A Novel Three-Phase Three-Wire Dynamic Voltage Restorer

W P Zhou 1, Z Y Wang 2 and Z G Wu 2
1 Naval University of Engineering, Wuhan, China.
2 Zhejiang Hangshen Electrical Group Ltd., Hangzhou, Zhejiang, China.
Email: *cnwhwp@126.com

Abstract. A novel optimal control method of three-phase three-wire Dynamic Voltage Restorer (DVR) and its simplified topological structure are proposed. Based on virtual-floating-ground analysis method, a time-domain mathematical model and the control equation of DVR’s converter are established; the optimal feasible solution with minimum objective function value of the control equation is deduced. Compensation voltage detection is based on digital phase lock, and the switching time is calculated by line voltages, the control performance under the proposed control strategy is analyzed, which greatly improve the utilization rate of DC side voltage and the DVR’s compensation capability. The simulation and experiment results of three-phase three-wire DVR under the proposed algorithm are given; the results show its validity and feasibility.

1.Introduction
With large numbers of industrial sensitive load in use, power users become more and more sensitive to power quality problem. The power quality disturbance problems such as the grid voltage sag, harmonic and flicker, and even instant loss of electric are inevitable, and voltage sag has become the most prominent and widespread problem which influence the safe operation of the power load, at the meantime, power quality problems will shorten the life of equipment and even lead to disastrous economic losses. Dynamic Voltage Restorer (DVR) is considered as the most economic and effective user power device to solve the problem of Voltage sag at present [1-16], the DVR by controlling the power electronics inverter produces a set of waveform controlled ac voltage, which can ensure the stability of the voltage of the sensitive load when there is a disturbance source voltage.

Dynamic voltage restorer in general can be divided phase voltage compensation type DVR and line voltage compensation type DVR. Phase voltage compensation type DVR is easy to control, can split phase compensation, can compensate zero sequence voltage, but also has disadvantages of more power switching devices demanded, big volume and high cost. Line voltage compensation type DVR has the advantages of simple structure, less power devices, relatively small volume, but has the disadvantages of complex control, can compensate zero sequence voltage. Because the non-ground neutral system is widely used in medium voltage distribution network[1], and three-phase three-wire system power supply is widely used in many occasions, so the line voltage compensation type DVR have broad application prospects.

In this paper, the line voltage compensation type three-phase three-wire DVR topology is analyzed and simplified, by analyzing the DVR time-domain circuit equations, the voltage control equation is obtained under the optimized index of the optimal solution. The optimal solution is based on the DVR output line voltage to calculate switch time, reducing the line voltage can be converted into phase voltage of the link, and can improve the utilization rate of DC side voltage and the compensation ability of DVR. Compensation voltage detection is based on digital phase locking method, the proposed control strategy and implementation scheme was analyzed, and the simulation and experimental results are given, the results show that the method is feasible.
2. SIMPLIFIED MAIN CIRCUIT TOPOLOGY STRUCTURE

Main power circuit of three-phase three-wire line voltage compensation type DVR is shown in figure 1, the rectifier module is a rectifier, and inverter module adopts three-phase Inverter Bridge. Set the imaginary point O as grid voltage reference point, \( u_{a'o}, u_{b'o}, u_{c'o} \) for grid side voltage, \( u_{ao}, u_{bo}, u_{co} \) for the load, \( u_{dc} \) for DVR dc side voltage value, assuming that injection transformer turn ratio of 1:1.

\[
\begin{align*}
    u_{ao} & = u_{a'o} + u_{ao'} = u_{a'o} - u_{a'o'} \\
    u_{bo} & = u_{b'o} + u_{bo'} = u_{b'o} - u_{b'o'} \\
    u_{co} & = u_{c'o} + u_{co'} = u_{c'o} - u_{c'o'}
\end{align*}
\]

(1)

\[\text{Figure 1. Main power circuit of three-phase three-wire DVR}\]

Set the DVR filtering inductances as \( L_f \), and considering inductance resistance \( r \), circuit equations can be written as:

\[
\begin{align*}
    u_{AO'} - u_{AO'}' &= L_f \frac{di_{ca}}{dt} + ri_{ca} \\
    u_{BO'} - u_{BO'}' &= L_f \frac{di_{cb}}{dt} + ri_{cb} \\
    u_{CO'} - u_{CO'}' &= L_f \frac{di_{cc}}{dt} + ri_{cc}
\end{align*}
\]

(2)

Actually for three-phase three-wire power system, only two equations are independent in equation (2), only two of the compensation voltages are independent, thus to ensure that conform to the requirements of the load line voltage, it can choose a kind of control method makes the \( u_{cc'} = 0 \), so the topology of the figure 1 can be simplified as shown in figure 2.

\[\text{Figure 2. Simplified topological structure of three-phase three-wire DVR}\]

3. DVR OPTIMIZATION CONTROL STRATEGY

3.1. Offset voltage detection and the control equation. Voltage disturbance can be detected based on coordinate transformation method [5]. But in this paper, by using the orthogonality of trigonometric function principle, the detection method based on digital PLL is adopts. The fundamental wave phase of line voltage can be detected, and the ideal value of load end line voltage can be written as follows:
\[ u_{sc}^* = 380\sqrt{2} \sin(\omega t + \varphi) \]
\[ u_{se}^* = 380\sqrt{2} \sin(\omega t + \varphi - \pi / 3) \]  
(3)

In which, \( \omega \) for fundamental wave angular frequency, and \( \varphi \) for the fundamental phase of \( u_{sc}^* \).

\[ u_{xsc}^* \] for fundamental wave angular frequency, and \( \varphi \) for the fundamental phase of \( u_{se}^* \).

\[ u_{xsc}^* = u_{xsa}^* = u_{sc}^* - u_{se}^* \]
\[ u_{xse}^* = u_{xsb}^* = u_{se}^* - u_{sc}^* \]  
(4)

In which, \( \omega \) for fundamental wave angular frequency, and \( \varphi \) for the fundamental phase of \( u_{sc}^* \).

\[ u_{xsc}^* \] for fundamental wave angular frequency, and \( \varphi \) for the fundamental phase of \( u_{se}^* \).

\[ u_{xsc}^* = u_{xsa}^* = u_{sc}^* - u_{se}^* \]
\[ u_{xse}^* = u_{xsb}^* = u_{se}^* - u_{sc}^* \]  
(6)

In which, \( \omega \) for fundamental wave angular frequency, and \( \varphi \) for the fundamental phase of \( u_{sc}^* \).

\[ u_{xsc}^* \] for fundamental wave angular frequency, and \( \varphi \) for the fundamental phase of \( u_{se}^* \).

\[ u_{xsc}^* = u_{xsa}^* = u_{sc}^* - u_{se}^* \]
\[ u_{xse}^* = u_{xsb}^* = u_{se}^* - u_{sc}^* \]  
(7)

Switch state \((j_a, j_b, j_c)\) has eight kinds of switch state, according to the corresponding binary \((j_a, j_b, j_c)\) defines them as numerical order \(k0 \sim k7\), the voltage vector of each switch state can also be controlled by (7). DVR time-domain circuit of voltage control equation is obtained:

\[ \frac{1}{S} [u \cdot \Delta t] = \begin{bmatrix} u_{aco}^* \\ u_{bco}^* \\ u_{cao}^* \end{bmatrix} \]  
(8)

In which \( u = [u(0), u(1), ..., u(6), u(7)] \)
\[ \Delta t = [\Delta t(0), \Delta t(1), ..., \Delta t(6), \Delta t(7)] \]  

3.2. the optimization control based on the equation optimal solution. According to the built DVR time-domain circuit equations of voltage control, to discuss the solution of the equation under \( u_{aco}^* > -u_{bco}^* \geq -u_{cao}^* > 0 \). Due to the absolute value of \( u_{aco}^* \) is the largest, and positive, and thus switch state of \( k4(1,0,0), k5(1,0,1)k6(1,1,0) \) can be selected, which can make \( u_A \) increasing, that is:
The above equations is strange, if add the conditions optimization index of \( J = \sum_{i=1}^{\phi} \Delta t(i) = \min \), it leads to

\[
\begin{align*}
\Delta t(4) + \Delta t(5) + \Delta t(6) &= \frac{T}{u_{ck}} (u_{co}^{*} - u_{co}) + \Delta t(6) \geq \frac{T}{u_{ck}} u_{ck}^{*} / u_{ck} \\
\Delta t(4) + \Delta t(5) + \Delta t(6) &= \frac{T}{u_{ck}} u_{ck}^{*} / u_{ck} + \Delta t(5) \geq \frac{T}{u_{ck}} u_{ck}^{*} / u_{ck} \\
\Delta t(5) &= \frac{T}{u_{ck}} u_{ck}^{*} / u_{ck} + \Delta t(6) \geq \frac{T}{u_{ck}} u_{ck}^{*} / u_{ck}
\end{align*}
\]

The optimal solution under \( \sum_{i=1}^{\phi} \Delta t(i) = \min \) is:

\[
\begin{align*}
\Delta t(4) &= \frac{T}{u_{ck}} (u_{co}^{*} - u_{co}) = \frac{T}{u_{ck}} u_{ck}^{*} \\
\Delta t(5) &= \frac{T}{u_{ck}} u_{ck}^{*} / u_{ck} = \frac{T}{u_{ck}} u_{ck}^{*} \\
\Delta t(0) &= TS - \Delta t(4) - \Delta t(5)
\end{align*}
\]

The optimal solution of equation (8) can be list as table 1.

| case | \( u_{AB}^{*} \) | \( u_{BC}^{*} \) | \( u_{CA}^{*} \) | optimal solution |
|------|-----------------|-----------------|-----------------|------------------|
| I    | +               | +               | -               | \( k4 \times t(A,B) + k6 \times t(B,C) \) |
| II   | -               | +               | -               | \( k2 \times t(B,A) + k6 \times t(A,C) \) |
| III  | -               | +               | +               | \( k2 \times t(B,C) + k3 \times t(C,A) \) |
| IV   | -               | -               | +               | \( k1 \times t(C,B) + k3 \times t(B,A) \) |
| V    | +               | -               | +               | \( k1 \times t(C,A) + k5 \times t(A,B) \) |
| VI   | +               | -               | -               | \( k4 \times t(A,C) + k5 \times t(C,B) \) |

The proposed approach is based on the DVR output line voltage command to calculate switch time, reducing the line voltage can be converted into a first phase voltage; This article is based on the optimization index for effective vector K1 ~ K6 "minimum level", to meet the requirements of the output voltage, the purpose of making effective vector can have the ability to make a larger output voltage. The method is based on the optimal solution of control equation is obtained, for the rest of the Ts in added by k0, to ensure the DC side voltage must improve the utilization rate of DC side voltage and to improve the compensation capacity of DVR (9, 18).

4.THE SIMULATION AND EXPERIMENTAL VALIDATION

In order to verify the proposed method, the simulation and experimental validation studies. Figure 3 and figure 4 is three-phase three-wire simulation results of dynamic voltage restorer, figure 3 is a three phase three wire line voltage is falling slowly compensation results (Uac), voltage get a good compensation. Figure 4 is three-phase DVR compensate three-phase voltage instantaneous fall by more than 40%, after DVR compensating load voltage becomes normal.
Experimental platform of controlled power tube for SKM75GB128D IGBT tube, maximum switching frequency of 10 kHz; Detection and control core is TMS320F28335 DSP unit. Figure 5 is the experimental results of three-phase voltage falls slowly compensation; Figure 6 is three-phase voltage sags and severe distortion of the experimental results, the voltage amplitude of short-term fell nearly 50%, and serious distortion, THD value reached 30%, after DVR compensating load voltage to maintain in the given value, THD value also dropped to nearly 3%, it can be found that the experimental results and simulation results are consistent, DVR can compensate voltage harmonic distortion and voltage sag at the same time.
5. CONCLUSION

In this paper, the line voltage compensation type three-phase three-wire DVR topology is analyzed and simplified, the time domain analysis equation of DVR is established, and the optimal solution of the voltage control equation is obtained under the optimized index, which calculate switch time based on the line voltage, and can improve the utilization rate of dc side voltage and the compensation ability of DVR. The optimal performance can be obtained by using the proposed performance optimization objective function. And the optimal solutions can be got by simple judgments and computations, which can significantly decrease computational complexity. The simulation and experimental results are given; the results show its validity and feasibility.

References

[1] Liu H, Han M X, You Y and Xiao X G 2003 Analysis Of Compensation Capability Of Line Voltage Compensation Based Dynamic Voltage Recovery (DVR). Automation of Electric Power Systems. 27 54-57.
[2] Huang B R, Xia L, Wu Z G and etc 2011 Double Feed forward Plus Feedback Control Strategy Based On Line Voltage Compensation For Dynamic Voltage Restorer. Electric Power Automation Equipment 31 61-64.
[3] Wang Z Y, Wu Z G and Zhou W P 2009 A Deadbeat Control Based Dynamic Voltage Restorer With Line Voltage Detection. Power System Technology. 33 106-112.
[4] Guo W Y, Xiao L Y, Guo J D and etc 2009 An Optimal Control Strategy for Dynamic Voltage Restorer With an Optimal Filter. Proceedings of the CSEE, 29 48-54.
[5] Zhou X S, He J, Ma Y J and etc 2008 Main Circuit Topology and Control Algorithm of Dynamic Voltage Restore. High Voltage Engineering, 34 753-758.
[6] Wang Z Y, Wu Z G, Zhou W P and etc 2009 A Novel Reference Wave Generating Algorithm Based on Characteristic Vector Extracted for DVR. Transactions of China Electrotechnical Society., 24 168-174.
[7] Wang Z Y, Wu Z G and Zhou W P 2009 Study on the dynamic voltage restorers with capacitor direct-coupled. Power System Protection and Control, 37 82-87.
[8] AWAD H and BLAAJ ERG F 2004 Transient performance improvement of static series compensator by double vector control. Proceedings of 19th IEEE Applied Power Electronics Conference and Exposition Vol 1 Anaheim, CA., USA. Piscataway 607-613.
[9] Li T, Wang B, Guo C P and Huang B J 2008 Simulation Research on Three-phase Four-leg DVR Based on Sliding Mode Variable Structure Control. Electric Power Science and Engineering, 24 5-8.
[10] LIU N, ZHOU Li D, YAO G and etc 2012 Dynamic voltage restorer based on robust H∞ controller. Electric Power Automation Equipment, 32 98-102.
[11] CHEN G D, ZHANG L and CAI X 2012 Compensation strategy based on positive and negative sequence extraction for dynamic voltage restorer. Electric Power Automation Equipment, 32 87-91.
[12] XIAO C, TANG Z D and JIN X 2010 A Novel Dynamic Voltage Restorer and Simulation. Journal of Jiamusi University (NaturalScience Edition), 28 891-893.
[13] ZHU J X, WANG T X 2010 A novel dynam ic voltage restorer w ith flywheel energy storage system. Journal of Mechanical & Electrical Engineering, 27 93-96.
[14] GE C H, CHENG H Z, WANG X H and etc 2009 DVR controlal gorithm based on minimal energy. Electric Power Automation Equipment, 29 70-74.
[15] WANG S C, YU K S and TANG G F 2008 Performance Analysis and Improvement of Digital Vector Control Algorithm for Dynamic Voltage Restorer. Proceedings of the CSEE, 28 64-71.
[16] HOU S Y, LIU Z C, JI L M and etc 2009 Cascaded inverter dynamic voltage restorer based on minimum active power injection strategy. Electric Power Automation Equipment, 29 33-36.
[17] Zhou W P, Wu Z G and Xia L 2004 Harmonic and reactive current detection in APF based on high-accuracy phase and frequency detection. Proceedings of the CSEE, 24 91-96.
[18] Zhou W P, Wu Z G, Tang J S and etc 2006 Novel algorithm of SVPWM and the study on the essential relationship between SVPWM and SPWM. Proceedings of the CSEE, 26 133-137.