Study on the Solution to Network Voltage Interruption of Hybrid EMU Network Side Converter

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Abstract. Take the hybrid EMU as the research background, aiming at the possible network voltage interruption of its network side converter, this paper proposes a method to detect the network voltage interruption in time. Also, order to avoid the damage by the AC current shock on the system after the network voltage interruption is restored, a method to deal with the network voltage interruption is proposed and verified by simulation and experiment.

1. Introduction

China's railway industry has been promoted by leaps and bounds with the development of economy and science. Since the official opening of Wuhan-Guangzhou high-speed railway on December 26, 2009, the "harmony" has brought people's travel into the era of high-speed railway[1][2][3]. The CRH series trains are also increasingly welcomed by people. The hybrid EMU proposed in this paper is based on the development and design of CRH train.

The hybrid EMU has a variety of energy sources, such as catenary, lithium batteries and diesel generators. The EMU has two configuration modes: one is powered by 25kV catenary network under the electric section, and is powered by diesel generator under the non-electric section; the other still supplied by the catenary in the electric section, while in the non-electric section lithium batteries provides energy.

In the electric section, when the train runs at high speed, it is inevitable to encounter the phenomenon of pantograph-catenary separation, which is the key factor restricting the speed increase of electrified railway. With the increasing of railway transportation volume, the speed of train keeps increasing, and the development of off-line pantograph-catenary monitoring system has become the urgent demand of railway bureau and its subordinate locomotive depots[4][5].

For the hybrid EMU, if the pantograph-catenary separation occurs during the high-speed operation of the electric section for a short period of time, which causes the network voltage interruption, and this period is not enough to switch from the catenary mode to the power pack, diesel generator mode or the battery mode. In that way the EMU network side converter needs to adopt certain measures to monitor the phenomenon of pantograph-catenary offline in time and protect the converter. The network side converter mentioned here refers to the PWM rectifier capable of operating in four quadrants, and its topology is shown in figure 1.
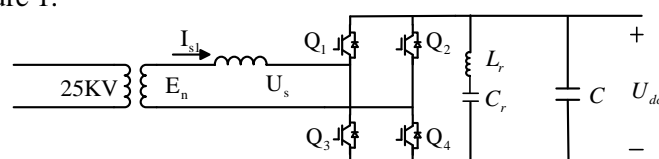

Figure 1. The topology of network side converter

2. Causes and harms of network power interruption

In the course of the train operation, many factors can cause the separation of pantograph and catenary. For example, the speed is a key factor, if the speed is too fast it will increase the lifting force of the pantograph to the contact wire. In the lifting process, if the elastic of the anchor point at both ends of the same span decrease or the slope of the radar tube is small, a hard spot can be generated when the positioning is raised to a certain extent, crash the pantograph and cause pantograph-catenary separation[6]; The line is also one of the influencing factors. At the slope changing point of the line, it is easy to make the contact wire and the slope changing point of the rail surface do not coincide, which causes the offline of the pantograph. From the perspective of the pantograph, when the speed of the train reaches a certain degree, the pantograph itself will generate an vertical acceleration and leads to the vibration of the catenary suspension, so that the pantograph cannot make good contact with the contact wire during operation, causing the separation of the pantograph.

Pantograph-catenary offline will bring great harm to the whole system, it will unstabilize the operation of electric locomotive; cause abnormal wear of pantograph slide plate and contact wire; generate radio noise interference; cause overvoltage in the main circuit and deteriorate the rectification condition of the traction motor. If the arc is too large, it may burn down the contact network and even cause the trip of substation. Moreover, the abrasion caused by the arc will make the pantograph slide plate and the contact wire to be uneven, and there will be overheated spots and slight welding phenomenon on the contact surface. If the locomotive runs at high speed, the fusion point will fall off instantly, making the damage of the contact wire more serious[6].

Most of the pantograph-catenary offline is short-term, so is the network voltage interruption of the EMU grid-side converter caused by the pantograph-catenary offline, so whether the system can work normally after the network voltage is restored became a problem. The pantograph-catenary transit from disconnected to re-contact is equivalent to the process of converter being grid-connected again after disconnected from the catenary for a short time, it will lead to the amplitude and phase of the converter AC side voltage differ from the grid, if no measures are taken, a voltage difference will occur at the moment of grid connection. Its difference will be determined by the difference of amplitude and difference of phase between the surplus voltage of the converter AC side and grid voltage, this difference will inevitably lead to transient shock current in the loop formed by converter and grid, if the converter is not properly protected, the impulse current will have a certain influence on the switch tube and even burn it down.

As shown in the figure below, figure 2 is the non-equivalent circuit of the main transformer and the network-side converter, figure 3 is the equivalent circuit of the main transformer and the network-side converter. The circuit diagram is used to analyze the overcurrent generated during the reclosing after the network voltage of network-side converter is interrupted. IGBT module is used to replace the grid-side converter here.
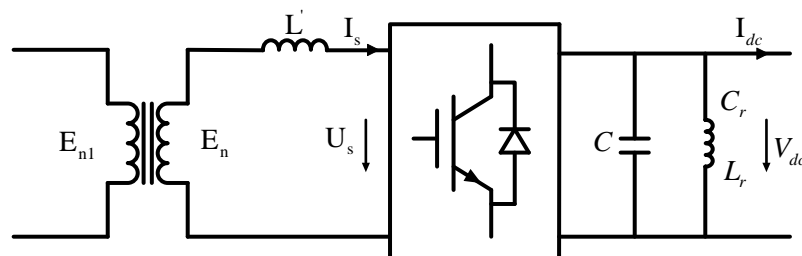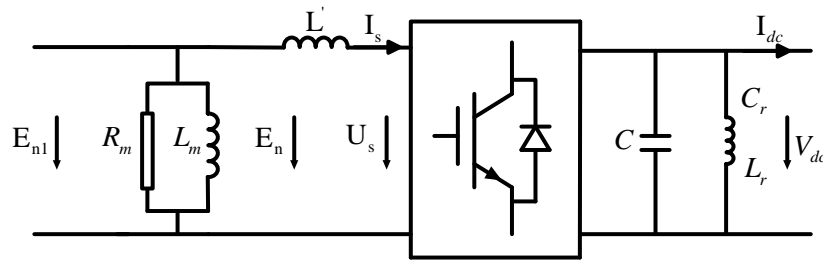

Figure 2. Non-equivalent circuit

Figure 3. Equivalent circuit

At the moment the network voltage interrupts, the voltage Us input to the network side converter remains the same due to the DC side capacitance. According to the equivalent circuit of transformer, during the network voltage interruption, the excitation inductance L_m and AC inductor L work to partial pressure, and because of the excitation inductance L_m is very large, far greater than AC inductor L, so voltage is most on both ends of excitation inductance, the inductance on AC inductor is almost 0, so the vice edge of main transformer E_n is equal to the leg voltage Us when the network voltage interrupt instantaneously. This Is equivalent to the original side of transformer has no load, and the load side acts as a power source to supply power to the original side. At this time, the AC current I_s is the excitation current, or the no-load current, which is very small so the AC current will immediately become 0 at the moment of power failure.

At the moment of recharging, the decrease of the DC side voltage cause the decrease of the leg voltage U_s, and the phase of U_s will constantly deviate from the network voltage E_n during the power-off period. Therefore, when the network voltage is recharged, a large voltage difference will be added to the AC inductor L, causing current shock.

3. Monitoring methods and countermeasures for network voltage interruption

It can be seen from the above analysis that it is very important to capture the interruption of network voltage successfully and adopt some countermeasures to protect the system. So far, there are some methods to monitor the interruption of network voltage caused by the separation of pantograph-catenary, but most of these methods are applied to inspection vehicle, none of which is complete and convenient inspection device in vehicle. In 1993, an automatically pantograph off-line inspection device was developed in Japan, which utilized the principle that the upper current of the pantograph is 0 when it is off-line, and so judges the off-line state by detecting the current of the pantograph. Although this method can easily determine the off-line state, it needs to install a current sensor on the pantograph, but the pantograph is in a high voltage state of thousands of volts. Therefore, the implementation of this method is complicated. Moreover, when the current of pantograph reduced sharply because of acceleration was slowed down, the off-line state can be detected while actually the pantograph still contacts with the wire, so this method is also inappropriate.

In this paper, an in-vehicle monitoring method is proposed based on the control of the network-side converter, and the countermeasures after the network pressure restore are given.

3.1 Monitoring Method of Network Voltage Interruption

The monitoring method of network voltage interruption adopted in this paper is judged by the change of the internal quantity controlled by the network-side converter at the instant of network voltage interruption. Therefore, before putting forward the monitoring method of network voltage interruption, it is necessary to introduce the control method adopted by the network-side converter ——the control method based on the dq rotating coordinate system.

3.1.1 Control Method Based on the dq Rotating Coordinate System

As mentioned above, the network-side converter is essentially a PWM rectifier, and its topology is shown in figure 1. In order to better control PWM rectifier, make its power factor close to 1, and output stable DC side voltage, we adopt a control method based on the rotation coordinate system. The essence of this control method is to convert AC to DC through coordinates transformation, so as to realize error free tracking of network current. The essence of dq synchronous rotation coordinate system control is the control method which converts

AC to DC. Since the network-side converter adopts single-phase PWM rectifier, the two-phase static rectangular coordinate system needs to be established through virtual axis, then establish the dq model. Figure 4 shows the the core of dq transform——park transformation.
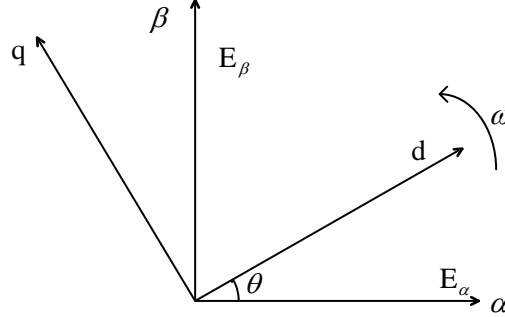

Figure 4. Park transformation

The beta axis is obtained by rotating the α axis by 90° counterclockwise. Make the active amount of the main transformer secondary side voltage E_n parallel to the α axis:

$$E_n(t) = E \sin \omega t \tag{1}$$

Thus:

$$\begin{cases} E_\alpha = E \sin \omega t \\ E_\beta = -E \cos \omega t \end{cases} \tag{2}$$

Because we chose the d axis as the active component and the q axis as the reactive component:

$$\begin{cases} E_d = E \\ E_q = 0 \end{cases} \tag{3}$$

As can be seen from Figure 4:

$$\begin{cases} E_d = E_\alpha \cos \theta + E_\beta \sin \theta \\ E_q = -E_\alpha \sin \theta + E_\beta \cos \theta \end{cases} \tag{4}$$

Plug equation (2) and (3) into equation (4):

$$\theta = \omega t - 90° \tag{5}$$

So we've got the relationship between θ and ωt, and we can get:

$$\begin{cases} E_d = E_\alpha \sin \omega t - E_\beta \cos \omega t \\ E_q = E_\alpha \cos \omega t + E_\beta \sin \omega t \end{cases} \tag{6}$$

$$\begin{cases} E_\alpha = E_d \sin \omega t + E_q \cos \omega t \\ E_\beta = -E_d \cos \omega t + E_q \sin \omega t \end{cases} \tag{7}$$

Subsequently, these formulas can be used to design the network-side converter double loop controller of outer voltage loop and inner current loop. It is not described in this article.

3.1.2 Network voltage interruption monitoring method based on network-side converter control According to the change of internal control quantity of the network-side converter at the moment of network voltage

interruption, the quantity that changes most obviously and easiest to capture is used as marker for judging the interruption of network voltage. Moreover, this quantity is required to change only when the network voltage is interrupted, but not when the system works normally, such as switching load.

In the analysis of the control quantity of network side converter, it is found that if the network voltage is interrupted, the change of E_d is very obvious. Under normal operation, the relationship between the secondary side voltage E_n of the main transformer and the leg voltage U_s of the network side converter is as follows:
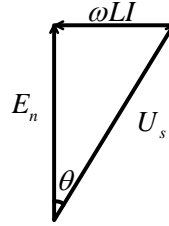

Figure 5. The relationship between E_n and U_s under normal operation

Normally, E_n and E_α has the following relationship:

$$E_n = E_\alpha = E \sin \omega t \tag{8}$$

It is analyzed in 2 that at the moment of network voltage interruption, E_n and U_s have the same size and same phase, so at the interruption moment:

$$E_\alpha = E \sin(\omega t + \theta) \tag{9}$$

Thus, when the network voltage is interrupted, the expressions of E_d and E_q' are:

$$Ed^{'} = E\sin(\omega t + \theta)\sin\omega t + E\cos(\omega t + \theta)\cos\omega t = E\cos\theta \tag{10}$$

$$Eq^{'} = E\sin(\omega t + \theta)\cos\omega t - E\cos(\omega t + \theta)\sin\omega t = E\sin\theta \tag{11}$$

By comparing equations (10), (11) and (3), it can be seen that E_d and E_q will change immediately when network voltage is interrupted. However, due to the moment of network voltage interruption, the deviation angle θ of leg voltage U_s and actual network voltage is very small, so $\cos\theta$ is very large and $\sin\theta$ is rather small. Therefore, it is appropriate to use E_d as the monitoring amount of network voltage interruption.

3.2 The Response Option of Network Side Voltage Interruption
Network voltage interruption can be divided into two cases. The first one has a relatively long interruption time, after the network voltage is restored, the network side leg voltage U_s of the converter become relatively small, and is greatly different from the actual network voltage. At this time, the network side converter is required to disconnect the main contactor, reconnected to network then go through the pre-charging process, also called the system restart.

The second one is the method introduced in literature [7]: when the network voltage interruption time is short, the system can enter the normal operation state through self-adjustment without system restart, which is more conducive to the rapid recovery of the system and protects the pre-charging resistance to a certain extent. The following mainly study on the situation that the time of network voltage interruption is short, i.e. the system can re-enter the stable operation state through self-recovery.

The dq model of PWM rectifier can be described as [8] :

$$\begin{bmatrix} E_d \\ E_q \end{bmatrix} = \begin{bmatrix} R+Lp & \omega L \\ -\omega L & R+Lp \end{bmatrix} \begin{bmatrix} I_d \\ I_q \end{bmatrix} + \begin{bmatrix} U_d \\ U_q \end{bmatrix} \tag{12}$$

Expand this matrix equation:

$$U_d = E_d + \omega L I_q - (R + Lp)I_d \qquad (13)$$

$$U_q = E_q - \omega L I_d - (R + Lp)I_q \qquad (14)$$

Where; E_d、E_q——d and q components of network electrodynamics force vector E_n;;

U_d、U_q——d and q components of voltage vector U_s on AC side of single-phase VSR；

I_d、I_q——d and q components of current vector I_{s1} on AC side of single-phase VSR；

p——differential operator。

U_d and U_q are the main components to calculate the the modulation wave, so at the time of the network voltage interruption the modulation wave will change due to changes in E_d and E_q, therefore certain measures must be taken to suppress the the change of U_d and U_q, to ensure that after the recovery of network voltage the modulation wave will not be significantly distorted, and the system will be in a stable operation state again.

In equations (13) and (14), the d axis component is active and the q axis component is reactive, ignore the resistance in the line. When the system is running normally, the q-axis component, wLI_d and LpI_d are relatively small. For simple analysis, they are ignored here, so we get:

$$U_d = E_d \qquad (15)$$

$$U_q = E_q \qquad (16)$$

In order to unify the system clock, the technology of phase-locked loop is adopted. The principle is to collect the network side voltage E_n, convert it to the dq axis, and lock the q-axis component E_q to 0, so as to achieve the purpose that the internal quantity of the system has the same phase with the network pressure, so E_q=0.

Referring to the reference [7], this paper proposes a new method to deal with the interruption of network voltage, at the moment of switch closing, instead of assign E_d directly to U_d, we use E_d as the target value and gradually assigns it in a stepwise manner, this method can make the value of U_d rises more gently, thus avoid the impact of overvoltage and overcurrent at the instant of switch closing to the system. This assignment method is more gentle and suitable for many live switch closing systems.

4. Experimental Verification

This experiment is carried out on the network side converter of the hybrid EMU with a power rating of 960 kW, an AC voltage rating of 900 V and a DC voltage rating of 1650 V.

Figure 6 is the experimental waveform without protection after the network voltage is interrupted for more than 50 ms when the actual network side converter is loaded.
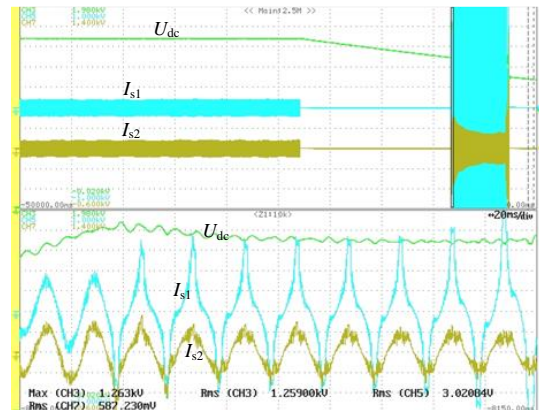

Figure 6. Experimental waveform without protection

As can be seen from the figure, we can see that after the network voltage is restored, there will be a large impact current in the first period of AC current, which will bring a great impact on the system, and make the subsequent current waveform in abnormal state. The DC voltage cannot be restored to its original value in a short time after reclosing.

Figure 7 is the experimental waveform with protection after the network voltage is interrupted for more than 50ms when the actual network side converter is loaded.
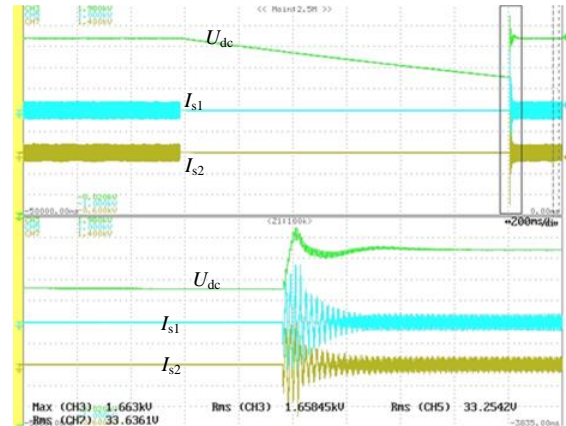

Figure 7. Experimental waveform with protection

It can be seen from the figure that there is no impact current in the first period of AC current and DC voltage can be restored to its original value after the network voltage is restored. Therefore, this protection measure is feasible in the case of short-term network power interruption.

5. Conclusion

Network voltage interruption can be judged by the change of the internal control quantity E_d of the converter. If the network voltage is interrupted for a long time, after the network voltage is restored, the main circuit should be cut off and adopt the pre-charging process to protect the system. If the network voltage is interrupted for a short time, the method of U_d and U_q reassignment is adopted to protect the system, and the U_d assignment process should be relatively slow, use the ladder method to gradually approach the target value. It has been proved to be very effective.

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