Analysis of Abnormal Causes and Renovation Measures for Voltage Monitor Board of Light Triggered Thyristor in Zhaoqing Converter Station

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Abstract. In September 2018, 25 thyristor voltage monitor (TVM) boards of the Y4 valve of Pole 2 in Zhaoqing converter station did not have feedback signal. In order to make clear the root cause of this incident, the paper draws the detailed schematic diagram of the TVM board of converter valve in Zhaoqing station, and then studies the working principle of the TVM board and its feedback signal circuits, and analyzes the information interchange among all the functional modules. The pulse generation of positive voltage signal, negative voltage signal and overvoltage signal of the board are dissected. Then the equivalent circuit of each functional module is established to deduce the real reason of TVM board abnormality by quantitative calculation. Then the optimized scheme of TVM board circuit is proposed. Finally, comparative tests between the original circuit and the optimized circuit are carried out with the power supply of 459V RMS sinusoidal voltage and 7kV magnitude overvoltage respectively. The results show that the analysis of the TVM board working principle is correct, and the optimized scheme of TVM board circuit is effective.

1. Introduction
The converter valve of HVDC system mainly consists of thyristor, damping capacitor, damping resistance and equalizing capacitor [1-4], among which thyristor is the core component of converter valve, which determines the valve’s through-flow capacity. Multiple thyristors are connected in series to obtain the expected voltage. Thyristor is divided into electronic triggered thyristor (ETT) and light triggered thyristor (LTT) according to its trigger mode [5-9]. And converter valve is divided into electronic triggered valve and light triggered valve correspondingly. The TVM circuit of LTT constitutes the voltage equalizing circuit of thyristor level and monitors the thyristor’s two-end voltage and generates corresponding feedback signal [10]. Whether the TVM board functions normally or not has a great influence on the reliability of converter valve [11-12].

On Sep 18th 2018, after solving the leaking problem of the valve hall roof of Pole 2 caused by typhoon, 25 TVM boards of the Y4 valve received abnormal feedback signal while the operators in Zhaoqing converter station were turning Pole 2 into deblocked status from blocked status, and then Pole 2 was withdrawn into standby status.

At present, in order to enhance the reliability of TVM board, some researchers propose to decrease the resistance and capacitance in overvoltage monitor pulse width control RC circuit of TVM board [13-15], however, these measures only show improvement on the overvoltage feedback signal pulse.
width of TVM board, and the positive voltage and negative voltage feedback signal pulse width are still not up to standard.

The paper takes the TVM board in Zhaoqing converter station as research object, and analyzes the internal electric working principle of the TVM board, and deduces the feedback signal generation process and relevant influence factors according to circuit theory. Waveforms of relevant measuring points in TVM board circuit are sampled on the test platform in China Southern Grid DC Transmission Equipment Status Evaluation and Fault Diagnosis Laboratory. The reason of TVM board abnormality is clarified according to the test results and circuit theory. Then the paper propose to add new diodes in the original TVM board feedback signal pulse width control circuit to make the characteristics of the positive voltage, negative voltage and overvoltage feedback signal waveforms all consistent with the technical specification requirement. The proposed renovation measures are easy and effective, which do not change the parameters and the structure of original circuit and have complete compatibility with original converter valve control system. The research results of the paper are helpful for all the analysis of TVM board fault as well as converter valve voltage monitor, and are also useful for converter valve operation and maintenance.

2. TVM board working principle

2.1. TVM board function introduction

The function diagram of TVM board is shown as figure 1, which consists of AC voltage divider, DC voltage equalizing circuit, negative voltage monitor circuit, positive voltage monitor circuit, overvoltage monitor circuit, pulse generator and electro-optical conversion emitter.

![TVM board function diagram](image)

In each working condition, the capacitive impedance of AC voltage divider is in series with the capacitors of negative voltage monitor circuit, positive voltage monitor circuit and overvoltage monitor circuit, which are used to control the transmit signal’s pulse width. The capacitor capacitance of the three circuits are different, and thus the generated pulse width are different. The negative voltage monitor circuit transmits signal to the electro-optical conversion emitter through a pulse generator, while the positive voltage monitor circuit and the overvoltage monitor circuit share one pulse generator to transmit signal to the electro-optical conversion emitter.

2.2. TVM board feedback signal circuit

The negative voltage signal’s pulse width is 2~3us. The positive voltage signal’s one is 6~8us. The overvoltage signal’s one is 12~15us. The pulse width control circuit is composed of RC circuit. When
the voltage of $Y_1$ reaches the threshold value of negative voltage monitor circuit, positive voltage monitor circuit or overvoltage monitor circuit, the pulse width control circuit can be simplified as figure 2.

![Figure 2. Pulse width control circuit schematic diagram](image)

When $Y_1$’s voltage reaches the corresponding threshold value, the switch $S$ of the circuit is closed instantly, and the capacitor $C$ begins to discharge and $U_c$ begins to decrease from $U_0$. The voltage of $R_n$ varies with $U_c$ due to the voltage dividing effect of $R_m$ and $R_n$.

In the pulse generator of the negative voltage signal, an enhanced mode MOSFET is in parallel with the depletion mode MOSFET is in parallel with the optical emitter. 

MOSFET is turned on, the electric pulse signal of the following circuit is permitted to go through the optical emitter.

In the communal pulse generator of the positive voltage signal and the overvoltage signal, a depletion mode MOSFET is in parallel with $R_n$. The type of the MOSFET is BSS129, whose gate turn-off voltage $U_{gs}$ is $>1.2V$. Only when the MOSFET is turned off, the electric pulse signal of the following circuit is permitted to go through the optical emitter.

The disposal of stabilivolt D1 in figure 2 is divided into 2 cases:

The first case is that if the voltage of $R_n$ $U_{in}$ is $\geq 15V$ at the initial moment, the voltage of $R_2$ will be fixed at 15V and a large current will flow through the stabilivolt and $R_n$ will be bypassed. Then $U_{in}=U_c-15$. When the voltage of $R_n$ decreases lower than 15V, it turns into the second case.

The second case is that if the voltage of $R_n$ $U_{in}$ is $<15V$ at the initial moment, the diode can be removed equivalently, and the circuit experiences a zero-input response of pure RC circuit.

The pulse width of negative voltage signal, positive voltage signal and overvoltage signal is calculated below according to specific parameters.

1) For the RC pulse width control circuit of negative voltage signal, the voltage of $R_n$ exceeds 15V at the initial moment, which belongs to the first case. Let $T_{neg}$ be the turn-on time, then

$$T_{neg}=-R_C C \ln \left( \frac{U_n+R_n U_{di}}{U_n} \right)$$

Where $U_{di}$ is the stable voltage of the stabilivolt, $R_n=R_{neg}=820\Omega$, $C=C_1=1nF$, $R_0=680\Omega$, $U_0=88V$. $U_{gs}$=1.2V. Substitute the parameters and $T_{neg}$ is obtained:

$$T_{neg}=4.4374us$$

2) For the RC pulse width control circuit of positive voltage signal, the voltage of $R_n$ is lower than 15V at the initial moment, which belongs to the second case. Let $T_{pos}$ be the turn-on time, then

$$T_{pos}=-(R_m+R_n) \ln \left( \frac{U_m+R_m U_{gs}}{U_m} \right)$$

Where $U_{di}$ is the stable voltage of the stabilivolt, $R_m=R_{pos}=2.2k\Omega$, $C=C_2=1nF$, $R_0=390\Omega$, $U_0=88V$, $U_{gs}$=1.4V. Substitute the parameters and $T_{pos}$ is obtained:

$$T_{pos}=5.8213us$$

3) For the RC pulse width control circuit of overvoltage signal, the voltage of $R_n$ is lower than 15V at the initial moment, which belongs to the second case. Let $T_{bod}$ be the turn-on time, then

$$T_{bod}=-(R_m+R_n) \ln \left( \frac{U_m+R_m U_{gs}}{U_m} \right)$$
Where \( U_{d1} \) is the stable voltage of the stabilivolt, \( R_{d1}=R_{bod}=10k\Omega \). \( C=C_3=1nF \). \( R_9=680\Omega \). \( U_r=88V \). \( U_{p}=1.4V \). Substitute the parameters and \( T_{bod} \) is obtained:

\[
T_{bod}=8.9189\mu s
\]  

(2.6)

The reference value of \( T_{bod} \) is 12~15\( \mu \)s.

There is a deviation between theoretical calculation and reference value, which is related to the RC circuit component parameters, the surrounding circuits parameters, the energy pulse provided for the optical emitter, etc.

3. TVM board feedback signal analysis

In order to analyze the abnormality of the optical feedback signal in Zhaoqing station, the schematic circuit diagram of pulse generator and electro-optical conversion emitter are drawn as figure 3, where

![Figure 3. TVM board optical feedback signal pulse width control circuit](image)

1) \( U_n, U_p, \) and \( U_b \) are three pulses that have certain width. They are respectively the pulse generated at secondary side of the pulse transformer when the voltage of \( Y_1 \) reaches the threshold value of negative voltage monitor circuit, positive voltage monitor circuit and overvoltage monitor circuit and the corresponding energy-storage capacitor discharges at primary side. As the three circuits cannot be triggered at the same time, it is impossible for the three pulses to be generated simultaneously.

2) \( U_{neg}, U_{pos}, U_{bod} \) are three pulses whose width increase in sequence. The pulse width of the three signals are controlled by the RC circuits which are composed of \( C_1, R_{neg}, C_2, R_{pos}, C_3, R_{bod} \) shown in figure 2, and the analysis can be referred to Section 2.2.

3) \( (U_n, U_{neg}), (U_p, U_{pos}), (U_b, U_{bod}) \) are three pulse pairs and the two pulses in each pair are generated simultaneously. In each pulse pair, the width of the latter one is wider than the former one. The function of the former pulse is to provide energy for the following circuits shown in figure 3, and the function of the latter pulse is to determine the light signal’s pulse width of the light emitting diode V49.

4) \( A_0 \) to \( A_{12} \) and \( B_0 \) to \( B_{10} \) are measuring points in the circuit.

3.1. When the voltage of \( Y_1 \) reaches negative voltage monitor circuit threshold value across zero

The energy-storage capacitor of the main circuit \( C_n \) discharges rapidly, and through the pulse transformer whose primary side voltage is 88V and the ratio is 2:1, the voltage at secondary side is
about 44V. When the pulse $U_n$ is generated, $U_p$ and $U_b$ are at low level, and the energy of light emitting diode V49 is provided by $U_p$. $U_{ag}$ controls the on-off state of V37, and the on-off state of V37 determines the on-off state of V38, and the on-off state of V38 determines the on-off state of V46. When V46 is turned on, the light emitting diode satisfies one of the necessary requirements of passing through current.

The dotted arrow in the figure indicates current reference direction. When $U_n$ is at high level and V46 is turned on, the direction of the current $i_1$ between A2 and A3 is same as the reference direction.

3.2. When the voltage of $Y_i$ reaches positive voltage monitor circuit threshold value across zero
The energy-storage capacitor of the main circuit $C_p$ discharges rapidly, and through the pulse transformer the pulse $U_p$ is generated, and $U_b$ and $U_n$ are at low level. The energy of light emitting diode V49 is provided by $U_p$. $U_{pos}$ controls the on-off state of V36, and the on-off state of V36 determines the on-off state of V48. When V48 is turned on, the light emitting diode satisfies one of the necessary requirements of passing through current.

The dotted arrow in the figure indicates current reference direction. When $U_p$ is at high level and V48 is turned on, the direction of the current $i_2$ between B2 and B3 is same as the reference direction.

3.3. When the voltage of $Y_i$ reaches overvoltage monitor circuit threshold value across zero
The overvoltage signal pulse generator shares the same circuit with the positive voltage’s one. The energy-storage capacitor of the main circuit $C_b$ discharges rapidly, and through the pulse transformer the pulse $U_b$ is generated, and $U_n$ and $U_p$ are at low level. The following process of V49 is same as the positive voltage’s one.

3.4. Renovation measures of feedback signal circuit
The pulse width of positive voltage feedback signal is approximately same as the overvoltage’s one in the test of the TVM board. After analysis, it is found that when V46 and V48 are turned off, the pulse current of V49 cannot be cut off immediately.

When the upper part circuit in figure 3 generates the pulse $U_n$, or the lower part circuit generates the pulse $U_p$ or $U_b$, $i_{49}$ is formed and passes through V49 and flows into 2 directions V45 and V47, so if V46 and V48 are turned off at different time, $i_{49}$ cannot be totally cut off.

To solve the problem, the proposed optimized scheme is to add a diode between A2 and A3 and between B2 and B3 respectively. The A2 side of the diode is positive pole, and the A3 side is negative pole. The B2 side of the diode is positive pole, and the B3 side is negative pole. After adding the two diodes, when V46 and V48 are turned off at different time, $i_{49}$ can be cut off.

The current direction is analyzed below.

When $A_1$ and $A_9$ are at high level simultaneously, V46 is turned on, and B1 is at low level and B8 is at high level. Because V36 is a BSS129-type N channel depletion mode MOSFET and is turned on when its gate pole is at high level, V48 is turned off. Current $i_{45}$ flows to B3, and then $i_{45}=i_{25}$, $i_{45}=i_{47}+i_1$.

The type of light emitting diode V49 is HFBR-1537Z, and when the current of V49 reaches 40mA, the diode can emit the signal that has sufficient light intensity that can be identified by the receiver.

When $A_1$ and $B_8$ are at high level, and $A_9$ and $B_1$ are at low level, V46 and V48 are turned off. Current $i_{47}$ is close to zero, and $i_{49} \approx i_{45}$ while $i_{45}=i_{25}$. Current $i_{45}$ flows through R45, R55, R41, R42, V35 and gets to the ground. In this condition, V39 is deduced to be turned off through calculation so $i_{49}=0$.

The simplified circuit in this condition is shown as figure 4(a). Calculate the lowest voltage of $A_1$ and judge whether the voltage provided by the main circuit for the following circuits is able to satisfy the requirement of V49 to emit light at the moment. Let $i_{49}$ and $i_{45}$ be the turn-on voltage drop of V49 and V45 respectively. Let $U_{31}$ and $U_{35}$ be the voltage of $A_1$ and V35 respectively in the condition that V49 is emitting signal normally.
After finding that the TVM board feedback signal in Zhaoqing station is abnormal, the fault TVM board was sent to take a test to acquire its parameters. The result is shown as Table 1.

**Table 1. TVM test data**

| Test Item                                              | Reference Value | Test 1 | Test 2 | Test 3 | Test 4 | Test 5 | Test 6 | Test 7 | Mean value |
|--------------------------------------------------------|-----------------|--------|--------|--------|--------|--------|--------|--------|------------|
| Pulse width of positive voltage feedback signal (us)   | 6–8             | 11.3   | 11.4   | 11.7   | 11.5   | 11.9   | 11.7   | 11.8   | 11.7       |
| Voltage when positive voltage signal is returned (V)   | 100–200         | 123    | 119    | 120    | 118    | 123    | 126    | 125    | 126        |
| Pulse width of negative voltage feedback signal (us)   | 2–3             | 4.2    | 4.4    | 4.1    | 3.9    | 4.2    | 4.3    | 4.4    | 4.1        |
| Voltage when negative voltage signal is returned (V)   | -150–100        | -109   | -110   | -108   | -103   | -102   | -103   | -109   | -110       |
| Pulse width of overvoltage feedback signal (us)        | ≥12–15          | 10.9   | 11.3   | 11.4   | 11.1   | 11.5   | 11.7   | 11.8   | 11.7       |
| Overvoltage protection action voltage (V)               | ≥6500           | 4235   | 4197   | 4162   | 4187   | 3388   | 4276   | 4308   | 4185       |

It is seen that

![Simplified circuits](image)

**Figure 4. Simplified circuits**

In figure 4, \( R_{45}=470\,\Omega \), \( R_{55}=1000\,\Omega \), \( R_{41}=4.7\,\Omega \), \( R_{42}=470\,\Omega \), \( u_{49}=2.1\,V \), \( u_{45}=0.7\,V \), \( u_{35}=12\,V \), \( i_{43}=40\,mA \). And

\[
U_{a1}=u_{49}+u_{45}+u_{35}+i_{43}\times\frac{R_{42}+R_{41}}{(R_{45}+R_{42})+(R_{55}+R_{42})}
\]

(3.1)

Substitute the parameters and \( U_{a1} \) is obtained:

\[
U_{a1}=29\,V
\]

(3.2)

The magnitude of the pulse at \( A_1 \) can reach 44V higher than the voltage needed for maintaining light signal transmission 29V.

When \( B_1 \) and \( B_2 \) are at high level and \( A_1, A_2, A_3 \) are at low level, V46 and V48 are turned off. Similarly, as the simplified circuit is transversely zygomorphic, the following is obtained

\[
U_{b1}=29\,V
\]

(3.3)

It is concluded from the two cases above that \( U_{\text{neg}}, U_{\text{pos}}, U_{\text{bod}} \) which are supposed to control the pulse width of light signal actually do not take effect.

It is because the current between \( A_2 \) and \( A_3 \) and the current between \( B_2 \) and \( B_3 \) flow opposite to their reference direction, and as long as the voltage of \( A_1 \) or \( B_1 \) is at high level, V49 will emit corresponding light signal, and at this moment the pulse width depends on \( C_n, C_p, C_b \) and corresponding circuit resistance and transformer equivalent impedance. As other equipment parameters are same, the larger capacitance is, the longer capacitor discharges. So the pulse is wider theoretically.

The optimized scheme shown as figure 4(b) is to add a diode Vnew between \( A_2 \) and \( A_1 \) of which \( A_2 \) is the positive pole and \( A_3 \) is the negative pole, and add a diode Vnew between \( B_2 \) and \( B_3 \) of which \( B_2 \) is the positive pole and \( B_3 \) is the negative pole. After adding the diodes, the current is cut off, which makes that \( U_{\text{neg}}, U_{\text{pos}}, U_{\text{bod}} \) are able to control the current pulse width of V49, and therefore control the pulse width of light signal.

4. **Analysis of TVM board abnormality in Zhaoqing station**

After finding that the TVM board feedback signal in Zhaoqing station is abnormal, the fault TVM board was sent to take a test to acquire its parameters. The result is shown as Table 1.
1) The mean value of positive voltage feedback signal pulse width is 3.9us more than the corresponding max reference value.

2) The mean value of negative voltage feedback signal pulse width is 1.4us more than the corresponding max reference value.

3) The mean value of overvoltage feedback signal pulse width is 1.1us less than corresponding max reference value.

4) Positive voltage feedback signal pulse width and overvoltage feedback signal pulse width are consistent.

5) The mean value of overvoltage protection action voltage is 3112V less than the corresponding min reference value.

Two points are concluded. First, the three feedback signals’ pulse width are abnormal. Second, the overvoltage protection action voltage is less than its min reference value. In order to find the reasons, the pulse generator circuit and the overvoltage monitor circuit should be analyzed.

For the abnormal phenomena 1~4, according to Section 2, the three kinds of pulse width control circuit do not take effect, leading that all the pulse width are related to the main circuit’s energy-storage capacitor discharge pulse. And the pulse width provided by the energy-storage capacitor is wider than each signal’s reference pulse width, which explains why the pulse width is wider before optimization.

For the phenomenon 5, the pulse that is longer than 10us and shorter than 15us captured in the overvoltage test by TVM board test equipment is assumed to be an overvoltage protection action, and before optimization the positive voltage signal pulse width is consistent with the overvoltage one, so the first positive voltage signal captured by TVM test equipment is assumed to be the overvoltage signal and the voltage at this moment is passed upward. The voltage is around 4100V because the rapid rising steep wave detected by the main circuit is different from the feedback signal monitored by sinusoidal voltage.

5. TVM board comparative test between original circuit and optimized circuit

5.1. Waveforms in Low Voltage Condition

5.1.1. Comparison Between Original Circuit and Optimized Circuit.

1) Waveform of negative voltage pulse test

[Figure 5. Original circuit waveform of negative voltage pulse test]
2) Waveform of positive voltage pulse test

Figure 7 and Figure 8 are the waveforms of positive voltage signal pulse with the power supply of 380V RMS sinusoidal voltage. The waveform from up to down in the figure is light pulse of V49, voltage waveform of B10 and voltage waveform of A10 respectively. Figure 7 is the waveform of original circuit. Figure 8 is the waveform of optimized circuit. The optimized circuit waveform is shown in Figure 8.

5.1.2. Result analysis in low voltage condition. Figure 5 and figure 6 are the waveforms of negative voltage signal pulse with the power supply of 380V RMS sinusoidal voltage. The waveform from up to down in the figure is light pulse of V49, voltage waveform of A12 and voltage waveform of A10 respectively. Figure 5 is the waveform of original circuit. Figure 6 is the waveform of optimized circuit. It is seen that after optimization the light signal pulse width is same as the voltage pulse of A12, which proves that V46 in the optimized circuit is able to control negative voltage light signal pulse width, satisfying the requirement of TVM board’s negative voltage function design. Figure 7 and figure 8 are the waveforms of positive voltage signal pulse with the power supply of 380V RMS sinusoidal voltage. The waveform from up to down in the figure is light pulse of V49, voltage waveform of B10 and voltage waveform of A10 respectively. Figure 7 is the waveform of original circuit. Figure 8 is the waveform of optimized circuit.
waveform of optimized circuit. It is seen that after optimization the light signal pulse width is same as the voltage pulse of B10, which proves that V46 in the optimized circuit is able to control positive voltage light signal pulse width, satisfying the requirement of TVM board’s positive voltage function design.

5.2. Waveform in overvoltage condition

5.2.1. Comparison between original circuit and optimized circuit.

![Figure 9. Original circuit waveform of overvoltage pulse test](image)

![Figure 10. Optimized circuit waveform of overvoltage pulse test](image)

5.2.2. Result analysis in overvoltage condition. Figure 9 and figure 10 are the waveforms of overvoltage signal pulse whose magnitude is 7kV. V49 emits several pulses in figure 10. In the overvoltage test mode, the short pulse is filtered and the pulse whose width is between 10us and 14us is identified and the voltage at the moment which is around 4kV is returned meanwhile. Then the next pulse will not be detected. In figure 10 the first pulse is a positive voltage signal pulse whose width is 7.2 us, and the second pulse is an overvoltage signal pulse whose width is 10.8 us. The first pulse is filtered and the second pulse as well as the voltage at the moment when the second pulse is detected which is about 6.5 kV are returned. So the optimized circuit satisfies the requirement of TVM board’s overvoltage protection design.

6. Conclusions
Firstly the paper analyzes the principle of pulse generator circuit of TVM board, and then conduct research by theoretical calculation and test. The results show that:

- Before renovation the TVM board feedback signal pulse width is the energy-storage capacitor discharge pulse width of negative voltage monitor circuit, positive voltage monitor circuit and overvoltage monitor circuit. The three RC pulse width control circuits do not take effect. After adding diodes at corresponding place the negative voltage signal pulse width and the positive
The overvoltage feedback signal pulse width is within the prescribed range, but the overvoltage feedback signal pulse width is less than reference range.

- The cause why the overvoltage feedback voltage is low is that in the original circuit the positive voltage signal pulse width is close to the overvoltage one, leading that the overvoltage feedback signal is returned in advance at the transient steep wave front.

- The theoretical analysis and test results corroborate each other, indicating the necessity of the optimization scheme.

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