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Development of the High Input Voltage Self-Power for LVDC

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〈Abstract〉

Distributed resources such as renewable energy sources and ESS are connected to the low voltage direct current(LVDC) distribution network through the power conversion system(PCS). Control power is required for the operation of the PCS. In general, controller power is supplied from AC power or DC power through switch mode power supply(SMPS). However, the conventional SMPS has a low input voltage, so development and research on high input voltage self-power suitable for LVDC is insufficient. In this paper, to develop Self-Power that can be used for LVDC, the characteristics of the conventional topology are analyzed, and a series-input single-output flyback converter using a flux-sharing transformer for high voltage is designed. The high input voltage Self-Power was designed in the DCM(discontinuous current mode) to reduce the switching loss and solve the problem of current dissipation. In addition, since it operates even at low input voltage, it can be applied to many applications as well as LVDC. The validity of the proposed high input voltage self-power is verified through experiments.

Keywords : Low Voltage Direct Current(LVDC), Switch Mode Power Supply(SMPS), Self-Power, Flyback Converter

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1. Introduction

Due to the expansion of distributed resources such as renewable energy and ESS, interest and research on DC power distribution are being actively carried out recently. DC distribution is easy to connect with distributed resources, can control power flow, and has high efficiency compared to AC distribution[1-3]. DC distribution can be divided into HVDC, MVDC, and LVDC according to the voltage level. In particular, low voltage direct current(LVDC) has a voltage level of 1500V or less and is used as a DC microgrid in long-distance low-load areas and island areas[4]. Distributed resources are connected to the LVDC distribution network through the PCS(power conversion system). The power for controller is required for the operation of the PCS. In general, controller power is supplied from AC power or DC power through Self-Power SMPS. However, since most of the conventional SMPS are manufactured for an effective value of 220 [V] or 380 [V], development and research on high input voltage SMPS suitable for LVDC is insufficient[5-7].

In this paper, Self-Power with high input voltage connected to LVDC is developed. Since Self-Power for LVDC operates at higher input voltage than conventional SMPS, SMPS is designed using series-input single-output flyback topology suitable for high input voltage. This structure has the advantage that the voltage of each capacitor is automatically balanced in terms of the topological structure. After analyzing the operation mode of the conventional flyback converter, the principle of automatic voltage balancing of series-input single-output flyback converter will be described. Finally, the validity of the proposed method is verified through experiments.

2. The high input voltage Self-Power

2.1 A flyback converter

Figure 1 shows the circuit considering the parasitic capacitor C_{ds} across the drain-source of the conventional flyback converter. In order to analyze the operation mode according to the turn-on/off of the switching device Q_1 in Figure 1, the current path according to each mode is shown in Figure 2, and the discontinuous current mode(DCM) will be described as the basis. Figure 3 shows the voltages and currents for each mode.

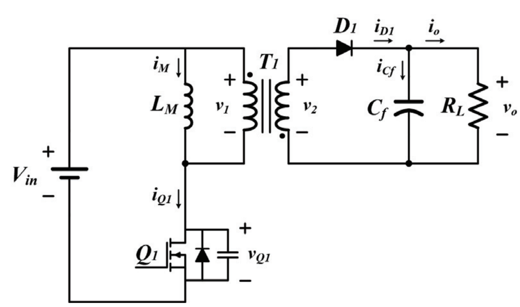


Fig. 1 Flyback converter

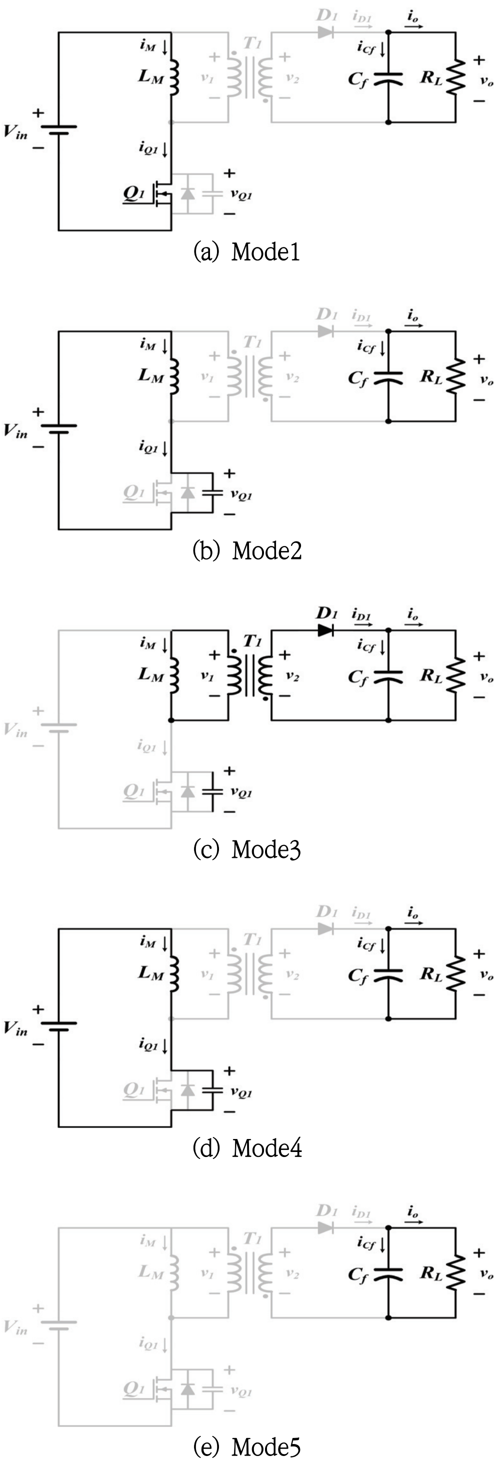


Fig. 2 Current paths of flyback converter mode

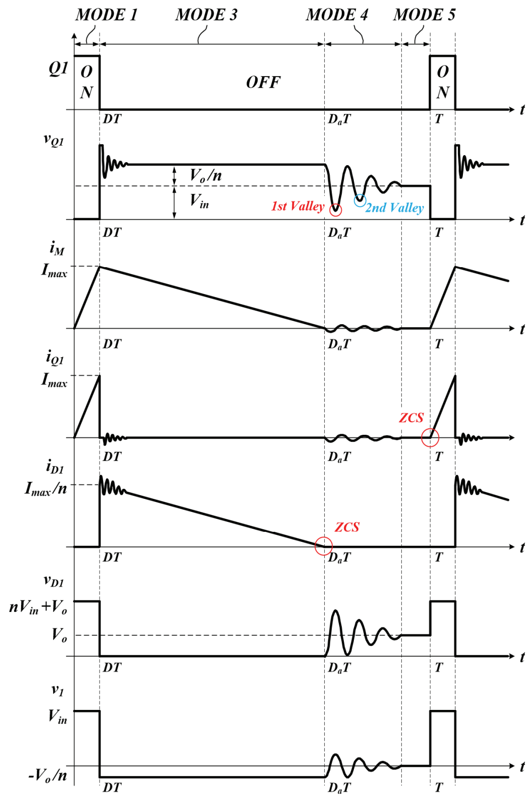


Fig. 3 Voltages and currents of flyback converter

Mode 1 :

Q_1 is turned on so that the voltage v_{Q1} becomes 0, and the current i_M of the magnetizing inductance L_M rises with a constant slope by the input voltage V_{in}. ΔI_M is described as

$$\Delta I_M = I_{\max} = \frac{V_{in}}{L_M} DT \tag{1}$$

where D is duty ratio, and T is a switching period. At this time, since the magnetizing current rises from 0, a zero current switching (ZCS) operation occurs when Q_1 is turned on, and ΔI_M is equal to I_{max}.

Mode 2 :

As Q_1 turns off and energy is stored in the parasitic capacitor component C_{ds}, the voltage v_{Q1} rises. Since this time is very short, it is excluded from Figure 3.

Mode 3 :

In the beginning of Mode 3, initial voltage spike and vibration will occur in v_{Q1} due to C_{ds}. At this time, energy is stored in the C_{ds}. In Mode 3, i_M decreases from I_{max} to 0, and the time point at which i_M becomes 0 is defined as D_aT. ΔI_M in Mode 3 is described as

$$\Delta I_M = \frac{V_o/n}{L_M}(D_a - D)T \tag{2}$$

In the case of a steady state, since ΔI_M in Mode 1 and Mode 3 is the same, Equations (1) and (2) are expressed as

$$\frac{V_{in}}{L_M}DT = \frac{V_o/n}{L_M}(D_a - D)T \tag{3}$$

Then, voltage transfer ratio G_V is defined as

$$G_v = \frac{V_o}{V_{in}} = \frac{nD}{D_a - D} \tag{4}$$

This means that G_V is determined by the ratio of the time flowing through Q_1 to the time flowing through D_1. At this time, D_1 perform ZCS as the current becomes 0.

Mode 4 :

As the magnetizing current i_M is extinguished to 0, D_1 is turned off. At this time, the energy stored in the C_{ds} is transferred to the L_M, and L_C resonance occurs. The minimum point of v_{Q1} caused by these oscillations is called a valley. If Q_1 is turned on at this valley point, switching loss can be reduced, and this switching method is called valley switching.

Mode 5 :

Mode 5 is defined as the state in which the magnetizing current i_M becomes to 0 and the resonance disappears. v_{Q1} becomes V_{in}, and v_{D1} becomes V_o. At this time, since the average capacitor current I_{Cf} is 0, the average load current I_o is equal to the average current I_{D1} of the diode. Therefore, I_{D1} is described as

$$I_{D1} = \frac{1}{T}\int_0^T i_{D1}(t)dt = \frac{(D_a - D)I_{\max}}{2n} = \frac{V_o}{R_L} \tag{5}$$

where R_L is load resistance. After substituting (2) into (5), arrange for $(D_a\text{-}D)$, and substituting it into (4), G_V is redefined as

$$G_v = D\sqrt{\frac{R_L T}{2L_M}} \tag{6}$$

From equation (6), it can be seen that the output of the flyback converter in DCM is determined by the time ratio, load resistance, magnetizing inductance, and switching period.

As analyzed above, DCM can reduce switching loss by ZCS operation during turn-on of Q_1 and turn-off of D_1. In case of valley switching using resonance, the switching loss can be further reduced. However, in the flyback converter, the maximum voltage applied to the switch is $V_{in}+V_o/n+V_{RCD}$, where V_{RCD} is RCD snuber voltage. So, a switching device with high withstand voltage is required to design Self-Power for LVDC. A switching device having a high withstand voltage is expensive and has a high loss due to high $R_{ds(on)}$. In addition, it is difficult to design the Self-Power to have a wide input voltage of 250~1200V using the conventional flyback converter. And EMI problem occurs due to high dv/dt. Therefore, the 60 [W] Self-Power developed in this paper has a greater switching loss than conduction loss, so it is designed with DCM and uses a topology that uses a low withstand voltage switching device.

2.2 High input voltage flyback converter

Figure 4 shows a series-input single-output flyback converter used in this development. It has a structure in which three flyback converters are connected with three capacitor voltage sources connected in series to one high-frequency transformer with three excitation windings and one output winding. In this structure of N converters using one high-frequency transformer, all converters share magnetic flux through one high-frequency transformer and apply multiple excitation voltages to the transformer terminal voltage by a synchronized signal. By this structure, the voltages of all converters automatically converge to the same voltage.

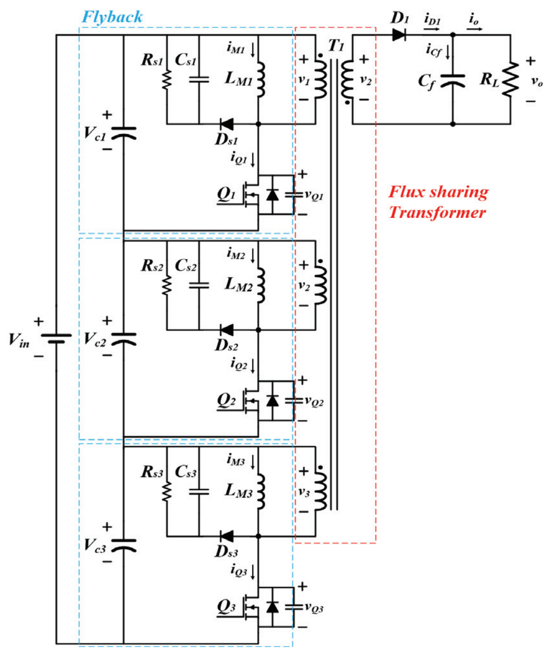


Fig. 4 A series-input single-output flyback converter

In Mode 1 where switches Q_1, Q_2, and Q_3 are turned on, the magnetizing currents i_{M1}, i_{M2}, and i_{M3} of each flyback converter are expressed as

$$\begin{aligned} i_{M1} &= \frac{v_{c1}}{L_{M1}}DT \\ i_{M2} &= \frac{v_{c2}}{L_{M2}}DT \\ i_{M3} &= \frac{v_{c3}}{L_{M3}}DT \end{aligned} \qquad (7)$$

as shown in (1) where v_{C1}, v_{C2}, v_{C3} are the capacitor voltages respectively. As shown in equation (7), the magnetizing current is proportional to the capacitor voltage and inversely proportional to the transformer magnetizing inductance. At this time, the energy stored in the magnetizing inductance is described as

$$E = \frac{1}{2}(DT)^2\left(\frac{v_{c1}^2}{L_{M1}} + \frac{v_{c2}^2}{L_{M2}} + \frac{v_{c3}^2}{L_{M3}}\right) \quad (8)$$

The voltage balancing of the series capacitors is automatically achieved by using more energy to the high voltage capacitor than the low voltage capacitor in the series capacitors.

Figure 5 shows the gate driver circuit for synchronous switching of a series-input single-output flyback converter. The primary side of the transformer is configured in an active clamp circuit. The upper switch and lower switch operate complementary. When the switch is turned on, a conduction path is formed from the power supply voltage to Rg.on through the transformer. When the switch is turned off, current conducts through Rg.off and the diode. It is similar with a half-bridge type gate driver. The gate

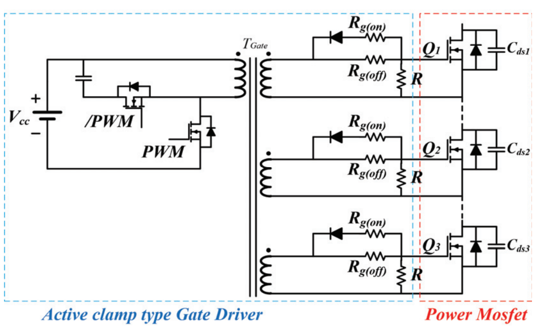


Fig. 5 Gate driver for a series-input single-output flyback converter

driver in Fig. 5 is suitable for high-density DC/DC converters because the switch in the gate driver operates as a ZCS during turn-on and turn-off, and the switching speed is fast.

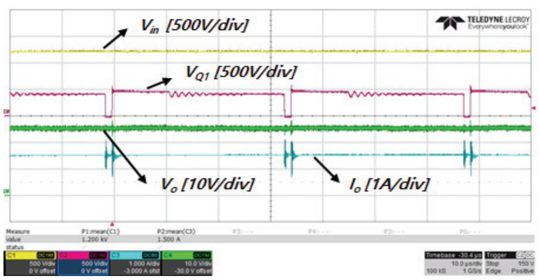
In this magnetic flux sharing structure, there is no energy consumption of the conventional passive voltage balancing method and the active voltage balancing method is not needed because the voltage balancing of the series capacitor is performed with only one transformer. However, one of the disadvantages of this structure is the saturation of the transformer, so it is necessary to control the current not to be saturated. Therefore, if the transforemr of a flyback converter is designed as DCM, it is possible to improve efficiency by reducing the switching loss and solve the saturation of the transformer.

3. Experiment result

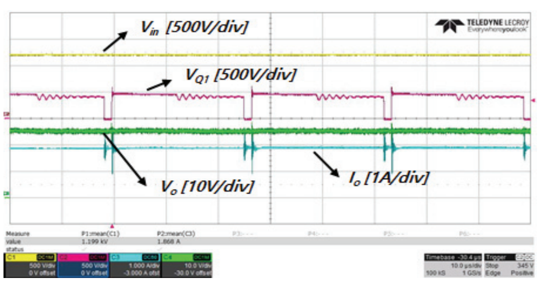
Table 1 shows the parameters of designed self-power SMPS for experiment. Figure 6 shows the input/output voltage and current waveforms in the case of 1200 [V] input voltage of the manufactured high input voltage Self-Power. It can be seen that the output voltage is constantly controlled at 24 [V]. When the output power is 36 [W], the switching frequency is about 29kHz, and the duty ratio is about 0.04. And, when the output power is 48 [W], the switching frequency is about 37 [kHz] and the duty ratio is about 0.05. As shown in equation (6), it can be seen that the output can be controlled through the switching frequency in DCM. Since the input voltage is high and the switching frequency is low, valley switching is not performed. Figure 7 shows the input/output voltage and current waveforms when the input voltage is 250V. As the input voltage is low, the switching frequency is controlled higher than in Figure 6, and it can be seen that valley switching is performed according to the load condition.

Table 1. Parameters of Self-Power

R_s	200 [KΩ]	$R_{g(on)}$	100 [Ω]
C_s	12 [nF]	$R_{g(off)}$	10 [Ω]
C_f	1000 [μF]	C_{ds}	75 [pF]

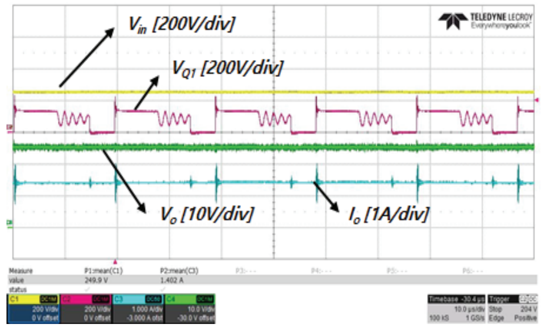


(a)

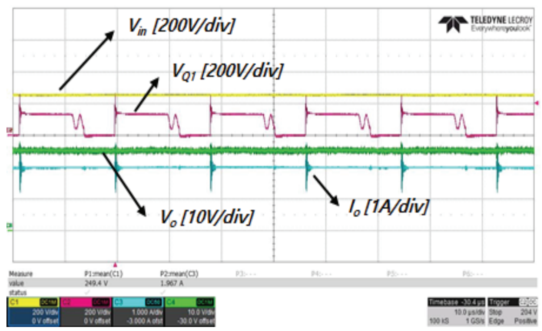


(b)

Fig. 6 Voltages and current according to load (V_{in} = 1200V). (a) P_o = 36W. (b) P_o = 48W



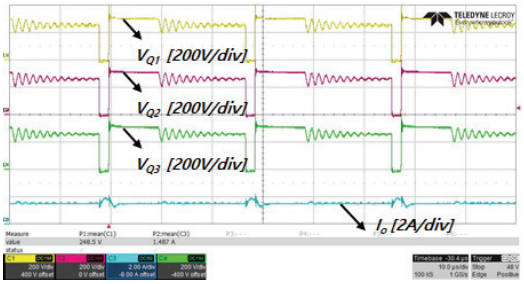
(a)



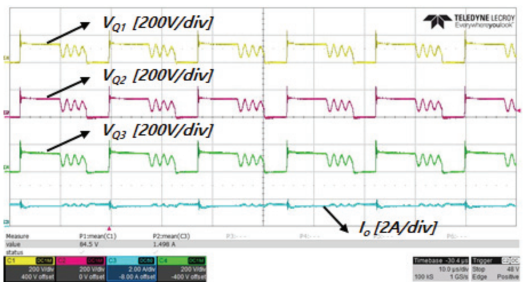
(b)

Fig. 7 Voltages and current according to load (V_{in} = 250V). (a) P_o = 36W. (b) P_o = 48W

Figure 8 shows each switch voltage according to the input voltage. It can be seen that each switch voltage is turned on/off at the same time and has the same voltage level. This means that the gate signal of each switch is synchronized and the voltage of each capacitor is balanced. Figure 9 shows the change in capacitor voltage when an input voltage of 1000 [V] is applied. When input voltage rises from 0 [V] to 1000 [V], the capacitor voltages draw the same curve, and it can be seen that the capacitor voltage has the same value even when the load current starts flowing as Self-Power starts to control.



(a)



(b)

Fig. 8 Switch voltages according to input voltage (P_o = 36W). (a) V_{in} = 1200V. (b) V_{in} = 250V

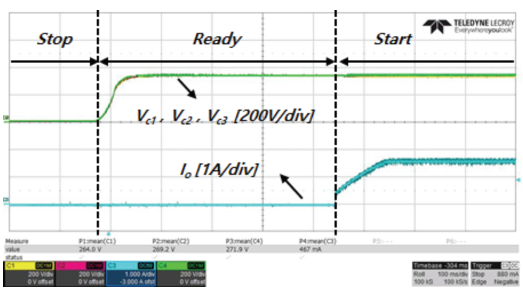


Fig. 9 Capacitor voltages and load current

4. Conclusion

In this paper, to develop Self-Power with high input voltage for LVDC, a series-input single-output flyback converter was designed. By connecting three flyback converters in series, the applied voltageapplied to each switch could be reduced, and the capacitor voltage automatically converges to the same voltage by sharing the magnetic flux through one high-frequency transformer. In addition, it was designed as DCM to increase efficiency and to operate in a wide input voltage range by controlling the switching frequency and duty ratio. From the experimental results, the superiority and stability of the developed Self-Power with high input voltage was verified.

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