The Design of Regional Compensation DVR in Medium Voltage System

Abstract: The design of a Dynamic Voltage Restorer that is suitable for compensating regional voltage sags in 10kV distribution system is introduced in this paper. The design of the main circuit based on cascaded H-bridge, the device for energize DVR and the transformer-less coupled circuit are presented. For the voltage sags in neutral point non-grounded system, a reference voltage calculation method with the aim is to restore the line voltages on the load side is put forward. The simulation model of a substation including the designed DVR device has been built in PSCAD, and the compensation results under different fault types are simulated and analyzed, the influence of the energize device on the distribution system is studied. The simulation results verify the correctness and effectiveness of the design of DVR hardware and the reference voltage calculation method.

Key words: Dynamic Voltage Restorer; Neutral-isolated network; Voltage sags; Reference voltage calculation

0 Introduction

Voltage sage is one of the most frequent and harmful power quality problems in distribution network. With the rapid development of high-tech industry, a large number of finance, communications, data center, electronics, semiconductor, precision machining and other enterprises that are especially rely on high quality power supply have emerged in one area of distribution network. For these sensitive users, even tens of milliseconds voltage sag may result in damage to their equipments, production line shutdown, and cause huge economic losses[1]. Dynamic Voltage Restorer(DVR) is recognized as the most effective means of controlling voltage sag problems. At present, the application of DVR installed in low-voltage network has been reported, this kind of DVR can only protect individual sensitive load from being affected by voltage sags. However, with the increase number and capacity of sensitive loads, the cost of installing DVR for each of sensitive users is obviously unacceptable for power company. Meanwhile, DVR installed in high voltage system can possess a wide protection area, but it has the disadvantages of complex realization and unable to control the voltage sags caused by the fault in distribution network. In fact, the voltage sags are mostly caused by the fault in distribution network, so to select feeders with major sensitive loads in the 6-35kV distribution network, and to install DVR to compensate voltage sags for one or several feeders in an area together is one more economic and feasible solution.

The currently studies on DVR mainly include the design of hardware and software. The hardware design includes the main circuit structure, energy storage, inverter, filter parameters and so on. Reference [2] discusses and compares four types of topology of DVR from the aspects of complexity, compensation capacity and cost. However, These topologies all access to the network through transformer, and the transformer may cause problems such as low response speed and voltage distortion. In order to reduce the costs, site area and improve the response speed, a transformerless DVR is proposed in [3]. Reference [4] studies the detailed steps to install a cascaded H-bridge based DVR in 6kV network, and this DVR couples with the network through capacitor directly, but the design process is too simple to ignore a number of problems. In Reference [5], a new topology that is characterized by applying high-frequency transformer to isolate the DVR from the network is proposed, this can reduce the switching device as compared with the cascaded H-bridge structure, but the experiment and simulation are in the low voltage level, and the cost and size of this type of DVR need to be analyzed when applied in high voltage

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level network. The researches on the software design mainly include the control strategies[6-7], voltage sags detection algorithm[8-11], compensation strategies[11-13] and so on. Control strategies and detection algorithm are independent with the structure of the network in which DVR is installed, but three-phase compensation strategies have a great relationship with the structure. The current researches are all based on phase voltage compensation approach, and can only be applied in three phase four-wire system. This means that for neutral-isolated medium-voltage distribution system, these compensation approaches are not entirely applicable. The reason is that under the asymmetric phase-grounding fault in neutral-isolated network, the drop of the voltage of the fault phase will be accompanied with the non-faulted phase voltage swell temporarily, only consider single-phase voltage compensation will inevitably lead to unbalanced three-wire voltage. Research on the phase-to-phase voltage compensation is relatively little. Reference[14, 15] carry out the relevant research on the phase-to-phase voltage compensation type DVR and, in Reference [16], a three phase-to-phase voltage compensation strategy is proposed which only need two-winding transformer. The mechanism of the phase-to-phase voltage based compensation is that the reference voltage of one phase of DVR is set to 0 or a certain DC voltage, and that of the other two phases are set according to the relation that the sum of three phase-to-phase voltages is zero. But this way of compensation needs to compensate temporary voltage swell and will force the DVR to absorb active power, or the DC voltage will increase.

In this paper, the main-circuit, software algorithms design and simulation of a cascaded H-bridge based transformerless DVR that aims at dealing with the voltage sags problems in a 10kV neutral-isolated distribution network has been present, the reference voltage calculation method for DVR in neutral-isolated network that only need to compensate the voltage of the phase with sag under unbalance fault is introduced in detail. The correctness and effectiveness of the design of the DVR are verified by simulation.

1 Engineering background

The power grid of a city in China not only have large industrial loads, but also all kinds of modern high-tech enterprises which are densely distributed. According to power quality statistics, from 2010 to 2012, the power grid has received more than 20 complaints from large customers that are due to power quality problems (wherein more than 70% are caused by voltage sags), the economic losses of users is huge. In order to reduce the economic losses caused by voltage sags, the city power supply authorities decides to carry out demonstration project that apply DVR to deal with voltage sags regionally.

Under the jurisdiction of the city power supply authority, there are many customer complaints in a 10kV substation, and according to statistics, the depth of voltage sag in this station is 10-50%. Therefore, select the appropriate feeder at this station to install 10kV DVR, and compensate voltage sags between 50% to more than 90% of rated voltage amplitude. The total capacity of the selected feeder load is 8.375MVA, the average power factor is 0.92 and rated current is 0.4835kA. The DVR capacity is designed for 5MVA, and is installed in the outlet of two feeders of 10kV bus, the maximum compensation voltage is 0.5pu.

2 The design of Main-circuit of the DVR

The structure of DVR proposed in this paper is shown in Fig.1, it mainly includes energy storage unit, inverter, filter unit and coupling unit and bypass system.

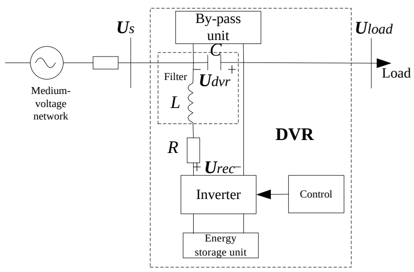


Fig.1 Structure diagram of DVR

2.1 The design of energy storage unit

When DVR works, it will definitely exchange energy with the systems, the energy storage device can provide DVR the energy required to compensate for the voltage sag and maintain the DC voltage constant. Storage device can adopt a large capacitor storage, uncontrolled or controlled rectifier with the energy provided by the power grid, the superconducting storage and other storage modes. The energy provided from power grid can be seen as infinite and there is no DC energy shortage problems concerned by the study on voltage compensation strategy. But where to take power has a great influence on the grid and needs to be studied in detail. In theory, the DVR can be energized form the same bus which the protected feeder belongs to, but the feeder installed with DVR itself has sensitive load, to taking energy from this bus will make a sudden increase in the load capacity of this feeder and cause the voltage to drop deeper. Meanwhile, high-power rectifier will cause distortion in bus voltage. So to take energy from other 10kV bus of the same substation can relieve the impact of the DVR.

2.2 The design of invert

The most common topology of the DVR inverter is the three single-phase inverter structure that can inject positive sequence, negative sequence and zero sequence voltage into the network. It also can use a three-phase full-bridge structure, three-phase pulse need to be centralized control, but the three-phase out voltages can't be controlled independently to compensate the zero-sequence voltage. There are also three-phase four-wire inverter structure for three-phase four-wire system. The accessing of the inverter to the high-voltage network usually have three measures: The first is the use of a transformer to isolate the inverter power devices from the high voltage network, but the high cost, large size, and the non-linear ferromagnetic transformer brings great difficulties to the controller design; The second is using the form of series and parallel power devices directly, but it requires a good consistency switching devices, and will introduce current- and voltage-equalizing problems, this approach has not been applied in high-voltage situations; The third is a multi-level structure, including a diode-clamp and cascaded H-bridge structure. While when the diode clamp level is more than 5, the control will be very complicated. The control of cascaded H-bridge structure is simple, and this structure does not has DC voltage-equalizing problems. So the cascaded H-bridge structure is widely used in large-capacity high-voltage power electronic devices. Therefore, this paper adopts cascaded H-bridge inverter structure for the DVR.

As shown in Fig.2, this paper uses a H-bridge with independent DC voltage support as the basic unit and cascades each basic unit together to form a cascaded H-bridge. The number of the output voltage is $2N+1$, where N is the number of basic unit.

As the voltage rating of the commonly used IGBT module is 1700V, the DC bus voltage of a H-bridge is set to 1100V, and the maximum compensation voltage of DVR in 10kV voltage level is 0.5pu, i.e. the maximum output voltage of DVR is:

$$U_{dvr\max} = 0.5\times\sqrt{2}\times 10/\sqrt{3} = 4.09(\text{kV}) \quad (1)$$

It can be seen that four H-bridge can satisfy the output requirement of the DVR, so each phase of the DVR is consist of five cascaded H-bridge with the additional one as a backup, .

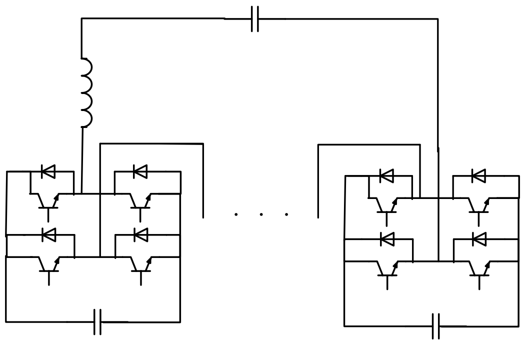


Fig.2 Diagram of cascaded H-bridge

2.3 The design of output filter

In condition of cascaded H-bridge based inverter, the coupling circuit of the DVR adopts capacitor coupling measure, and it is an LC low-pass filter formed by the coupling capacitance C and the filtering inductance L.

The filter is mainly designed for suppressing the harmonic component produced by inverter switching devices. From Fig.1, the transfer function of the DVR system is:

$$H(j\omega) = \frac{\boldsymbol{U}_{rec}(j\omega)}{\boldsymbol{U}_{dvr}(j\omega)} = -\frac{1}{(RCj\omega + LC(j\omega)^2 + 1)} \quad (2)$$

Select the attenuation coefficient of this second-order oscillation circuit as:

$$\varsigma = \frac{R}{2}\sqrt{\frac{C}{L}} \geq \frac{\sqrt{2}}{2} \tag{3}$$

The value of inductance is determined according to the principle that the fundamental voltage drop on the inductor is less than 1% of the output voltage, that is:

$$I_f \omega L \leq 1\% U_\varphi \tag{4}$$

Where U_φ is the RMS value of the maximum fundamental output voltage of DVR and I_f is the RMS value of the output current, we can obtain that:

$$L \leq \frac{1\% U_\varphi}{\omega I_f} = \frac{1\% U_\varphi}{\omega \frac{S}{\sqrt{3}U_\varphi}} = \frac{1\% \sqrt{3} U_\varphi^2}{\omega S} \tag{5}$$

According to the capacity S=5MVA and RMS value of the maximum output voltage U_φ=3.9kV of DVR, we can get the lower range of value of the filter inductor as:

$$L \leq 275 \mu H \tag{6}$$

Then calculate the value of the capacitor according to resonant frequency limited empirical formula as:

$$10 f_0 < f_c = \frac{1}{2\pi\sqrt{LC}} < f_s / 10 \tag{7}$$

Wherein f_0 represents the grid fundamental frequency, f_s is the maximum switching frequency and f_c is the resonant frequency of the LC low-pass filter.

According to above conditions and through simulation, the value of the DVR filter is that *L*=270uH and *C*=556uF.

3 Control algorithm

3.1 Voltage sag detection algorithm

The current voltage drop detection method mainly includes: RMS detection; peak detection; fundamental component testing; detection based on instantaneous reactive power decomposition and its improved detection algorithm; wavelet transform as the representative of the modern digital filtering detection algorithm; digital matrix testing. Various algorithms have their advantages and disadvantages, and applicable situation. Wherein the algorithm based on instantaneous reactive power decomposition has been widely applied to power electronic devices such as active filters, STACTCOM and so on. In this paper, the dq method based on instantaneous reactive power decomposition has been adopted.

3.2 Compensation strategy

Current compensation strategies include: full compensation method, i.e. to compensate the phase voltage on the load-side of DVR during fault to be that before fault; in-phase compensation method, i.e. only compensates the magnitude of the voltage to be of rated value; minimum power compensation method, i.e. by measuring the current phase angle, to compensate the voltage to the withstand range of the load to ensure that the output power of the DVR is the smallest. But these methods are all based on phase voltage compensation and only apply to the neutral-grounding network. Research based on the phase-to-phase voltage compensation is to detect the three phase-to-phase voltages, and when the unbalance of the three phase-to-phase voltages is detected, for example, if the deviation between U_{ab} and its rated value is ΔU_{ab}, then the reference voltage of phase A of DVR is ΔU_{ab} and that of phase B is zero, the reference voltage of phase C is determined by that the sum of the three phase-to-phase voltages is zero. Obviously, such a method is demanding a high output ability of DVR. So in this paper, an applicable reference voltage calculation method for DVR that only compensates the voltage of the phase with sag and the three phase-to-phase voltage can be compensated to the rated value is put forward based on the analysis of the characteristics of the voltage sags in neutral-isolated network.

The principle of the proposed method is to measure the amplitude of the three phase-to-neutral and phase-to-phase voltages of the 10kV bus during fault and then calculate the phase angle relationships between these voltages. Only the voltage of the phase with sag is compensated and that with voltage swell are ignored.

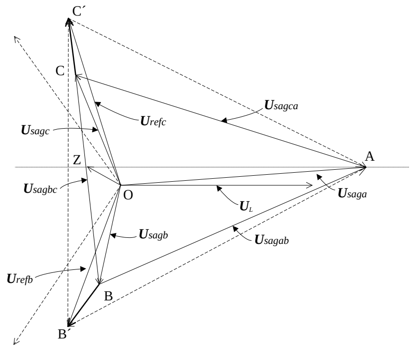


Fig.3 The diagram of analyzing the reference voltage when two phases grounded

Take the double phase-grounding fault (phase B and C) as an example, and Fig.3 shows the reference voltage analysis diagram. In Fig.3, U_{saga}, U_{sagb}, U_{sagc} are represent the phase-to-neutral voltage of the three phase respectively, and the endpoints of the vector of these voltages are denoted as A, B and C. We can see that a temporary voltage swell in phase A during fault, and voltage sags in phase B and C. Take the phase-to-neutral voltage of phase A as the benchmark, and draw a equilateral triangle to determine the endpoints B', C'. Through a simple triangle calculation, the reference voltage U_{refb} and U_{refc} of phase B and C can be obtained. The reference voltages of DVR is the difference between the voltage U_{refb}, U_{refc} and the measured voltage U_{sagb} and U_{sagc}.

3.3 The pulse width modulation method

The modulation algorithms suitable for cascaded H-bridge type inverter mainly include multiple-carrier modulation PWM method and space vector PWM method. Space vector PWM method becomes very complex with the increasing number of voltage levels, and is normally applied to inverter with the voltage levels less than 5. For equal voltage unit cascaded inverter circuit, the triangular carrier phase-shift PWM control method become the standard control method of H-bridge cascade multi-level inverter. This method refers that for a N cascaded H-bridge inverter, to control the triangular carriers move away $2\pi/N$ phase angle in turns, and then compare with the same sinusoidal modulation wave, to produce a group of $2N$ PWM modulation wave signals which drive N power units respectively.

Fig.4 shows the corresponding carrier waves and reference voltage signal of one phase of the DVR.

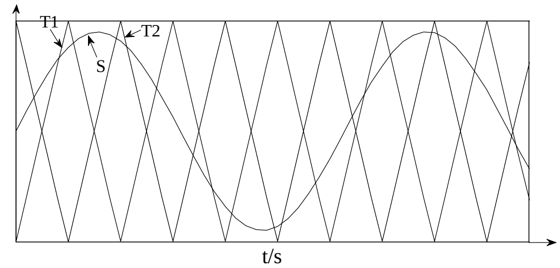


Fig.4 The diagram of the Phase shift PWM

In Fig.4, triangular carrier wave T1 correspondingly control the left arm of the H-bridge, and when T1 is larger than the modulation wave S, left upper arm conduct; When T1 is smaller than S, upper left arm off. T2 corresponds to the right arm of H-bridge, the state of lower arm is always on the opposite state of the upper arm. Adding the output voltage of each power unit up, we can get the equivalent multi-level PWM inverter output voltage waveform.

4 Simulation and verify

According to the software and hardware design of regional DVR, a PSCAD simulation model of a substation with DVR has been built up and shown in. Fig.5.

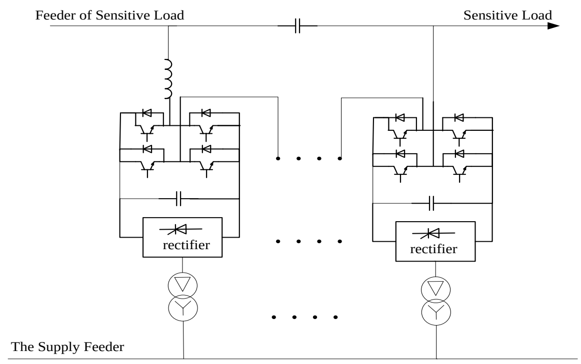


Fig.5 The structure of the DVR system

The 10kV bus of this substation is divided into three sections. A feeder with sensitive load of the 1M 10kV bus is selected to install the DVR and the energy is taken from the 2M bus.

4.1 The result of simulation of energy-taking circuit

When DVR is energized from three-phase rectifier, the three phase-to-phase voltages of the 2M bus and the DC capacitor voltage are shown in Fig.6 and Fig.7 respectively.

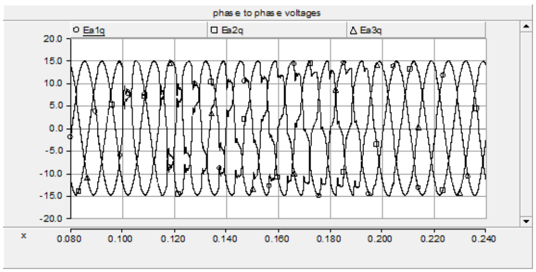


Fig.6 The phase-to-phase voltages of 10kV bus

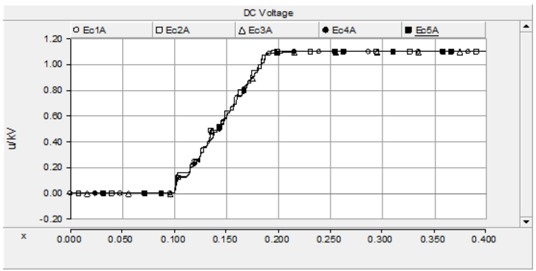
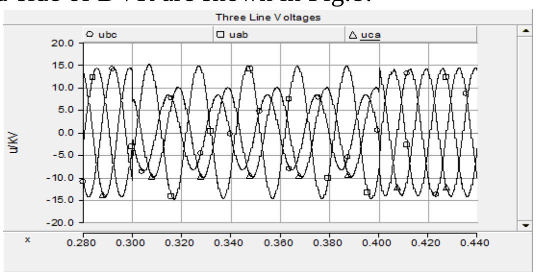


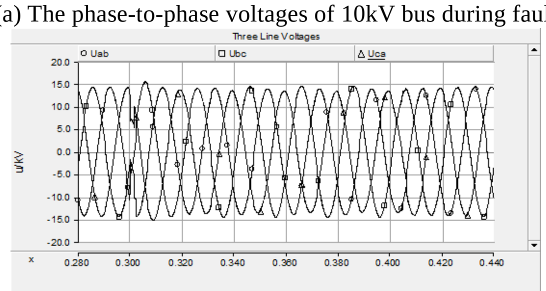
Fig.7 DC voltage of single H-bridge

We can see that the energy-taking device causes a certain distortion on the 10kV bus voltage and, the DC capacitor voltage can slowly arrive to the setting value of 1.1kV within 0.1s.

When a double-phase short-circuit fault occurs, the phase-to-phase voltages on the system-side and load-side of DVR are shown in Fig.8:



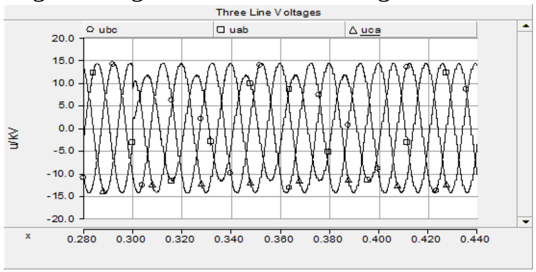
(a) The phase-to-phase voltages of 10kV bus during fault



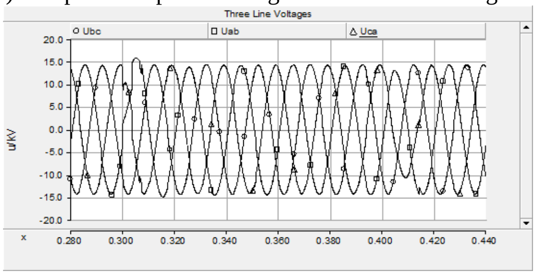
(b) The phase-to-phase voltages of load after compensation

Fig.8 Voltage waveforms during double-phase short-circuit fault

When the phase B and C short-circuited, AB line voltage rises slightly to 14.7kV, AC line voltage drops to 10.3kV and BC line voltage is 5.1kV. After compensation, these three phase-to-phase voltages are back to rated value. The phase-to-phase voltages on the system-side and load-side of DVR during a single phase-grounding fault are shown in Fig.9.



(a) The phase-to-phase voltages of 10kV bus during fault



(b) The phase-to-phase voltages of load after compensation

Fig.9 Voltage waveforms during single phase-grounding fault

When single phase-grounding fault occurs, the amplitude of the BC line voltage of the bus remains unchanged as 14.4kV, CA line voltage rises slightly to 14.6kV, and AB line voltage drops significantly to 12.2kV. After compensation, the three phase-to-phase voltage on the load-side is completely symmetrical and with the amplitudes are of rated value.

5 Conclusion

In this paper, the design of the main-circuit and software algorithm of a 10kV DVR that is applicable to compensate voltage sags in neutral-isolated network is introduced. And reference voltage calculation method applicable for the DVR in neutral-isolated network based on the analysis of the characteristics of voltage sags under unbalance fault are present. The PSCAD simulation model of a substation including the 10kV DVR has been built up to verify the correctness of the design of the DVR, and some conclusions can be drawn as following:

Large capacity DVR of regional compensation type is suitable for the use of energy-taking method from other 10kV bus to provide the energy needed during voltage sag compensation, but rectifier device will make influence on the voltage wave of the bus taking power side.

The voltage control of DVR in neutral-isolated network should be based on the goals to maintain the phase-to-phase voltage of the load.

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