in low input voltage range and full load (a) primary side waveforms at 25 V input (b) primary side waveforms at 75 V input (c) secondary side waveforms at 25 V input (d) secondary side waveforms at 75 V input.

Figure 6. Simulated results in high input voltage range and full load (a) primary side waveforms at 150 V input (b) primary side waveforms at 50 V input (c) secondary side waveforms at 150 V input (d) secondary side waveforms at 50 V input.

Figure 7. Experimental results in low input voltage range and full load (a) primary side waveforms at 25 V input (b) primary side waveforms at 75 V input (c) secondary side waveforms at 25 V input (d) secondary side waveforms at 75 V input.

Figure 8. Experimental waveforms of the leading-leg switch Q_1 in low input voltage range at (a) 25 V input and 20% load (b) 25 V input and 100% load (c) 75 V input and 20% load (d) 75 V input and 100% load.

Figure 9. Cont.

Figure 9. Experimental waveforms of the lagging-leg switch Q_3 in low input voltage range at (a) 25 V input and 20% load (b) 25 V input and 100% load (c) 75 V input and 20% load (d) 75 V input and 100% load.

Figure 10. Experimental results in high input voltage range and full load (a) primary side waveforms at 150 V input (b) primary side waveforms at 50 V input (c) secondary side waveforms at 150 V input (d) secondary side waveforms at 50 V input.

Figure 11. Experimental waveforms of the leading-leg switch Q_1 in high input voltage range at (a) 150 V input and 20% load (b) 150 V input and 100% load (c) 50 V input and 20% load (d) 50 V input and 100% load.

Figure 12. Cont.

Figure 12. Experimental waveforms of the lagging-leg switch Q_3 in high input voltage range at (a) 150 V input and 20% load (b) 150 V input and 100% load (c) 50 V input and 20% load (d) 50 V input and 100% load.

Figure 13. Measured circuit efficiencies (a) in low input voltage range (b) in high input voltage range.

6. Conclusions

A full-bridge PS-PWM converter with auxiliary secondary turns is investigated to demonstrate the capability of 6:1 wide input voltage range operation for railway vehicle low power units and solar power converters. To achieve wide voltage range operation, two sets of secondary windings are used in the studied circuit. According to the different secondary winding turns connected to output terminal, there are two input voltage range operations in the converter. In each voltage range, the circuit can realize the 3:1 input voltage range operation. For low voltage range, the high transformer turns-ratio is adopted to achieve higher dc voltage gain. On the other hand, a low turns-ratio of transformer is used to obtain lower dc voltage gain of the studied circuit. Therefore, a 6:1 wide voltage operation is implemented in the presented converter. PS-PWM scheme is used to accomplish soft switching operation for leading-leg switches. The feasibility of the studied converter is verified and confirmed by a design example and some experiments in this paper.

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