Effect of Diode Power Losses on the Operation of Boost Converter System

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Abstract

The paper presents a study on the effect of diode power losses on the operation of 5/24.4 VDC boost converter based on MOSFET switch type STP36NF06. In this concern, a comparative study between the system performances in the discontinuous conduction mode was carried out whenever; MBRS130LT3G Schottky diode and FR101 fast recovery diode were applied. It was found that, the boost converter output voltage was 20.0 Volts with voltage ripple of 1.4 Volts, using MBRS130LT3G Schottky diode. Moreover, the output voltage reached 18.6 Volts with voltage ripple of 1.6 Volts, whenever FR101 fast recovery diode was used. On the other hand, the peak ringing voltage and parasitic ringing values at the switch node were 4.8 Volts and 454 kHz, respectively applying Schottky diode. While, their values were 8.0 Volts and 463.1 kHz applying fast recovery diode.

Keywords: Boost converter system, discontinuous conduction mode, MOSFET switch, Schottky diode and fast recovery diode.

1.0 Introduction

In most DC-DC converter topologies, power diodes tend to be responsible for a part of power losses; conduction and switching losses that reduce their efficiency. Conduction loss is generated in the forward voltage of the diodes and its on-state resistance, whereas the switching loss is generated as result of reverse recovery charge in the bulk material and the diode junction. To maximize efficiency of DC-DC converters, it requires decreasing power loss in power diodes (P. Haaf, and J. Harper, 2007, S. Abdel-Rahman, et al, 2014). In this concern, the present paper is a trail to shed further light on the effect of diode reverse recovery and forward voltage on the performance of the DC-DC boost converter system.

1.1 Diode Power Losses

1.1.1   Conduction loss

Conduction loss is generated in the forward voltage of the diodes and its on-state resistance (B.P. Singh, 2016, R. Bürkel and Th. Schneider, 1999). Graphically, the on-state resistance can be determined from the (I-V) characteristic curve of a diode (Fig. 1). Where, the diode forward voltage (V_F) is related to the on-state resistance (r_{on}) according to Eq. (1).

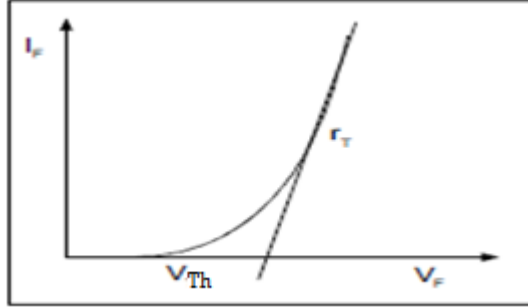Fig. (1): (I-V) characteristic curve of diode showing the on-state resistance.

$$V_F = V_{Th} + I_F r_{on} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (1)$$

Furthermore, the diode power dissipation (P_D) could be calculated according to Eq. (2).

$$P_D = V_{Th} I_F + r_{on} I_F^2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (2)$$

Where:
V_{Th}: Threshold voltage,
I_F: Forward current.

1.1.2 Switching losses

Diode switching loss is generated as a result of the reverse recovery charge in the bulk material and the diode pn junction [N. Krihely and S. Ben-Yaakov, 2010, R.W. Erickson 2015].

- **Reverse recovery effect of diode**

The current in a forward-biased junction diode is buildup of majority and minority carriers. When the forward current of a forward conducting diode has been reduced to zero, small current will continue to conduct for some small time after due to minority carriers stored in the pn-junction and bulk semiconductor material. These minority carriers require some finite time called the reverse recovery time (t_{rr}), to recombine with oppositely charges to be neutralized (M. H. Rashid, 2014 and C.M. Cheh, 2016). In this concern, there are two reverse recovery characteristics; namely: soft recovery and abrupt recovery (Fig. 2).
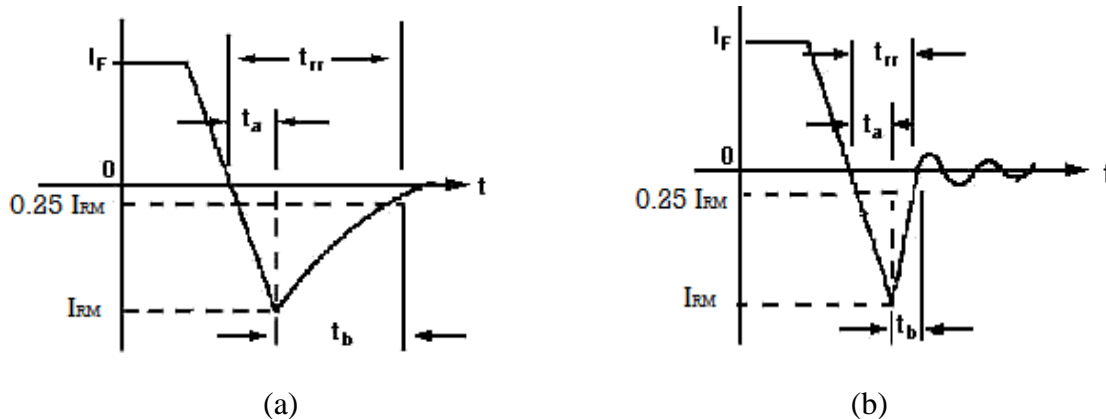
(a)   (b)

Fig. (2): Reverse recovery characteristics of diodes (a: soft recovery and b: abrupt recovery).

The abrupt reverse recovery if responsible for producing extremely high current rating (di/dt) which produces large voltage spikes across any stray inductances that are in series with the diode (B. J. Baliga,2008). When dealing with abrupt reverse recovery, the softness factor (SF) is ≤ 1, snubber circuit is required, whereas, SF is > 1 for soft recovery.

As shown in Fig. (2), I_{RM} is defined as the maximum reverse recovery current and could be calculated applying Eq. (3).

Where:

$$I_{RM} = t_a \frac{di}{dt} \quad \text{.. (3)}$$

Where:
t_a: Rise time,
t_b: Storage time, and
t_{rr}: Reverse recovery time.

The magnitude of t_{rr} depends on:

1. Junction temperature,
2. Forward current,
3. Rate of forward current fall (dI_f / dt),

Where;

$$t_{rr} = t_a + t_b \quad \text{... (4)}$$

SF: Softness factor, Ratio of t_b/t_a.

Where;

$$SF = \frac{t_b}{t_a} \quad \text{.. (5)}$$

- **Reverse recovery charge**

The reverse recovery charge (Q_{RR}) is the amount of charge carriers that flow across the diode in the reverse direction due to changeover from forward conduction to reverse blocking condition. Its value is determined from the area enclosed by the path of the reverse recovery current. That is:

$$Q_{RR} = \frac{1}{2} I_{RM} t_a + \frac{1}{2} I_{RM} t_b = \frac{1}{2} I_{RM} t_{rr} \text{.................................} (6)$$

$$I_{RM} = \frac{2Q_{RR}}{t_{rr}} \text{...} (7)$$

From equations (4) and (5) one gets;

$$I_{RM} = \frac{2Q_{RR}}{t_{rr}} = t_a \frac{di}{dt} \text{.................................} (8)$$

If t_b is negligible in comparison to t_a, then:

$$t_{rr} = t_a \text{...} (9)$$

Hence equation (7) becomes;

$$t_{rr} = \sqrt{\frac{2Q_{RR}}{di/dt}} \text{.................................} (10)$$

and,

$$I_{RM} = \frac{2Q_{RR}}{t_{rr}} = \sqrt{2Q_{RR} \frac{di}{dt}} \text{.........................} (11)$$

From the previously mentioned losses, the present paper is a trial to shed further light on the problem and introduces insight on the selection of the adequate boost diode. Practical examples are presented to assist selection of component that control ringing production.

2.0 Experimental Procedures
2.1 Boost converter design

The design, implementation, operation and efficiency evaluation of a DC-DC boost converter system operating in discontinuous conduction mode was investigated for circuit diode. The designed circuit needs to compile the following requirements; input voltage (V_{in}) = 5.0 Volts, output voltage (V_o) = 24.4 Volts, switching frequency (f_s) =2.0 kHz, duty cycle (D) =50 %

and voltage ripple (V_{ripple}) = 0.625 Volt. Based on the required V_{ripple}, the output capacitor (C_o) was selected. The standard values of coil inductance (L), output capacitor, load resistance (R_L) and input capacitor (C_{in}) were calculated (T. Eichhorn, 2008) using Eqs. (12 and 13) and is illustrated in Table (1).

$$Vo = \frac{1}{2}\left[1+\sqrt{1+\frac{2R_L D^2}{f_s L}}\right]V_{in} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(12)$$

$$C_o \geq \frac{I_o(1-\sqrt{\frac{2L}{R_L T_s}})}{f_s \; V_{ripple}} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (13)$$

Where;

I_o: Output current, and

T_s: Switching time.

Table. (1): Calculated circuit elements and parameters of boost converter system.

L, µH	C$_o$, µF	C$_{in}$, µF	R $_L$, Ω	Input current, A	Input power, W
330	100	100	100	1.89	9.45

Figure (3) shows the circuit diagram of boost converter design based on the previously suppositions and calculations. On the other hand, experimental investigation has been carried out to analyze the circuit parameters variations under different power switches.
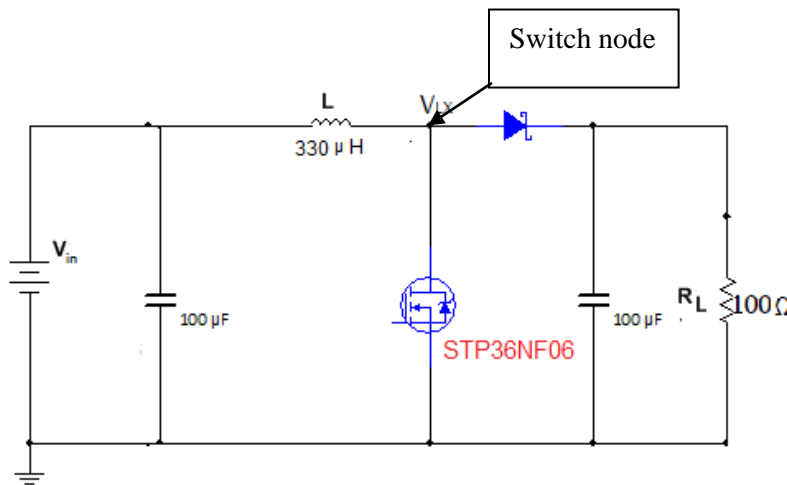

Fig. (3): Boost converter circuit.

Furthermore, Table (2) illustrates the voltage and current rating of the used MOSFET switch.

Table (2): Voltage and current rating of MOSFET switch.

Parameter	STP36NF06 MOSFET Switch
Breakdown voltage, V	60
Current rating, A	19.5

2.2 Diode selection

During the boost converter design, FR101 fast recovery and MBRS130LTG Schottky silicon diodes have been introduced. The matter is mainly due to the suitability of their voltage and current rating (B. Hauke, 2014). Where, their forward current (I_F) was measured to be 1.61 A and 0.7 A, respectively. On the other hand, their breakdown voltage (V_{RM}) was 50 Volts and 30 Volts.

3.0 Results and Discussions
3.1 Reverse recovery characteristics of diodes

The reverse recovery characteristics of fast recovery-and Schottky – diodes are shown in Fig. (4). From which, one can found that, the storage (t_a) and rise time (t_b) has been measured to be 53.5 ns and 98.2 ns, respectively for fast recovery diode. On the other hand, for Schottky diode t_a and t_b are measured to be 53.5 ns and 70.06 ns, respectively. The reverse recovery time (t_{rr}) for both devices was calculated using Eq. (4). It was found that, its value for fast recovery diode equal 151.7 ns and 123.5 ns for Schottky diode. Also, for fast recovery diode, the maximum reverse recovery current was measured to be 37 mA. From which, the total reverse recovery charge (Q_{RR}) was calculated to be 2.8 nC. Concerning, Schottky diode, the maximum reverse recovery current and the total reverse recovery charge were 20 mA and 1.23 nC, respectively.

The work was extended to calculate the softness factor (SF). Where, it was found that, the reverse recovery phenomena of two devices were soft recovery. This is mainly due to that, the values of SF equal 1.83 and 1.31 for fast recovery and Schottky diode, respectively, i.e SF >1. From the previous results, it is clearly shown that, the reverse recovery charge of Schottky diode is much less than that of fast recovery ones, it is attributed to the junction capacitance and slightly dependent on the reverse current rating (di/dt) as there is no excessive minority carriers (M. H. Rashid, 2014).
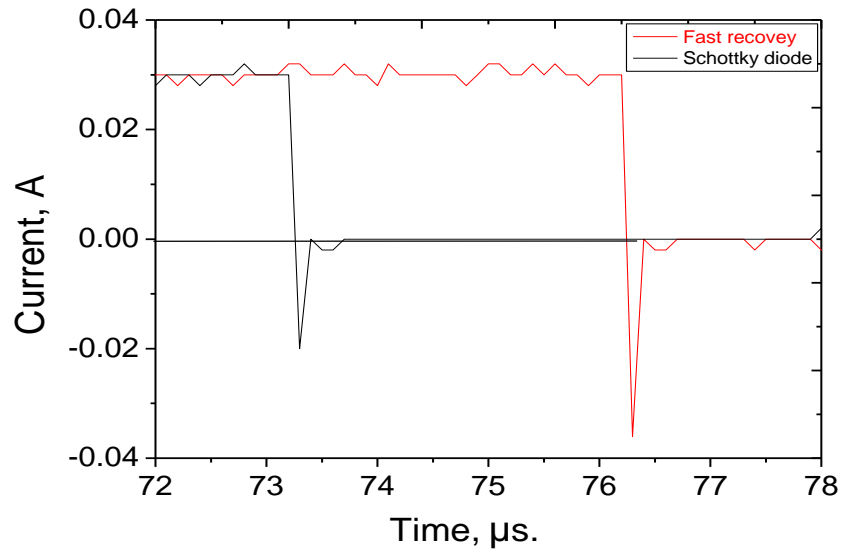
Fig. (4)**:** Reverse recovery characteristics of fast recovery - and Schottky -diodes.

For more confirmation of the obtained results, the reverse recovery characteristics of both diodes were simulated, plotted and a comparison between the experimental - and simulated - results were performed as shown in Fig. (5), and finally, Table (3) illustrates the detailed results.
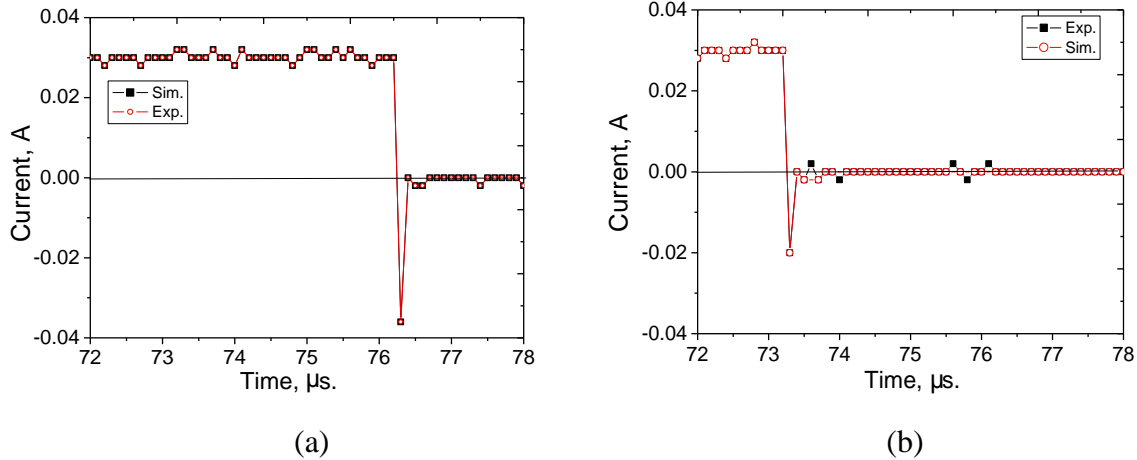

(a)   (b)

Fig. (5): Experimental and Simulated reverse recovery characteristics of (a) fast recovery- and (b) Schottky silicon diodes.

Table (3): Summery of the reverse recovery characteristics of fast recovery- and Schottky-diodes.

Electrical parameter	Diodes			
	Fast recovery		**Schottky**	
	Sim.	**Exp.**	**Sim.**	**Exp.**
Storage time (t_a), ns	50	53.5	53	53.5
Rise time (t_b), ns	101	98.2	70	70.6
Reverse recovery time (t_{rr}), ns	151	151.7	123	123.5
Reverse recovery charge (Q_{rr}), nC	2.79	2.8	1.23	1.23
Maximum reverse recovery current (I_{RM}), mA	37	37	20	20
Softness factor (SF)	2.02	1.83	1.32	1.31

3.2 Design and testing of boost converter system
3.2.1 Switch node ringing

As an important matter when constructing boost converter circuit, it is necessary to consider the ringing voltage at switch node as its maximum value (V_{pk}) mustn't exceeds the voltage rating ($V_o + V_{f\,(diode)}$) of the switch (J. Falin, 2007). In this concern, Fig. (6) shows the parasitic ringing measured at time scale of 5.0 µs showing the ringing voltage on applying fast recovery and Schottky diode. From which one found that, V_{pk} was measured to be 8.0 Volts at parasitic ringing frequency (f_p) of 463.1 kHz and 4.8 Volts at 454 kHz, respectively.
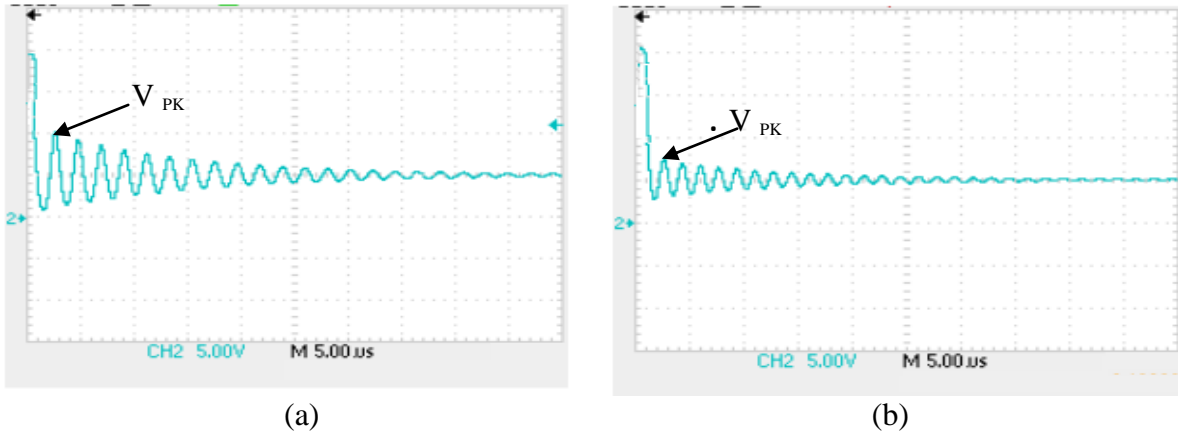

(a)   (b)

Fig. (6): Waveform of output voltage signal at switch node, showing the parasitic ringing for fast recovery and (b) Schottky diode.

3.2.2 Spike voltage

Moreover, the spike voltage (V_{spike}), during the turn-off conditions was plotted and analyzed. From which, V_{spike} values were calculated, for both the fast recovery - and Schottky - diode, to be 1.0 and 0.8 Volt, respectively (Fig. 7).

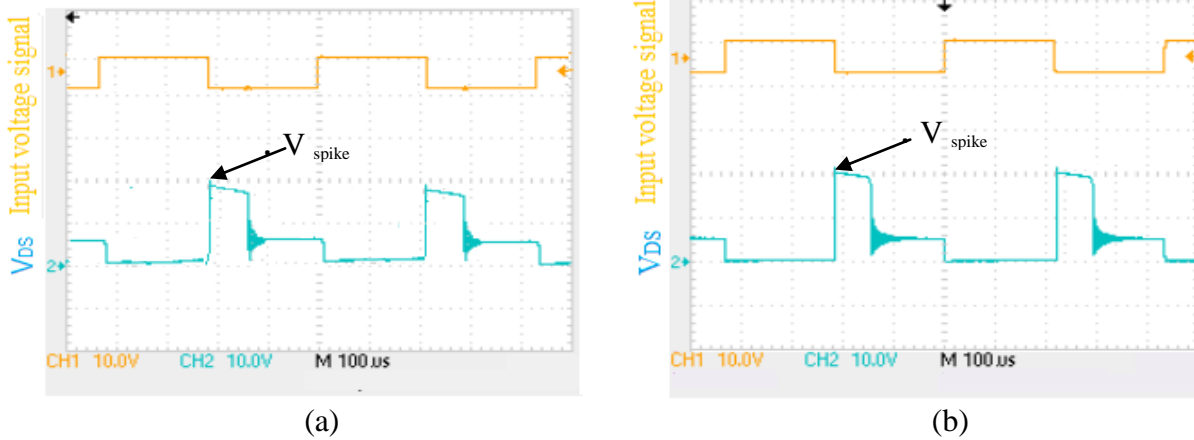(a)   (b)

Fig. (7): Input voltage signal waveforms, and output voltage signal at switch node for (a) fast recovery and (b) Schottky diode.

3.2.3 Output voltage

A snapshot of input voltage signal and the DC output voltage of the boost converter showing voltage ripple is shown in Fig. (8). It is clearly shown that, for the case of fast recovery diode V_o was measured to be 18.6 Volts. On the other hand, whenever applying Schottky diode V_o stepped up to 20.0 Volts.

Voltage ripple is one of the most critical problems affecting the performance of power electronic circuits as a whole. So, the work was extended to measure V_{ripple} superimposed on the DC output voltage of the boost converter system. Referring to Fig. (8), it is found that, V_{ripple} was measured to be 1.6 Volts whenever fast recovery is used and stepped down to 1.2 Volts for case of Schottky diode.

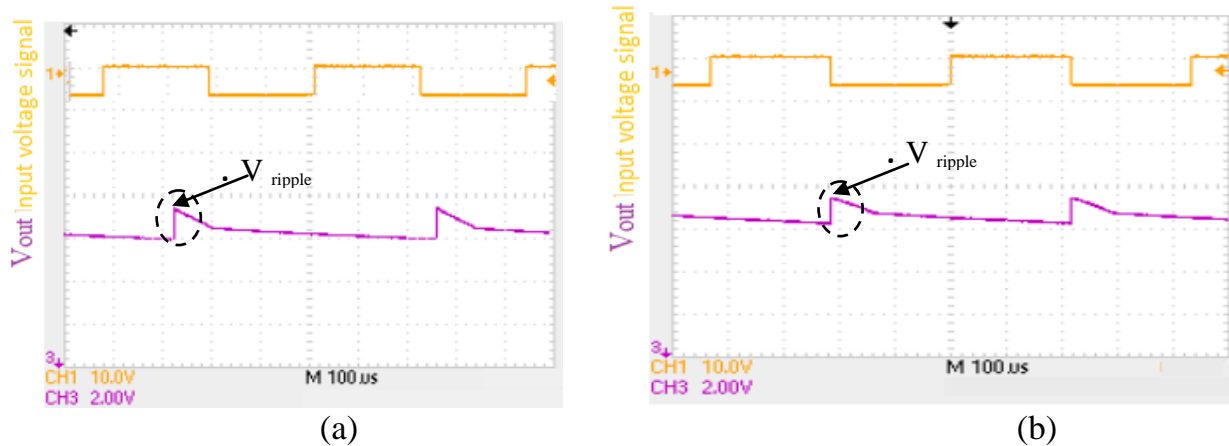(a)   (b)

Fig. (8): Input voltage signal waveforms and dc-output voltage of boost converter showing the voltage ripple for (a) fast recovery and (b) Schottky diode.

4. Conclusions

Due to the high importance of DC-DC boost converters in the world of electronics up to date, the present paper was concerned with a comparative study between the performance of Schottky and fast recovery diodes during the operation of such systems. In this concern, DC-DC boost converter operating in discontinuous conduction mode was designed, implemented and tested based on Schottky and fast recovery diodes. From the experimental work, results and analysis, it could be concluded that: High efficiency boost converter system: low power loss, low electromagnetic interference, low voltage ripple superimposed on the DC output voltage was achieved whenever the system based on Schottky diode rather than the fast recovery ones.

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الملخص العربى

تأثيرالطاقة المفقودة من النبيطة الثنائية ذات القدرة على آداء نظام المحول الإلكترونى الرافع للجهد

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تناول البحث الحالى دراسة عملية عن تأثير الفقد الناتج من نوعين مختلفين من النبائط الثنائية ذات القدرة (سريع التعافى من الطراز FR101) و شوتكى من الطراز (MBRS130LT3G) على آداء المحول الإلكتروني الرافع للجهد ذات جهد دخل/خرج؛ 5/24.4 فولت (5/24.4 VDC boost converter) الذي يعتمد فى تصميمه على نبيطة ترانزستور تأثير المجال الأكسيدى المعدنى من الطراز STP36NF06 المستخدم كمفتاح إلكترونى. فى هذا الصدد، تم عمل مقارنة لخرج نظام المحول الإلكترونى أثناء تشغيله فى وضع التوصيل المتقطع فى حالة إسخدام النبيطتين الثنائيتين ذات القدرة (سريعة التعافى وشوتكى). تم الحصول على جهد خرج للنظام يبلغ 20 فولت بجهد ضوضاء 1.4 فولت بإستخدام نبيطة شوتكى الثنائية، بينما وصل جهد خرج النظام فولت بإستخدام النبيطة سريعة التعافى إلى 18.6 فولت بجهد ضوضاء 1.6 فولت. وبدراسة جهد خرج (Switch node) المفتاح الإلكترونى بإستخدام نبيطة شوتكى الثنائية، وجد أن قيمة جهد و تردد إشارة الضوضاء الناتجة بلغت 4.8 فولت و 454 kHz على الترتيب، بينما بلغت القيم السابقة 8.0 فولت و 463.1 kHz بإستخدام النبيطة الثنائية سريعة التعافى.

من الدراسة العملية التى أجريت، وجد أنه بإستخدام نبيطة شوتكى الثنائية ذات القدرة أمكن الحصول على آداء أفضل للمحول الإلكترونى الرافع للجهد وذلك يرجع إلى صغر قيمة الجهد الحرج (V_{Th}).