Over-voltage Protection Using Power Zener Diode for Matrix Converter and Matrix-Z-source Converter

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Abstract - This paper proposes a method of over-voltage protection using power Zener diode for ac-ac matrix converter, ac-de matrix converter, and matrix-Z-source converter. The analysis and design consideration have been explained, and the discussion on both advantage and drawback of this method also has been given. The effectiveness of this method has been experimentally verified.

I. INTRODUCTION

In matrix converters, disturbance in ac source or fault in load current can cause serious over-voltage. In an ordinarily operating matrix converter, the normal shutdown action turns off all switches suddenly leading an equivalent load current fault. Over-voltage protection, therefore, is necessitated for matrix converters. Commonly used diode-capacitor configuration of over-voltage protection is shown in Fig. 1(a). 12 fast recovery diodes, one storage capacitor and one discharge resistor are used in this solution. The switch $X_r$ is closed only if the level of clamping capacitor voltage beyond the specified threshold. A simple method using six diodes of switch-network and six extra diodes to achieve the same purpose as the former was reported in [1]. It requires some particular arrangement in placing devices in the switch-network. An alternative method using 6 varistors and 18 voltage suppressors was proposed in [2]. The varistors are subject to the repetitive ESD (Electrostatic Discharge) events [3]. So this method is not optimal in long-term-run view. The conventional diode-capacitor configuration for ac-de matrix converter is shown in Fig. 1(b).

Matrix-Z-source converter (MZC) has two operating modes, one is the voltage-boost dc-ac inversion mode which is essentially the operating mode of a Z-source inverter; the other is voltage-buck ac-de rectification which is essentially the operating mode of an ac-de matrix converter. Each operating mode is capable of bidirectional power flow [4]. The diode-capacitor protection network may be directly used for MZC but an extra circuit brake $X_c$ has to be employed, as shown in Fig. 2. This is because when MZC acts as Z-source inverter in dc-ac inversion mode the clamping capacitor $C$ will affect the dc-link voltage $v_{pna}$ which is supposed to be controlled only by the modulation.

This paper proposes another alternative method using 9 power Zener bidirectional TVS (Transient Voltage Suppressor) for three-to-three matrix converter, consequently, using 6 foresaid devices for the ac-de matrix converter and MZC.

II. PROPOSED METHOD OF OVER-VOLTAGE PROTECTION

Fig. 1 Conventional diode-capacitor over-voltage protection in (a) three-to-three matrix converter; (b) ac-de matrix converter

Fig. 2 Conventional diode-capacitor over-voltage protection used for MZC, where switch $X_c$ is opened when MZC is in dc-ac operating mode (Z-source inverter mode) so as to avoid the possible clamping of voltage between $p$ and $n$ by the capacitor.
The proposed configuration for over-voltage protection of three-to-three matrix converter is shown in Fig. 3(a). The power Zener bidirectional diode provides high voltage protection by very fast clamping action and does not have aging problem as that of varistors. Fig. 4 shows the electrical characteristic of a uni-directional power Zener diode.

The proposed over-voltage protection circuit is symmetric as shown in Fig. 3(a). Either line-line input or line-line output terminal-pairs can be clamped by a pair of power Zener bidirectional diodes. Therefore, the differential mode over-voltage disturbance in ac source or the over-voltage caused by load current fault can be clamped provided that the clamping devices are properly selected. Obviously, no extra switch/brake or particular arrangement of certain device in the switch-network is required. Thus, a simple configuration is achieved. Application of the configuration for ac-dc matrix converter can be obtained straightforward in Fig. 3(b).

![Fig. 3 Proposed power Zener bidirectional diode TVS over-voltage protection for (a) three-to-three matrix converter; (b) ac-dc matrix converter](image-url)

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![Fig. 4 Electrical characteristic of power Zener unidirectional diode where, V_{RM} is stand-off voltage, V_{BR} is breakdown voltage, V_{CL} is clamping voltage, V_{F} is forward voltage, I_{F} is forward current, I_{LS} is leakage current at V_{SH}, and I_{PP} is peak pulse current](image-url)

III. CIRCUIT ANALYSIS AND DESIGN CONSIDERATION

The aforementioned MZC is used as a case study in the following discussion. Fig. 5(a) shows the equivalent view when the protection is applied to the MZC; the equivalent configuration viewed from ac source terminals and from dc-link terminals are shown in Fig. 5(b) and (c) respectively. The selection of power Zener diode for the over-voltage protection of MZC mainly lies in the consideration on both stand-off voltage and power rating of power Zener diode. Explanation is given as follows.

A. Preliminary Choice by Stand-off Voltage of Power Zener Diode

The conditions in the case are as follows: output voltage $V_{dcg} = 42$ Volts, input line-line peak voltage $V_{il-l} = 80$ Volts, and PWM carrier period is 50 μs.

The stand-off voltage $V_{RM}$ shown in Fig. 4 is required to cover the normal upper limit of ac source line-to-line voltage and less than the specified over-voltage range as in (1)

$$V_{il-l, RM} < V_{OV}$$

where, $V_{OV}$ is the upper limit of the acceptable over-voltage, usually a portion of the breakdown voltage of semiconductors to be protected, in this case, we set it at 280 Volts. The clamping device, for example, BZW50-120B [5] has a clamping voltage between 200 V and 274 V according to an acceptable level of pulsed current, and meets the relationship of (1).

B. Confirmation by Checking Power Rating of Power Zener Diode

The power rating of a given power Zener diode is usually depicted by the curve of “peak pulse power versus pulse duration” [5]. The peak pulse power should be sufficiently higher than the magnitude of power when power Zener diode is in clamping state within the same pulse duration.

$$P_{pp} > P_{pe}$$

where, $P_{pp}$ is the peak pulse power within certain pulse duration at a given junction temperature specified in the datasheet of a given power Zener diode; $P_{pe}$, as given by (3), is the estimated magnitude of power within the same pulse duration when power Zener diode is in clamping state.
where, $V_{CLz}$ is the clamping voltage of Zener diode at certain junction temperature; $I_{CLz}$ is the corresponding current. In the case of over-voltage protection of ac-dc rectification of the MZC, $I_{CLz}$ may be estimated by the magnitude of load current. Thus, the estimated peak pulse power during clamping action of power Zener diode in this case may be

$$P_{pc} = V_{CLz} \times I_{CLz}$$  \hspace{1cm} (3)

where, $I_{dc}$ is the dc load current. For example, assuming $I_{dc} = 48\ A$ (2000\ W at 42 \degree V), and $V_{CLz} \equiv 280$\ V (by checking “Clamping voltage versus peak pulse current” in [5] ), then

$$P_{pc} = 280\ V \times 48\ A = 13440\ W$$  \hspace{1cm} (5)

A matter of fact shows that the peak pulse power decreases as the pulse duration increases [5]. Thus, when the maximum pulse duration of a power Zener diode employed for over-voltage protection of MZC is known, a peak pulse power at that duration may be used as limit. In steady-state operation of MZC in ac-dc rectification, the pulse duration of the power Zener diode is the duration of the switch-unit to be protected. The maximum duty-cycle of ac-dc matrix converter is given in (6) (see appendix)

$$D_{max} = \frac{4}{3\sqrt{3}} \frac{V_{dc}}{V_{dc,z}} + \frac{1}{3}$$  \hspace{1cm} (6)

When the conditions mentioned at the beginning of section A are considered, the maximum duty-cycle, $D_{max}$, is around 0.74, hence the duration is 0.74×50\ \mu s = 37$\ \mu s. The peak pulse power, $P_{pc}$, at this pulse duration is higher than 30000 W (by checking Fig. 2 of [5] ), which is therefore much higher than $P_{pc} = 13440\ W$ (as in (5)). Consequently BZW50-120B in this situation meets the relationship of (2), and can be selected.

**IV. EXPERIMENTAL VERIFICATION**

Fig. 6 and Fig. 7 show the experimental record of effective power Zener diode TVS protection when the MZC was suddenly shut down with a load current at about 10 Amp. The voltage stress caused by the inductor may be approximated in (7) with the measured data and the given parameter of inductance $L$.

$$V_{stress_L} = -L \frac{\Delta I_L}{t_{off}} = -1.31 mH \times \frac{10 A}{400 ns} = -3275 V$$  \hspace{1cm} (7)

where, $V_{stress_L}$ is voltage stress; $t_{off}$ is the measured turn-off time. However, Fig. 6 shows that the inductor voltage was clamped within 200 V; Fig. 7 shows that sudden shut-down produced an acceptable disturbance in ac source.
V. DISCUSSIONS

An obvious advantage of the proposed power-Zener diode clamping solution over the traditional one is the ease of implementation in circuit design and device layout.

Another advantage over the traditional one is that it does not require any energy storage device, i.e. that it is an all-silicon based solution. This feature could contribute to the further compact design of matrix converters.

While, it can be seen that when repetitive current-commutation fault occurs, the clamping device will repetitively carry the pulsed dc load currents. This will contribute to the power dissipation of the clamping device hence heating up itself. The clamping capability is weakened as the device’s junction temperature increases. The worst case is either that the clamping device produces an unwanted clamping action because of the over-temperature of itself or that the clamping device is broken for the same reason. This problem can be solved by sensing the temperature of clamping devices. Each input phase needs one sensing point of that temperature; three sensors are required. The repetitive current-commutation faults usually are caused by faults in logic design or failure in logic circuitry. The temperature sensing used here can help the detection of those faults.

An obvious disadvantage of the proposed power-Zener diode clamping solution is the limit range of stand-off voltage of the market-available power Zener diodes nowadays. The top range of the stand-off voltages of market-available power Zener diodes has not reached the widely used popular levels, the voltage stresses are relatively low. This situation could be changed in future when the semiconductor technology for the power-Zener diode achieves the high level of stand-off voltages.

VI. CONCLUSIONS

An all-silicon based over-voltage protection solution for three-to-three or ac-dc matrix converters has been proposed, justified and experimentally verified. The advantage of the solution is the easy and compact design without the use of energy storage devices. While, due to the stand-off voltages of market-available power Zener diodes at present have not reached the widely used popular levels, the usage of the solution is limited within the low-voltage applications nowadays.

APPENDIX

A. Maximum and Minimum Duty-cycle of ac-dc Matrix Converter

From duty-cycle as given by (8) [6], the Maximum and minimum duty-cycle of \(d_{\text{pa}}(t)\) over one line cycle can be examined by (10).

\[
d_{\text{pa}}(t) = \frac{\sqrt{3}}{2} M \left[ \frac{1}{2} \cos(\omega t) + \frac{7}{36} \cos(2\omega t) - \frac{1}{36} \cos(4\omega t) \right]
\]

\[
d_{\text{pa}}(t) = \frac{\sqrt{3}}{2} M \left[ \frac{1}{2} \cos(\omega t - 2\pi/3) + \frac{7}{36} \cos(2\omega t + 2\pi/3) - \frac{1}{36} \cos(4\omega t) \right]
\]

\[
d_{\text{pa}}(t) = \frac{\sqrt{3}}{2} M \left[ \frac{1}{2} \cos(\omega t + 2\pi/3) + \frac{7}{36} \cos(2\omega t - 2\pi/3) - \frac{1}{36} \cos(4\omega t) \right]
\]

\[
d_{\text{pa}}(t) = \frac{\sqrt{3}}{2} M \left[ \frac{1}{2} \cos(\omega t) - \frac{7}{36} \cos(2\omega t) + \frac{1}{36} \cos(4\omega t) \right]
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d_{\text{pa}}(t) = \frac{\sqrt{3}}{2} M \left[ \frac{1}{2} \cos(\omega t - 2\pi/3) - \frac{7}{36} \cos(2\omega t + 2\pi/3) + \frac{1}{36} \cos(4\omega t) \right]
\]

\[
d_{\text{pa}}(t) = \frac{\sqrt{3}}{2} M \left[ \frac{1}{2} \cos(\omega t + 2\pi/3) - \frac{7}{36} \cos(2\omega t - 2\pi/3) + \frac{1}{36} \cos(4\omega t) \right]
\]

where,

\[
M = \frac{4 V_{\text{dcg}}}{3 V_{\text{d-lg}}}
\]

\[
0 < M < 2/\sqrt{3}
\]

where, \(V_{\text{dcg}}\) is the required output DC voltage; \(V_{\text{d-lg}}\) is the peak line-line AC voltage; \(\omega\) is the input AC angular speed.

\[
d'_{\text{pa}}(\phi) = 0 \quad \phi = \pi
\]

Then one has (11)

\[
-\frac{1}{2} \sin(\phi) - \frac{7}{18} \sin(2\phi) + \frac{1}{9} \sin(4\phi) = 0
\]

When \(\phi = 0\) and \(\phi = \pi\), \(d_{\text{pa}}(t)\) reaches the maximum \(D_{\text{max}}\) and minimum \(D_{\text{min}}\) respectively as given by (12)

\[
D_{\text{max}} = \frac{1}{\sqrt{3}} \left[ M - \frac{1}{3} \right]
\]

\[
D_{\text{min}} = -\frac{1}{2\sqrt{3}} \left[ M + \frac{1}{3} \right]
\]

where, \(M\) is the modulation index, \(0 < M < 2/\sqrt{3}\). From (9), the \(D_{\text{max}}\) and \(D_{\text{min}}\) can be estimated as given by (13).

\[
D_{\text{max}} = \frac{4 V_{\text{dcg}}}{3\sqrt{3} V_{\text{d-lg}}} + \frac{1}{3}
\]

\[
D_{\text{min}} = -\frac{2 V_{\text{dcg}}}{3\sqrt{3} V_{\text{d-lg}}} + \frac{1}{3}
\]

where, \(V_{\text{dcg}}\) is the required output DC voltage; \(V_{\text{d-lg}}\) is the peak line-line AC voltage. The duty-cycles are symmetric over whole line-cycle, so the \(D_{\text{max}}\) and \(D_{\text{min}}\) are valid for all individual duty-cycles.

REFERENCES


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