Emproved Z-Source Dynamic Voltage Restorer Based on the Minimum Energy

Yongxiang Li a, Mengda Li b *, Menglin Ma
College of Electrical Engineering, Shanghai Dianji University, Shanghai 201306, China

a 2538914742@qq.com, *, b Corresponding author e-mail: limd@sdju.edu.cn

Abstract. Dynamic voltage restorer (DVR) is a good choice to solve voltage sag problem. Aiming at the shortcomings of traditional DVR, an improved DVR model is proposed. The improved DVR took H-bridge inverter as the main frame, and the energy storage unit was based on the battery. The coupling unit directly connected the capacitor in LC filter to the power grid instead of the transformer, and connected a Z-source network between the energy storage unit and the inverter unit to improve the voltage compensation range and eliminate the impact of the series transformer. Finally, by connecting a current compensation device in parallel on the load side, combined with the minimum energy compensation control strategy, the amplitude and phase of the load voltage compensated by the improved DVR device were consistent with that before the drop. A MATLAB / Simulink simulation model is built to verify the effectiveness of the proposed improved DVR. The simulation results verify the effectiveness of the proposed improved DVR.

Keywords: Dynamic voltage restorer; voltage sag; minimum energy; z-source network.

1. Introduction
At present, the voltage sag is the most frequent electric energy quality problem since statistics, which also has the greatest impact on sensitive loads in many problems such as power quality [1-4]. Currently, the commonly used devices for treating voltage sag include DVR, uninterruptible power supply (UPS), static transfer switch (STS), transformer tap regulator, etc. the cost of DVR is lower in comparison with other devices such as UPS and STS, and when the electric energy sag occurred in voltage, DVR can provide the load to meet power consumption required by the normal voltage, moreover, the compensation efficiency is also very high. On the basis of these two points, DVR has become the most economical and efficient way to control the voltage sag problem [5-9].

DVR is connected between the grid and the load by the coupling unit, which is a voltage-type power electronic compensation device. The topology of DVR mainly consists of four units: energy storage unit, inverter unit, filter unit and coupling unit, owing to the limited energy stored by the energy storage unit, DVR not only need consider the magnitude and phase of the compensation voltage, but also considers the energy it consumes. As a control strategy that can reduce the active consumption of the DVR system, the minimum energy compensation control strategy is a promising control strategy [10-15].
Reference [16] put forward a general DVR topology, the battery structure was used as the energy storage unit in energy storage unit; the three-single-phase H-bridge inverter was used as the inverter unit; the LC filter was used as the filter unit, finally, the transformer which connected to the grid is used as a coupling unit, the compensation for the grid voltage drop is achieved by selecting the minimum energy compensation method as the compensation control strategy, so the end-side load can continue to operate normally.

The DVR device mentioned in reference[16], although it can control the grid voltage drop to a considerable extent, there are two problems, first, the traditional DVR adopts transformer to connect the grid, when the DVR starts, the series transformer generates the inrush current, it distorts the compensation voltage output by DVR, and the leakage inductance, iron loss, overload and other problems of the transformer also affect the output compensation voltage, besides, the parameter design of transformer is relatively complicated in practical applications; secondly, the minimum energy compensation control strategy is adopted in the traditional DVR, although DVR can output the minimum active power to ensure that the load voltage amplitude remains unchanged when the grid voltage drop occurs, it makes the DVR output the least active power by changing the phase angle of the load voltage after compensation, even zero active power (pure reactive compensation), thereby prolonging the compensation time of DVR. In other words, the phase of the load voltage compensated by traditional DVR produces a certain degree of phase jump in comparison with the voltage phase before drop, and this kind of phase jump is very fatal to some sensitive loads with phase requirements. After analysis and research, on this basis, this paper proposed an improved dynamic voltage restorer. The improved dynamic voltage restorer starts from the topology and compensation strategy of DVR, solved the problems mentioned above, further optimized its voltage compensation effect, and verified the effectiveness of the optimization method through simulation.

2. Research on Improved DVR

2.1. Improvement of traditional problems

The improved DVR adopts the filter capacitor to replace the transformer to directly connect the grid on the problems with the traditional DVR transformer, thereby eliminating all the negative effects with the transformer, but moreover, without the transformer, the voltage compensation range of the DVR system will be greatly reduced. In order to solve this problem, this paper connected a Z-source network topology in the energy storage unit and the inverter unit; the Z-source network can realize the boost output of the DC voltage on the energy storage side, thus expanding the voltage compensation range of the DVR system.

Z-source network topology is shown in Fig.1:

![Z-source network topology](image)

**Fig.1** Z-source network topology

Z-source network topology consists of two equivalent inductances and two equivalent capacitors; the addition of Z-source network makes the upper and lower bridge arms of the inverter unit can be directly connected, so that there are two working state in the inverter unit, its state equivalent graphs is shown in Fig.2.
A switching cycle time is set to be \( T \), in which the direct connection state time is \( T_0 \), and the non-direct connection state is \( T_1 \), and \( U_{L1} = U_{L2} = U_i \) and \( U_{C1} = U_{C2} = U_c \).

When the inverter works in the direct connection state (as shown in Fig.2a), \( U_L = U_C \), \( U_{dc} = 2U_C \), \( U_i = 0 \).

When the inverter works in the non-direct connection state (as shown in Fig.2b), \( U_L = U_{dc} - U_C \), \( U_i = U_C - U_L = 2U_C - U_{dc} \). It can be obtained from the inductive volt second principle [17].

Therefore, the peak voltage on the output side of Z-source network is:

\[
U_{L} = 2U_C - U_{dc} = \frac{1}{1-2D} \cdot U_{dc} = B \cdot U_{dc}
\]

In the formula: \( D = T_0/T \) is the direct connection duty ratio; \( B = 1/(1-2D) \) is the DC modulation ratio.

In the beginning, when there was no Z-source network topology, the relation between the DC power supply voltage \( U_{dc} \) and the inverter output voltage \( U_{dvr} \) was:

\[
U_{dvr} = \frac{M}{2} \cdot U_{dc}
\]

In the formula: \( M \) is the inverter modulation ratio.

After Z-source network topology was added, the relation between its DC power supply voltage \( U_{dc} \) and the inverter output voltage \( U_{dvr'} \) was:

\[
U_{dvr'} = \frac{M}{2} \cdot U_{i} = \frac{M}{2} \cdot BU_{dc}
\]

It can be known from formula (4) that as long as the suitable \( B \) and \( M \) are selected, the boost output of DC power supply of Z-source DVR can be realized, and the voltage compensation range can be expanded.

In allusion to the problem when load voltage phase jump after traditional DVR compensation, this paper connects a current compensation device on the load side, the current compensation device can provide an adjustable compensation current \( I_c \), it makes the phase angle difference between DVR compensation voltage \( U_{dvr} \) and DVR compensation current \( I_{dvr} \) to be 90° as soon as possible (see below for the specific principle), thus ensuring that the load voltage phase after compensated does not jump while the DVR consuming the least energy.

The specific analysis of the compensation control principle is as follows:

When the compensation voltage \( U_{dvr} \) output by DVR and the current \( I_{dvr} \) flowing through the DVR are perpendicular to each other, the active power consumed by DVR is the smallest.

Assuming that the power and power factor angle of the load are constant before and after the voltage sag, the voltages and current vector diagrams of DVR topology diagram before and after the improvement are shown in Fig.3:
**Fig. 3** Vector diagram of voltage and current

$U_s$ is the grid voltage before the sag, $U'_s$ is the grid voltage after the sag, $U_{dvr}$ is the compensation voltage output by the DVR, $U_l$ is the load voltage after compensation, $I_l$ is the current flowing to the load, $I_{dvr}$ is the current flowing through the DVR, and $I_c$ is the compensation current provided by the current compensation device. $\alpha$ is the phase jump angle of load voltage, $\theta$ is the power factor angle of the load, $\beta$ is the angle between the load current and the current output by DVR, and $\psi$ is the voltage phase angle that needs to be compensated.

Because the power factor angle $\theta$ of the load is constant, in order to ensure that the amplitude and phase of the load voltage $U_l$ after compensation are the same as before the sag, the magnitude and direction of the current $I_l$ flowing to the load need to be fixed. Because the current $I_l$ and the $I_{dvr}$ of DVR before the improvement flowing to load are the same current, in order to achieve the minimum active power consumption, the load voltage after compensation definitely produce a certain phase jump, as shown in Fig.3(a). Therefore, in order to ensure that there is no phase jump in the load voltage after compensation, then the phase angle of the compensation voltage $U_{dvr}$ will change, moreover, $I_{dvr}$ also needs to rotate the vector by a certain angle, so that it is perpendicular to $U_{dvr}$ as much as possible, and achieves minimum active power consumption. Since the magnitude and phase of the current flowing to the load $I_l$ are fixed, a compensation current $I_c$ is needed to superimpose with $I_{dvr}$ to get $I_l$, as shown in Fig. 3(b).

As can be known from the triangular relationship in Fig.3(b), the voltage amplitude that the DVR needs to be compensated is:

$$U_{dvr} = \sqrt{U'_s^2 + U_s^2 - 2U'_s \cdot U_s \cos \alpha}$$  \hspace{1cm} (5)

Phase angle to be compensated:

$$\psi = \frac{U'_s^2 + U_{dvr}^2 - U_s^2}{2U_s U_{dvr}}$$  \hspace{1cm} (6)

There is a minimum problem in $I_c$, only when $I_c$ is perpendicular to $I_{dvr}$, $I_c$ is the minimum. At this time, the power consumed by the compensation device is at a minimum. Then the current magnitude to be compensated is

$$I_c = I_l \cdot \sin \beta$$  \hspace{1cm} (7)

The phase angle is:

$$\beta = \frac{\pi}{2} - \psi - \theta$$  \hspace{1cm} (8)

The improved DVR can optimize the minimum energy compensation control strategy, and makes the amplitude and phase of the load side voltage do not change before and after the grid voltage sag.
2.2. Topology of improved DVR

The topology of improved DVR is shown in Fig.4:

![Improved DVR topology model](image)

The improved DVR topology takes three-single-phase H-bridge inverter as the main frame, adopts the structure of battery as the energy storage unit, and the filter unit is a general LC filter, DVR is connected to the grid through the capacitor in the filter, and it connects a current compensation device on the load side. When detecting the grid voltage sag, the DVR conducts corresponding voltage compensation to ensure the stability of load side voltage.

3. Compensation Control Process of DVR

In this paper, the main processes of compensating the grid voltage drop through DVR are as follows: the voltage detection system detects the grid voltage when detecting the grid voltage drop, the control system immediately controls the switch K off, starts the DVR. After that, according to the calculation formula deduced above, the control system controls the inverter unit and the current compensation unit through the PWM module, and outputs the corresponding $U_{dvr}$ and $I_c$, thereby meeting the compensation requirements and keeping the stability of load voltage. Fig.5 is a flow chart of the compensation control process of DVR.
Fig. 5 Compensation control flow chart of DVR

The specific control strategy and idea of DVR is shown in Fig. 6 below:
4. Simulation Experiment

In order to verify the feasibility of the improved Z-source DVR mentioned in this paper, under the Matlab/Simulink simulation environment, transformer without series, traditional DVR system without Z-source network topology and parallel current compensation device, and the improved DVR system mentioned in this paper were simulated, and the simulation model of improved DVR system is shown in Fig.7.

![Improved DVR system simulation model](image)

The system parameters are set as follows: the peak voltage of the fundamental wave peak on the grid side is 311V; the voltage on the DC bus side is 200V; $L_1=L_2=100\mu H$, $C_1=C_2=50\mu F$ in the Z source network; the filter inductance $L_f$ is 5mH, the filter capacitor $C_f$ is 30μF; the resistance of the load is 20Ω and the inductance is 1H.

This paper designed the voltage drop in two conditions to verify the voltage compensation range capacity and phase angle no-jump capacity of the improved Z-source DVR system, the simulation results are as follows:

1) 30% voltage drop occurred in the grid voltage within 0.1s to 0.2s, and accompanied by 30° phase angle jump, the voltage drop waveform of three-phase grid is shown in Fig.8:

![Three phase grid voltage waveform](image)
The load voltage waveform compensated by the traditional DVR system is shown in Fig.9:

![Fig.9 Load voltage waveform](image)

According to the analysis of Fig.9 and Fig.10, during 0.1s and 0.2s, when the grid voltage drop is not deep, the DVR before and after the improvement can fully compensate the grid voltage drop, but the traditional DVR without current compensation device can only compensate the grid voltage amplitude, the grid voltage phase after compensation still has a certain phase jump. The improved DVR can not only completely compensate the dropped power grid voltage, but also the grid voltage phase does not jump after the compensation.

(2) The 70% voltage drop occurred in grid voltage within 0.1s to 0.2s, accompanied by 30° phase angle jump, and the voltage drop waveform of three-phase grid is shown in Fig.11:

![Fig.10 Load voltage waveform](image)
Fig. 11 Three phase grid voltage waveform

The load voltage waveform compensated by traditional DVR system is shown in Fig. 12:

Fig. 12 Load voltage waveform

The load voltage waveform compensated by improved DVR system is shown in Fig. 13:

Fig. 13 Load voltage waveform
According to the analysis in Fig.12, during 0.1s and 0.2s, when the grid voltage drop is very deep, the traditional DVR without Z-source network cannot fully compensate the dropped grid voltage, DVR has a certain limited voltage compensation range. Through the analysis in Fig.13, even if the dropped extent of the grid voltage is deeper, the improved DVR with Z-source network can also fully compensate the grid voltage. It can be seen that the improved DVR has a wider voltage compensation range, which is further expanded in comparison with the traditional DVR.

5. Summary
In allusion to the two shortcomings of traditional DVR, this paper put forward an improved DVR topology with Z-source network, through analysis, deduced the phase relationship of each voltage and current under this structure, calculated the corresponding compensation voltage and compensation current, and conducted real-time compensation through the control system. Finally, the Matlab simulation model was built to verify the correctness of the idea. The simulation results show that the DVR topology with Z-source network and current compensation device mention in this paper has a wider dynamic voltage compensation range than the traditional DVR system, and the voltage phase after compensation does not produce jump, and the compensation effect is better.

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