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Grounding Effect on Common Mode Interference of Underground Inverter

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Abstract

For the neutral point not grounded characteristics of underground power supply system in coal mine, this paper studied common mode equivalent circuit of underground PWM inverter, and extracted parasitic parameters of interference propagation path. The author established a common mode and differential mode model of underground inverter. Taking into account the rise time of PWM, the simulation results of conducted interference by Matlab software is compared with measurement spectrum on the AC side and motor side of converter, the difference is consistent showing that the proposed method has some validity. After Comparison of calculation results by Matlab simulation, it can be concluded that ungrounded neutral of transformer could redue common mode current in PWM system, but not very effective, the most efficient way is to increase grounding impedance of inverter and motor.

Keywords: *underground PWM inverter, common mode, conducted interference, coal mine*

1. Introduction

Neutral grounding method refers to neutral point grounding operation of star-connected generator and transformer in power system. Neutral grounding methods of power system can be divided into five modes:not grounded, grounded by resistance, grounded by reactance, grounded by coil and direct grounding. Neutral grounding used in China electric power system currently is: 220kV system directly grounding: 110kV system directly grounding; 35kV system grounded by coil; 10kV system not grounded,grounded by coil, grounded by resistance or reactance; 380/220V system directly grounding.While neutral grounding methods of power supply system adopted by China coal mine could be three: directly grounding, not grounded and grounded by arc suppression coil. According to "Coal Mine Safety Regulations " section 443 provides: "No neutral grounding of underground distribution transformer, neutral grounding transformer or generator is prohibited power supply directly to the underground. "[1, 2] Therefore, power supply system of underground coal mine does not use neutral grounding method. From a grounding point of view, different neutral grounding method does not affect low frequency system, but for inverter system, these grounding method have different impacts on conducted interference, these issues will be discussed in this paper.

PWM drive system for its saving energy, simple maintenance and easy adjustment, becomes more and more widely used in coal mining enterprises. As a result of using high-speed switching devices such as IGBT, MOSFET, which could speed up the converter dynamic response time,on the other hand, these high-speed switching power devices makes voltage and current significant changes in very short time, thus the current and voltage signal contain a wealth of high harmonics, which frequency range could be a few kHz to tens of MHz, and the magnitude may have far exceeded the limit prescribed by EMC standards. Underground converters such as electric locomotive, electric shearer produced strong electromagnetic interference, their high harmonic noise include both conducted and radiate interference.Compared to radiate interference, conducted interference could spread to far distance [3]. Therefore conducted interference is the main form of current noise in electrical equipment. Electromagnetic interference generated by inverter not only affect working of out load and shorten its life, but also brought great harm to converter itself.

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The inverter drive system includes two power conversion: AC/DC rectifier and DC/AC inverter. Therefore, regardless of differential mode or common mode interference exist two noise sources: rectifier bridge source and inverter source.Interference propagation path is given by dotted line as shown in Figure 1. Conducted interference generated by converter can be divided into differential mode (DM) noise and common mode (CM) interference, when the inverter circuit using a differential mode filter, common mode EMI dominates conducted interference.

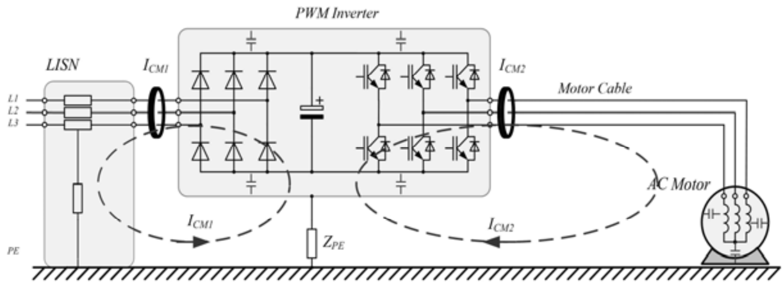


Figure 1. Two Main Path of Common Mode Current in PWM drive System

2. Common Mode Interference Test Program

As shown in Figure 2, CISPR standard specifies measurement arrangement of PWM inverter to test conducted interference.

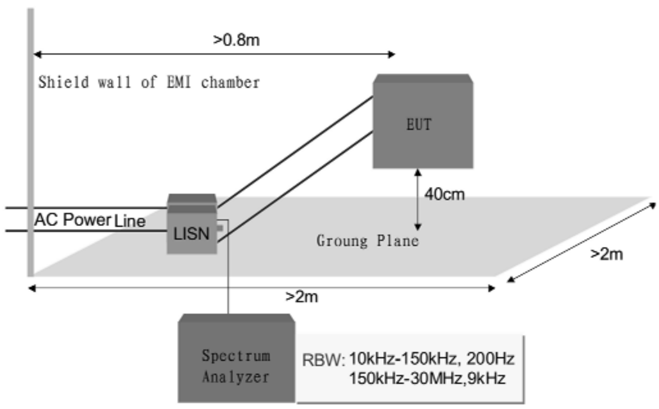


Figure 2. CISPR Standard Specifies Test Methods

In accordance with requirements of EMC standard EN55014-1,we need a 1m×2m aluminum plate as reference ground, linear impedance stabilization network (LISN) connected to the aluminum plate, and heat sink of PWM inverter must also connected with ground plate [4, 5]. LISN has two main functions:

1) provide equipment under test (EUT) a stable 50Ωimpedance to ensure the comparability of experimental results;
2) reduce power interference on experimental results.

To analyze the interference propagation path, set up a common mode equivalent circuit model as shown in Figure 3. Where C_{rp} is parasitic capacitance between heat sink and rectifier diodes; C_{ip} is parasitic capacitance between heat sink and IGBT collector; R_{c1} and L_{c1} are resistance and inductance of input cable; R_{c2} and L_{c2} are resistance and inductance of output cable; L_{b1} and L_{c3} are distributed inductance of DC bus; Z_{mCM} is common mode equivalent impedance of motor. If neglecting rectifier switching mode, any time only two diode conducted, LISN is equivalent to 25Ω in common-mode propagation path.

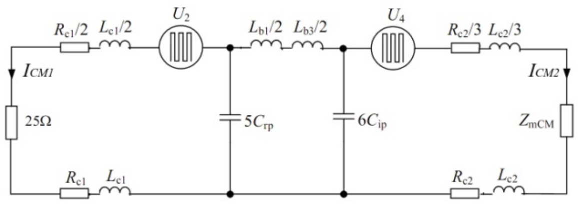


Figure 3. High Frequency Circuit Models of Common Mode Interference

As shown in Figure 3, using spectrum analyzer R&S ESIB26 we measured interference sources U_2 and U_4 of rectifier and inverter, with impedance analyzer Agilent 4294A measured cable parameters, motor parameters and parasitic capacitance, in the end we obtain the whole interference propagation path,detailed experimental method is described in [6,7]. Having interference source and propagation path, the response in propagation path can be obtained by transfer function, that is, the noise measured at LISN is $25 \cdot I_{CM1}$.

Using current probe measured current interference of EUT to power line, we could make a direct measurement of EMI noise in normal state of EUT ,without contacting EUT and not changing circuit structure. Current probe having a round structure, which can easily enclose wires under test. The core part of current probe is a ferrite toroidal core [8, 9]. When current probe wraps a wire, wire under test is equivalent to one turn of primary coil, N-turn coil around the core is the secondary coil, which can measure current value.

Conducted interferences can be measured by HF current probes.When utilized magnetic probe with toroidal shape, proper wire arrangement can be used to evaluate CM current components. Figure 4 shows wire arrangements for 3-wire and 2-wire systems respectively. Thus, CM currents are mostly calculated directly without additional analog circuitry which could limit measurement bandwidth [10, 11].

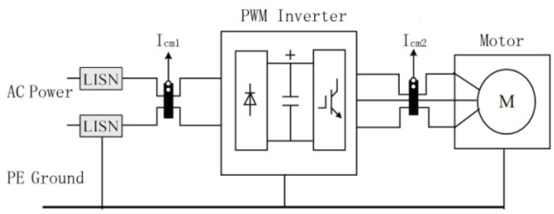


Figure 4. Measured Circuit of Common Mode Interference

For two-line system (DC side), common mode current is defined as the i_{CM1} , as follows:

$$i_{CM1} = \frac{i_{L1} + i_{L2}}{2} \tag{1}$$

For three-wire system (AC side) common mode current is defined as expression of phase current i_{L1}, i_{L2}, i_{L3}:

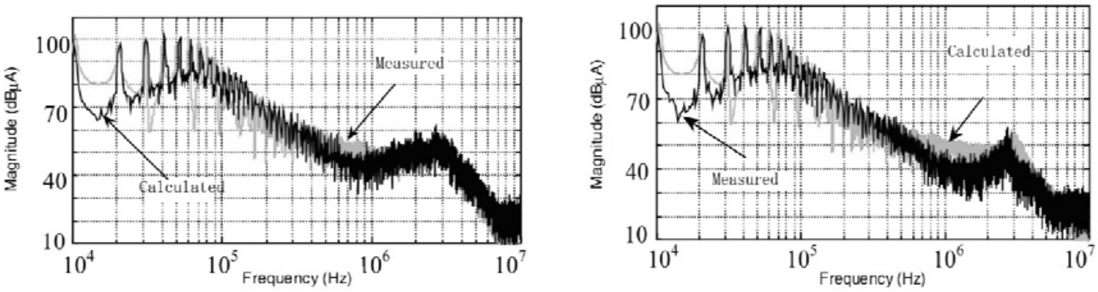
$$i_{CM2} = \frac{i_{L1} + i_{L2} + i_{L3}}{3} \tag{2}$$

When need to use current probe measuring conducted interference, the current probe output connected to spectrum analyzer, the value measured by current probe adding conversion factor is the magnitude of interference current [12]. For the same device, results can be voltage values measured at LISN 50Ω resistor and can also be current values measured with current probe on the wire, the conversion relationship is:

$$V(dB\mu V) = I(dB\mu A) + 20\lg 50 \qquad (3)$$

3. Measurement Results

In this paper, an industrial product PowerFlex700S inverter driven motor system is chosen for a experimental test. Figure 5 shows conducted EMI current testing results where: Converter line voltage is 390V/50Hz, switching frequency 10kHz, modulation ratio 0.8. Motor rated parameters are 380V/50Hz,22kW, 1480r/min. Current probe is Solar9209-1, EMI receiver is HP4195A, test bandwidth is 1kHz.



(a) common mode current of I_{CM1} (b) common mode current of I_{CM2}

Figure 5. Experimental and Computational Results of CM Current

From Figure 5, the simulation results of conducted interference by Matlab software is compared with measurement spectrum on the AC side and motor side of converter, we could conclude that the difference is consistent, thus showing that the proposed model has some validity.

While conducted interference at power side and load side of an underground PWM motor drive is prominent, we have not considered extracted parasitic parameters of propagation path, to improve accuracy of common mode and differential mode EMI of PWM system, we need take into account grounding effect to approximate high-frequency conducted EMI in motor drive system .

4. Frequency Converter Conducted Emi Propagation Path

Figure 6 shows EMI propagation path of PWM inverter system. PWM drive system generally include AC / DC rectifier and DC / AC inverter. Since both circuits contain non-linear device, in general there exist two EMI source in system: rectifier and inverter bridge interference source. input Adding a linear impedance stabilization network (LISN) has two purposes: First, provide power supply and a stable impedance of 50Ω for equipment under test (EUT); secondly, blocking power interference on the device under test, and the LISN can also be replaced by feed through capacitors. From view points of power and load, there are two major interference paths [13]: one is common mode and differential mode interference on LISN side; the other is common mode and differential mode interference on motor side, direction of interference propagation path shows as arrows in Figure 6.

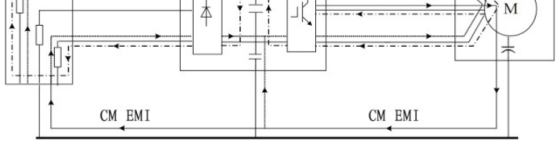


Figure 6. PWM Inverter System EMI Propagation Paths

Motor drive systems often chose different grounding methods based on various requirements, such as compliance with safety standards, transient over-voltage limit to the ground, or interruption of program requirements etc. Except for these, the impact of grounding configuration is also an important aspect of EMC performance. As mentioned above, noise voltage source and current source is subject to the impact of rectifier and inverter configuration. The following section focuses on general and idealized way of grounding configuration. Actually grounding method does not significantly change the interference source characteristics. Nevertheless, through changing high-frequency current flowing path ground configuration can indeed affect EMC performance.

5. Different Grounding Configurations

As shown in Figure 7, the impedance between AC power neutral point and ground is denoted as Z_{NG}. In addition, the impedance between inverter chassis and ground is noted as Z_{FG}, and electrical resistance between motor frame and ground is defined as Z_{MG}. Select a different impedance means a different grounding method.

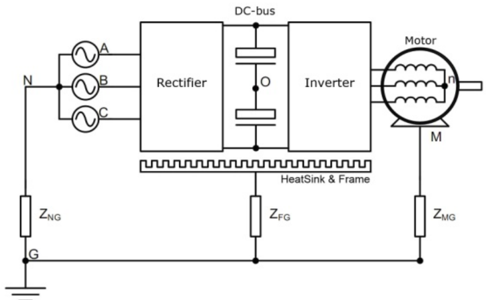


Figure 7. Grounding Method Diagram

In general switching function of inverter can be defined as s_i *(i = a, b, c, u, v, w)*, then the voltage between DC-link midpoint (point O in Figure 7) and rectifiers can be expressed as:

$$\begin{cases} v_{Oa} = (\tfrac{1}{2} - s_a)V_{dc} \\ v_{Ob} = (\tfrac{1}{2} - s_b)V_{dc} \\ v_{Oc} = (\tfrac{1}{2} - s_c)V_{dc} \end{cases} \tag{4}$$

Considering the symmetry of three-phase power, v_{ON} can be expressed by:

$$\begin{aligned} v_{ON} &= \frac{v_{aG}+v_{bG}+v_{cG}}{3} + \frac{v_{Oa}+v_{Ob}+v_{Oc}}{3} \\ &= \frac{i_a sL_a + i_b sL_b + i_c sL_c}{3} + (\frac{1}{2} - \frac{s_a+s_b+s_c}{3})V_{dc} \end{aligned} \tag{5}$$

Here the first term means voltage on boost inductors with common mode current. The second is due to rectifier transistors switching on and off.

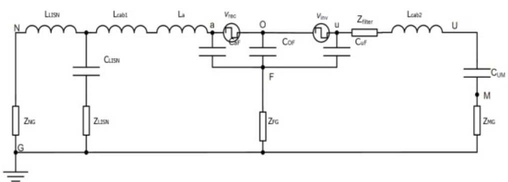


Figure 8. Common mode equivalent circuit with ground parameters

The inverter part of PWM converter can be expressed by the same method, v_{nO} can be represented as:

$$v_{nO} = \frac{i_u sL_u + i_v sL_v + i_w sL_w}{3} + (\frac{s_u + s_v + s_w}{3} - \frac{1}{2})V_{dc} \quad (6)$$

So we can get a simplified high-frequency equivalent circuit of PWM inverter as shown in Figure 8, where:

Z_{NG} represents impedance between AC power neutral point and ground,

Z_{OG} represents impedance between DC bus and ground,

L_u represents motor winding inductance,

Z_{MG} represents impedance between motor and ground.

It is discussed in [14] all the grounding possibilities of low and medium voltage drive system. According to Z_{NG} the grounding configurations can be divided into four methods: solidly grounding, low resistance grounding, high resistance grounding and ungrounded system. Due to its simplistic structure, solidly grounding method is commonly used. Ungrounded system does not become a standard on account of its relative uncertain capacitance between power lines and ground. Thus reference [15, 16] suggested that the correct implementation of high resistance grounding system should be an industry regulation.

In addition we have another grounding option of inserting a damping resistor Z_{MG} between motor frame and ground [17-19]. Generally most motor chassis grounded solidly, grounding methods typically affects CM current flowing into ground.

A simplified common-mode equivalent circuit shown in Figure 9 is to be discussed. Usually, it is necessary for measurement to insert LISN between power supply and equipment under test (EUT). In accordance with measurement standard requirements, LISN require solidly grounding. Consequently high-frequency EMI produced by EUT could be bypassed by LISN, thus Z_{NG} has little effect on noise propagation path.So only Z_{FG} and Z_{MG} can play an important role on noise propagation paths.

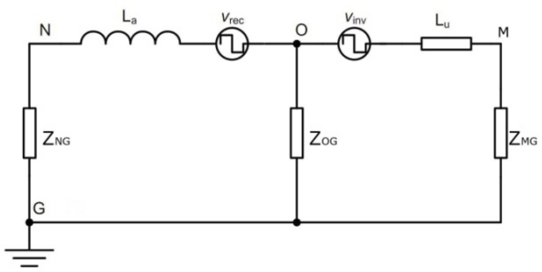
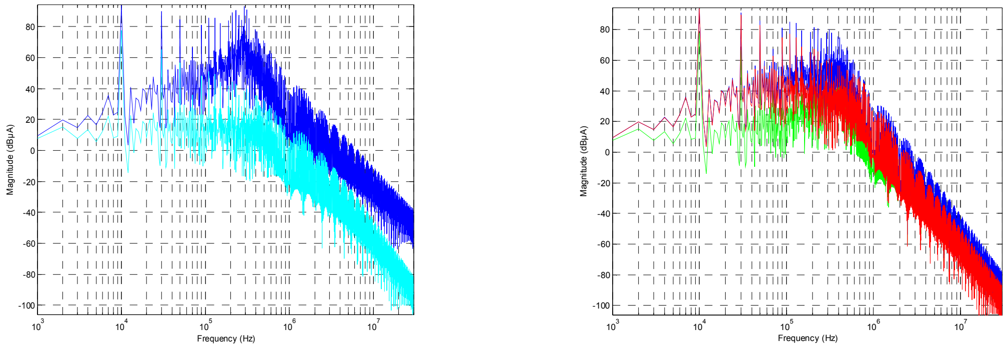


Figure 9. Equivalent Circuit of PWM Inverter System

6. Molding Results

As can be seen in Figure 10(a), grounding impedance (cyan lines) can indeed reduce common mode current, the difference is nearly 20dB at high frequency range. We can see in Figure 10(b), Z_{MG} (green lines) has the most obvious effect, Z_{FG} (red lines) has relatively worse results, while Z_{NG} (blue lines) reduce the worst. When Z_{NG}, Z_{FG} and Z_{MG} are all connected with damping resistor, the system have minimal common-mode currents. Therefore, the ungrounded neutral point of transformer secondary coil, which is equivalent to Z_{NG} =200Ω,is beneficial for reducing common mode interference in PWM system, but not very effective, the most efficient way is to increase impedance of Z_{FG} and Z_{MG}.

Nevertheless, motor frame must be grounded sloidly due to safety reasons. Recent years some scholars proposed installing a damping resistance in converter frame, and the frame must be grounded. Attention must be paid to avoid connecting resistance between chassis and ground, because this connection will increase risk of body electric shock, which is strictly prohibited by National mandatory safety standards.



(a) Z_{NG},Z_{FG} and Z_{MG} all goundied or all equal to 200Ω (b) Either of Z_{NG}, Z_{FG} and Z_{MG} equal to 200Ω

Figure 10. Common-mode Current in Different Grounding System

7. Conclusion

This paper put forward a new model to analyze the grounding effect on conducted EMI of a typical PWM motor drive. Based on a real object of industrial products, proposed extracting method of parasitic parameters on propagation path, established common mode EMI circuit model, proposed approximation method of high-frequency interference model to ensure the accuracy of high frequency prediction, and made quantitative experiment of conducted interference at power side and load side of PWM drive motors. The research ideas and practical calculation methods could be reference for prediction of conducted EMI system. In case motor frame is grounded solidly, common-mode current can flow through motor windings to motor frame, and then effectively into ground plane. Add a damping resistance in Z_{MG} is a usefull method of inhibiting motor-side high-frequency current. Even the PWM rectifier is replaced by a diode rectifier, adding resistance in Z_{FG} is also very effective,the noise generated by voltage source v_{rec} can be mainly attenuated by Z_{FG}. While the balance of Z_{MG} and Z_{FG} value should be considered, because the choice of a large Z_{FG} will reduce the frequency impact of capacitor C_Y in inverter.

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