The Resistive Ground Fault of PWM Voltage Inverter In The EV Charging Station

Marta Zurek-Mortka (m.zurek-mortka@uthrad.pl)
Łukasiewicz Research Network - Institute for Sustainable Technologies
Jerzy Ryszard Szymański
Kazimierz Pułaski University of Technology and Humanities in Radom

Research Article

Keywords: voltage, harmonic frequency, milliamps, RCD

Posted Date: June 11th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-580057/v1

The Resistive Ground Fault of PWM Voltage Inverter in the EV Charging Station

Marta Zurek-Mortka[1,*,+] **and Jerzy R. Szymanski**[2,+]

[1]Lukasiewicz Research Network – Institute for Sustainable Technologies, Department of Control Systems, Radom, 26-600, Poland
[2]Kazimierz Pulaski University of Technology and Humanities, Faculty of Transport, Electrical Engineering and Computer Science, Radom, 26-600, Poland
[*]marta.zurek-mortka@itee.lukasiewicz.gov.pl
[+]these authors contributed equally to this work

ABSTRACT

During the direct touch of the inverter output voltage, the nonsinusoidal ground currents with a basic harmonic frequency between 1.5 kHz and 16 kHz, flow via a human's body. Here was proved that Residual Current Device (RCD) type AC/$I_{\triangle n}$ = 30 mA does not switch off the power supply when a ground current with a value of about some hundred milliamps occurs. Because RCDs do not disconnect the power supply, the touch on the inverter's voltage is dangerous to the health and life. For the authors, RCD usage in Voltage Frequency Converters is not a good engineer practice. The article presents tests of RCD operation in the event of a ground fault during EV battery charging.

Introduction

In drive frequency converters, the PWM voltage inverter is a DC/AC converter which is usually connected to the motor. The drive frequency converters can also be used as a part of EV battery charger converters[1].

Fig.1 shows the concept of using a drive frequency converter for the implementation of two functionalities: control of induction motors and charging of EV batteries and energy storage. The main difference between these two functions is that for motor drives, the PWM drive converter produces a three-phase sinusoidal voltage with a frequency of basic harmonic from 0.5Hz to 50Hz, where 50Hz is usually the frequency of steady-state motor operating. On the other hand, when rectifying the three-phase voltage, the maximum frequency of the basic harmonic is used for battery charging and it changes within a small range, e.g. 250-300Hz or 900-1000Hz, depending on the properties of the drive converter. The presented solution is descried in detail in[1] and[2]. The basic harmonics of the phase voltage of PWM inverter reaches the frequency up to kilohertz[3] when PWM modulation factor is near zero. Drives with frequency converters are commonly powered by transformers with TN network arrangement[4]. In the event of a resistive earth fault to the phase voltage of the inverter, the resulting short-circuit current has a limited effective value and does not stop the inverter, therefore there is a risk of electric shock. In drive systems with frequency converters, the RCDs, regardless of their type and design, must not be sensitive to earth currents caused by the inverter's common-mode voltage (CM), otherwise they may prevent the operation of the frequency converter[5].

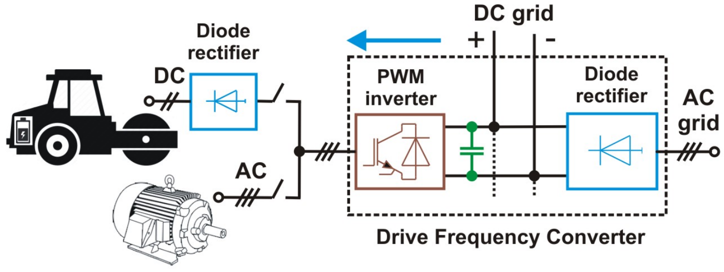

Figure 1. Proposed solution of the double function in the drive frequency converter[1].

Common-mode distortion currents caused by common-mode voltage have a frequency that depends on the switching frequency of the inverter power elements (IGBT, GTO, and others). One method is the usage of CM filters[6], which are designed to limit the common voltage of the inverter on common mode disturbances on the motor and cable or to create disturbing current flow circuits that bypass the earthed parts of the drive system, in particular the PE protective installation and the transformer.

A resistive short-circuit is a direct human contact with the phase voltage of the inverter. Under normal environmental conditions, the human body resistance has a normalized value of 1 kΩ[4],[7]. In the event of human shock, the earth fault currents caused by the inverter voltage are not detected by the residual current devices used in drive systems[8],[9]. In the electric shock protection system (PE), short-circuit currents that pose a risk of electric shock flow.

The safe operation of an EV battery charging station depends on the presence of appropriate protections on the supply side, including a fuse or an overcurrent circuit breaker, correct connection to the ground and a residual current device (RCD) disconnecting the power supply if the leakage current is greater than a specified value (e.g. 30mA). The problem of the lack of adequate protection concerns EV batteries in mode 1, where the EV is connected to the AC network through a standardized socket with currents up to 16A is described in[10],[11]. In[12] the method of detecting earth faults in modern electrical installations is described, especially with the use of a drive frequency converter. In[13] the tests of the sensitivity of the type A RCD are presented, showing a differentiated check depending on the harmonic current content. The main conclusion from [13] is that so far there are no properly functioning RCDs for protection against electric shock. When using RCDs with frequency converters containing a PWM inverter, the author suggests using magnetic material with high efficiency and a narrow hysteresis loop for the construction of the Ferranti coil. This will enable the correct measurement of capacitive earth leakage currents with harmonics with frequencies of the order of kHz (e.g. from 3kHz to 20kHz). In[14], the authors propose a comprehensive solution for an AC charging station for EV batteries in mode 3, which includes a communication system, RCD protection, and an application for controlling the energy flow.

This paper is another attempt to demonstrate the complexity of the problem of applying a RCD in the protective system of a drive with a frequency converter.

The paper is organized as follows: Section II describe the design of EV charging system with a voltage frequency converter and a rectifier. Sections III and IV provides the model of simulation tests and the simulation results to the observations. Section V shows the laboratory stand for detection the earth fault. The experimental test were conducted for the following cases: shorting of the phase voltage of the inverter and shorting of the unearthed screen of the screened three-phase cable between the inverter and the rectifier. This experiment confirms the made assumptions and simulation results. The concluding remarks are given in Section VI.

1 Drive System and EV Charging Station with a Frequency Converter

As a protection against earth fault, a residual current device with an AC Ferranti coil was used and showed in Fig. 2. The charge EV battery converter with a voltage frequency inverter and a RCD shown in Fig. 3 is powered by a transformer with a TN network system.

The earth fault current of the inverter voltage flows via the PE (protective earth) conductor to the transformer, then via the summation transformer to the residual current device (Ferranti coil) to complete the current circuit in the inverter. The short-circuit resistance R_h (human resistance) has a value of 1 kΩ and represents the resistance of the human body in direct contact. The short-circuit current is here forced by the high-frequency phase voltage of the inverter. In the PWM sinusoidal modulation, the phase voltages of the inverter U_u, U_v, U_w have the shape of a square wave with the modulated waveform (carrier frequency) frequency fc. The inverter phase voltage frequency f_c with IGBT transistors is between 2.5 kHz and 16 kHz[3]. When a resistive earth fault occurs, distorted common currents with the fundamental harmonic frequency f_c flow via the RCD.

Manufacturers of RCDs usually specify their properties for the 50-60Hz industrial network voltage frequency, while the properties of these devices at frequencies in the order of several kHz are not tested and currents at these frequencies may lead to accidental shutdown of the protected devices[15],[16]. The widespread use of drives with frequency converters contributes to the use of residual current devices as protection against earth faults also in industrial drives. Apart from the insignificant CM voltage of rectifier (Fig.3) $U_{cm-rec} = U_{N'}$[17], the phase voltages of the inverter with the modulation factor M = 0 are rectangular voltages with the same filling, there is no phase shift between them and are described by the relationship 1:

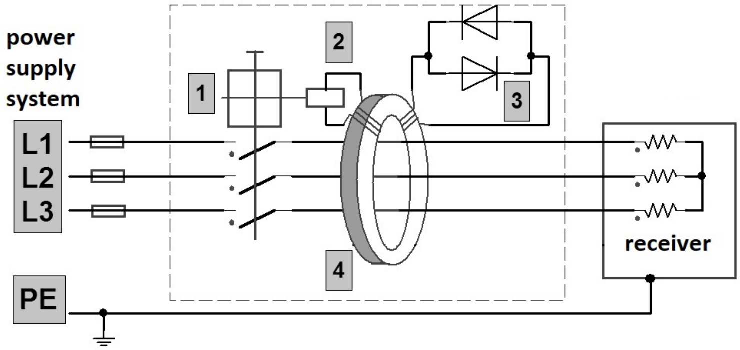

Figure 2. Residual Current Device RCD with a Ferranti coil: 1 - lock, 2 - differential release, 3 anti-parallel diodes 4 – Ferranti coil[8].

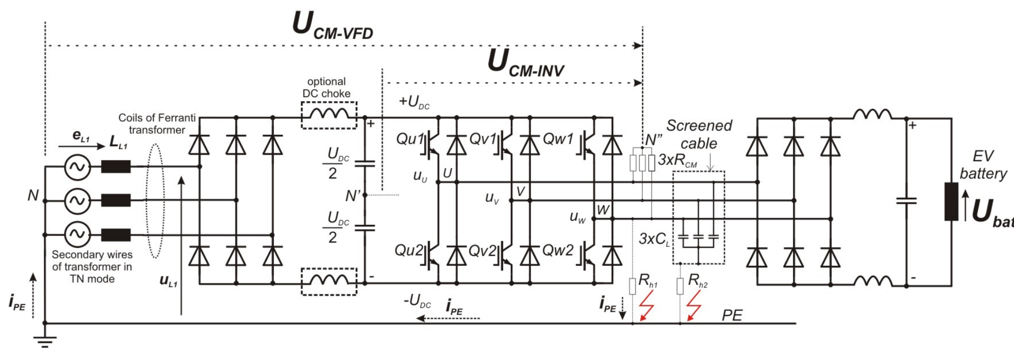

Figure 3. The model of the EV charging system with the frequency converter and the residual current device for protection against earth fault.

$$U_u = U_v = U_w = 1.27U_p sin\omega_c t + 0.424U_p sin3\omega_c t + 0.255U_p sin5\omega_c t + ... \tag{1}$$

where: U_p - square pulse amplitude, which is: $\frac{\sqrt{2}U_{ij}}{2} = \frac{U_{DC}}{2}$, where U_{ij} - phase-to-phase voltage of the transformer feeding of the frequency converter.

For the industrial network voltage of 3×400V/50Hz, the square wave amplitude Up is 280V, $\omega_c = 2\pi f_c$ - frequency of the PWM sinusoidal modulation of the IGBT inverter. For industrial drive frequency converter up to about 100kW, a carrier frequency has typically the range from 4kHz to 5 kHz[3].

The equation 1 shows that the earth fault current on R_{h1} (Fig. 3.) of the inverter phase voltage will contain odd harmonics and the amplitudes of successive harmonics are quickly suppressed. The basic short-circuit current energy is transferred by the basic harmonic with the frequency of f_c = 5 kHz.

2 Model of the EV Charging System

A linear mathematical model of the EV charging system with an inverter controlled by a sinusoidal PWM modulator was built to conduct computer simulation tests of the resistive earth fault current of the inverter voltage. For the simulation research, the ANSYS Twin Builder was used. The mathematical model has been symbolically written using the wiring diagram shown in Fig. 4. The current-voltage characteristics of the inverter's diodes and transistors have been linearized. In the inverter model, universal valve characteristics of freewheeling diodes and IGBT transistors were adopted. The phase voltage of the inverter was investigated in the range of continuous sinusoidal modulation[18], i.e., for the modulation factor from M = 0 to M = 1, where M

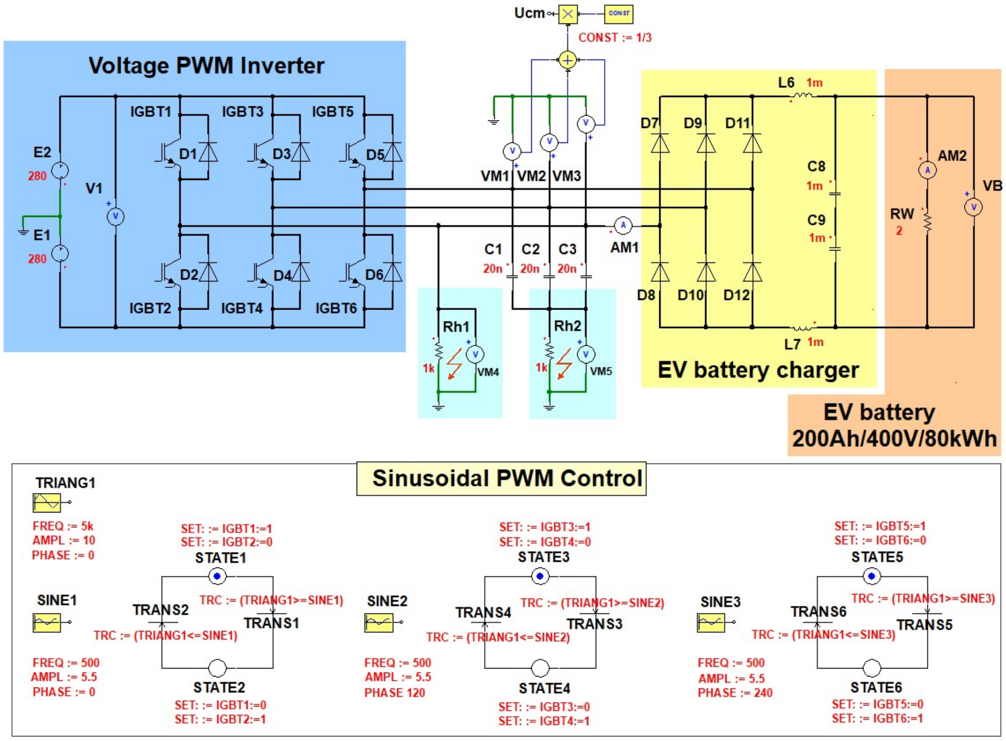

Figure 4. The model of the EV battery charging system with a voltage inverter.

is defined as (according to the sinusoidal PWM control in Fig. 4):

$$M = \frac{amplitude\ of\ sine\ modulating\ voltage}{amplitude\ of\ carrier\ wave\ (triangular)} = \frac{amplitude\ SINE1}{amplitude\ TRIANG1} \tag{2}$$

Voltage PWM inverters produce a three-phase AC voltage, the inherent feature of which is the presence of the voltage on the ground - the inverter common-mode voltage CM described by (Fig. 3):

$$U_{CM} = \frac{1}{3}(U_{N'U} + U_{N'V} + U_{N'W}) \tag{3}$$

Common-mode voltage has an RMS value other than 0 and forces the flow of capacitive leakage current via the converter, power supply system and power protections system. When using RCDs for electric shock protection or fire protection, the capacitive leakage current may cause accidental operation of these switches or their inactivity in the event of an electric shock or fire hazard.

Due to the equal effective value of the inverter phase voltage $U_w = 280V\,(U_w = [\sqrt{2}\cdot 400V] : 2)$, independent from value of PWM modulation coefficient M. In the event of a resistive earth fault to the inverter voltage (Fig. 3) when M $\neq$ 0, distorted currents has a dominant amplitude value of carrier harmonic frequency f_c = 5 kHz (Fig. 4) and the RMS value equal to 280 mA (280V/1kΩ), flows via the RCD.

Fig. 5 shows the waveforms of voltages and earth currents obtained in simulation tests at the occurrence of an earth fault, via a 1kΩ resistor (symbolic contact resistance). The short-circuit current waveform with phase voltage earth fault is shown in Fig. 5a, while Fig. 5b shows the short-circuit current waveform with ungrounded cable screen earth fault between the inverter and the rectifier due to the occurrence of the inverter CM voltage on the screen of the three-phase cable. The obtained waveforms of short-circuit currents indicate that the dominant amplitude value harmonic of these currents is 5kHz in both cases (fig. 5a and fig. 5b). Hence, it should be concluded that the use of RCD protection on the power supply of the drive frequency converter will not work properly.

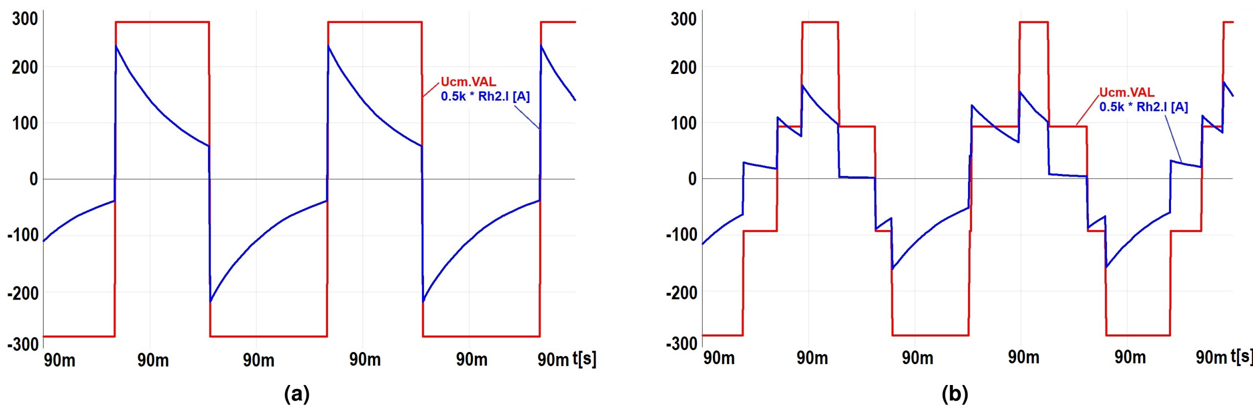

Figure 5. Waveforms of CM voltage and ground current with 1kΩ resistance for modulation factor: a) M=0, b) M=0.55.

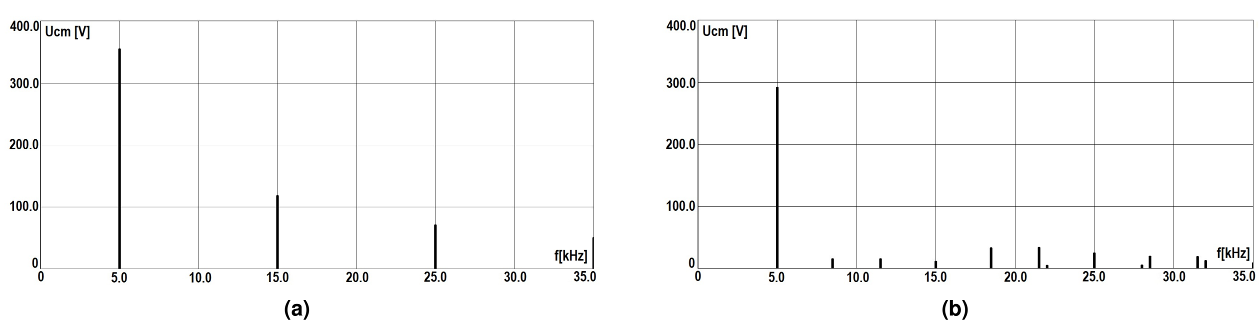

Figure 6. Amplitude spectrum of common-mode voltage for modulation factor: a) M=0, b) M=0.55.

(a) (b)

Figure 7. Laboratory stand for short ground current flowing via the human body caused by inverter phase voltage and common-mode voltage: a) current probe measure of leakage current in PE wire in RCD protection of drive VFC's power system, b) measuring of leakage current on an equivalent resistance of the human body 1kΩ.

Based on the frequency analysis of the inverter common mode voltage of the inverter (VM5) in the model in Fig. 4, the amplitude spectra of the harmonics were obtained, as shown in Fig. 6a and 6b. They show that:

- the basic harmonic of the inverter phase voltage with the frequency f_c = 5kHz has greater amplitude at the modulation factor M = 0 than at M = 0.55 (Fig.6a),
- for the modulation factor M greater than 0, the harmonics of the sidebands related to the frequency of the modulating sinusoid will appear, distributed around the even and odd multiple of the modulated frequency f_c (Fig. 6b).

3 Results

Fig. 7a and 7b shows the test stand for measuring earth fault currents in the event of an earth fault through a resistance of 1kΩ for the following cases:

- shorting of the phase voltage of the inverter,
- shorting of the unearthed screen of the three-phase cable between the inverter and the rectifier.

The basic elements of the test stand are: an oscilloscope set with a 1:100 voltage probe and a current probe with an amplifier, an adjustable resistor with a range from 0 to 10kΩ.

The earth current waveforms obtained on the laboratory stand at the occurrence of a resistance short-circuit with phase voltage are shown in Fig. 8a. Fig. 8b shows a resistive short circuit in the ungrounded screen of the three-phase cable (inverter common-mode voltage). The tests were performed at an output voltage frequency equal to 35Hz. The waveforms of the currents of the resistive earth fault at the frequency of 500Hz are similar in nature, but they are not included in this paper. The waveforms of the resistive earth fault currents obtained in the experimental tests fully confirm the obtained results of the simulation tests.

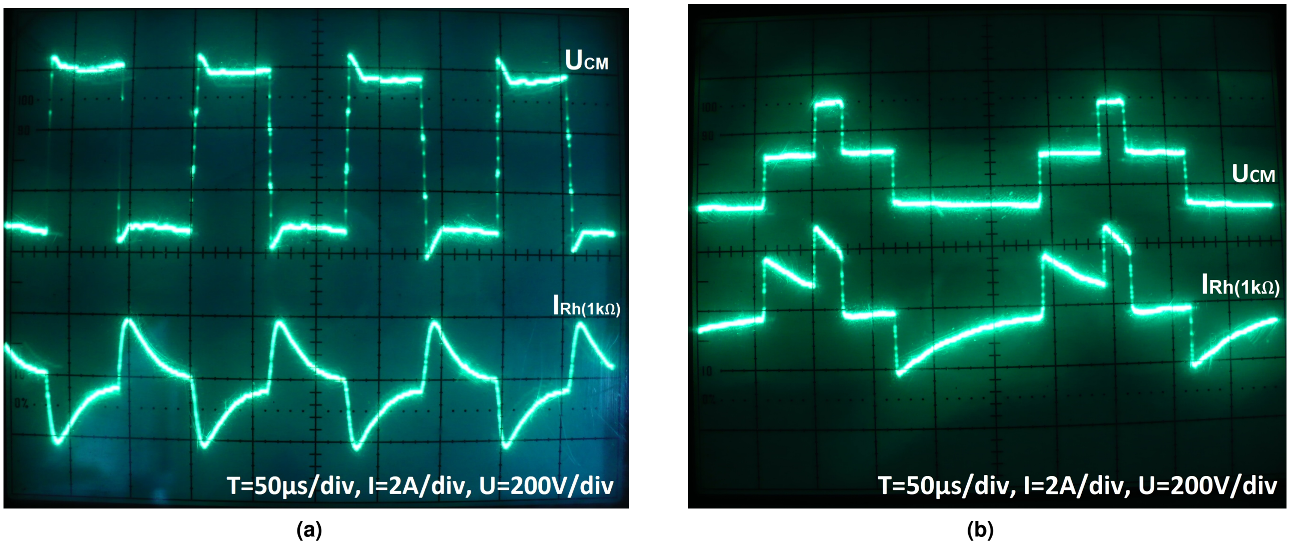

Figure 8. Waveforms of earth fault currents at ground resistance 1kΩ while: a) common-mode voltage UCM is for M≈0, b) UCM is for M=0.55 (inverter output basic harmonic frequency is 35Hz)

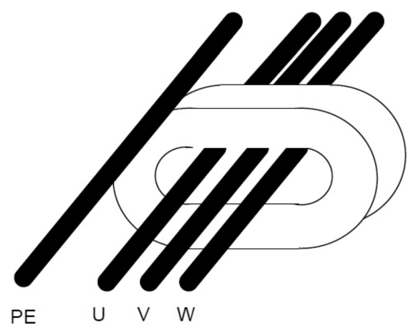

Figure 9. Scheme of special nanocrystalline magnetic cores as a common-mode filter.

3.1 Methods for Minimizing the Capacitive Ground Leakage Currents

Until now, there are no RCDs correctly operating in the environment of high-frequency ground leakage currents caused by the CM voltage inverter in the industrial offer[13]. The galvanic connection of the PE protective conductor with the common point of the transformer of the TN system supplying the converter produces a low-impedance electric circuit for the ground leakage current. For this reason, the EMC filters of converters have a limited ability to absorb the capacitive leakage current caused by the inverter CM voltage.

The authors of this paper propose to limit the capacitive leakage current through the use of a screened cable connecting the frequency converter with the rectifier with reduced, in comparison to traditional cables, parasitic capacitance to earth, and the use of a common-mode filter with the special nanocrystalline magnetic cores[19], as shows Fig. 9.

Figures 10 shows three-phase screened cables: a traditional one - Fig.10a and dedicated to connect the inverter with loads - Fig.10b. Based on the catalogue data of screened cable manufacturers[20], it should be stated that the values of the parasitic ground capacitances CCM of a screened traditional cable are nearly 10 times higher than for a screened cable dedicated to inverters. By using dedicated cables, it is possible to reduce high-frequency leakage currents from the inverter wiring with a load by nearly 10 times. Reducing the high-frequency ground leakage currents is essential to ensure proper operation of the RCD under normal inverter operating conditions.

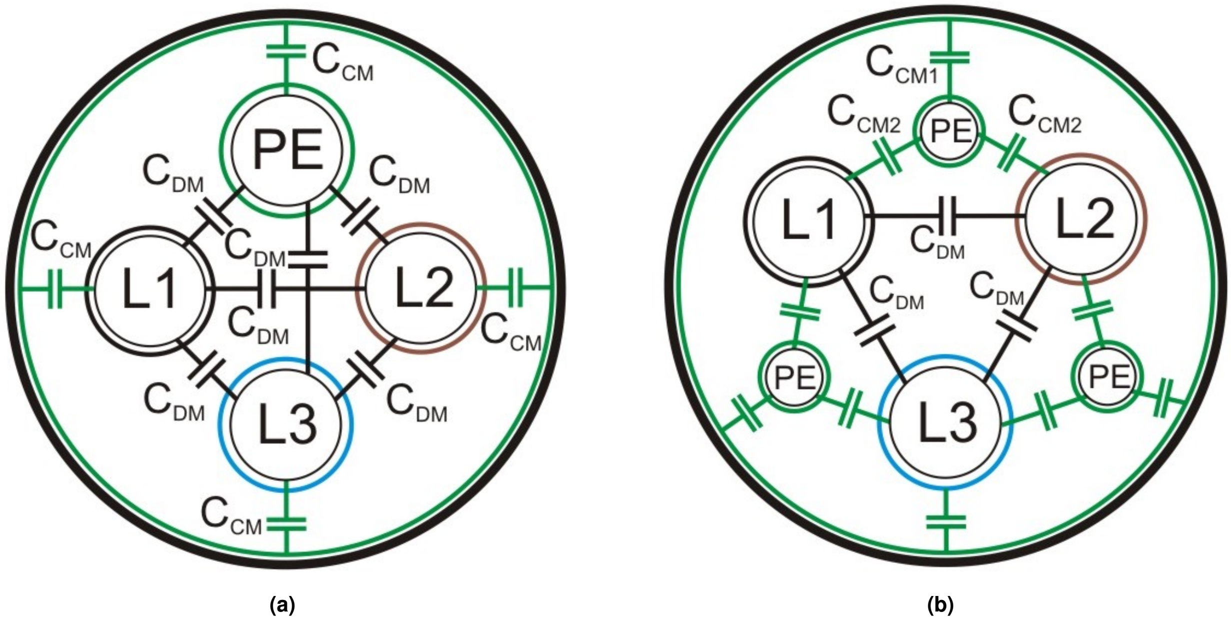

Figure 10. Cross-section of 3-phase screened cables with green marked parasitic line-to-line capacities C_{DM} and parasitic ground leakage capacities C_{CM} in: a) with 1 PE wire b) with 3 PE wires.

The occurrence of a resistive ground fault in the phase conductor of the inverter will result in a high-frequency short-circuit current that will flow via the RCD. Often, such a short-circuit current will not cause the correct operation of the RCD[13]. The authors suggest the use of an additional ground leakage current's sensor on the inverter phase outputs to stop the inverter operation at the set ground current values, e.g. in the range of 100mA-300mA. The proposed range will enable the converter to operate under normal conditions and will stop it, e.g. when directly touching the phase conductor (e.g. 560V:2=280V, 280V:1kΩ = 280mA).

4 Conclusions

The conducted tests of tripping of the AC residual current device with the nominal differential current $I_{\triangle n}$ = 30 mA showed that it is insensitive to residual currents with frequency f_c, regardless of the value of the modulation factor M of the inverter phase voltage.

Measurements of the tripping of the residual current device RCD were performed at the stationary electrical switching station equipped with a residual current device, which is the supplementary part of the basic protection system.

The selection of an appropriate residual current device is a very complex task, because the frequency, amplitude, and effective values of the fundamental harmonic of the resistive short-circuit current must be taken into account. Manufacturers of residual current devices do not specify the properties of residual current devices for high-frequency distorted currents.

The conducted tests showed the lack of effective operation of the tested RCD in the presence of a high-frequency short-circuit current of both the phase voltage and common-mode voltage of the inverter. According to the authors, the accidental tripping of the RCD on the Ferranti coil disqualifies it as a supplementary electric shock and fire protection in powering drive frequency converters used in EV battery charging stations and motor drives.

Lowering the value of the ground leakage currents through the use of dedicated screened cables and CM filters enables the correct operation of the RCD installed on the power supply of the converter with the voltage inverter. The occurrence of a resistive ground fault should be identified with an additional sensor that will stop the inverter operation immediately if the CM current exceeds the allowed value.

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Acknowledgements (not compulsory)

The ANSYS Software national scientific software license has been used in the part of the article related to the modelling of the electric circuit, which was funded by a computational grant obtained by Kazimierz Pulaski University of Technology and Humanities in Radom, Poland.

Author contributions statement

Conceptualization, methodology, software, validation, formal analysis, resources, writing review and editing, visualization: M.ZM and J.S. All authors have read and agreed to the published version of the manuscript.

Additional information

The corresponding author is responsible for submitting a competing interests statement on behalf of all authors of the paper. This statement must be included in the submitted article file.

Figures

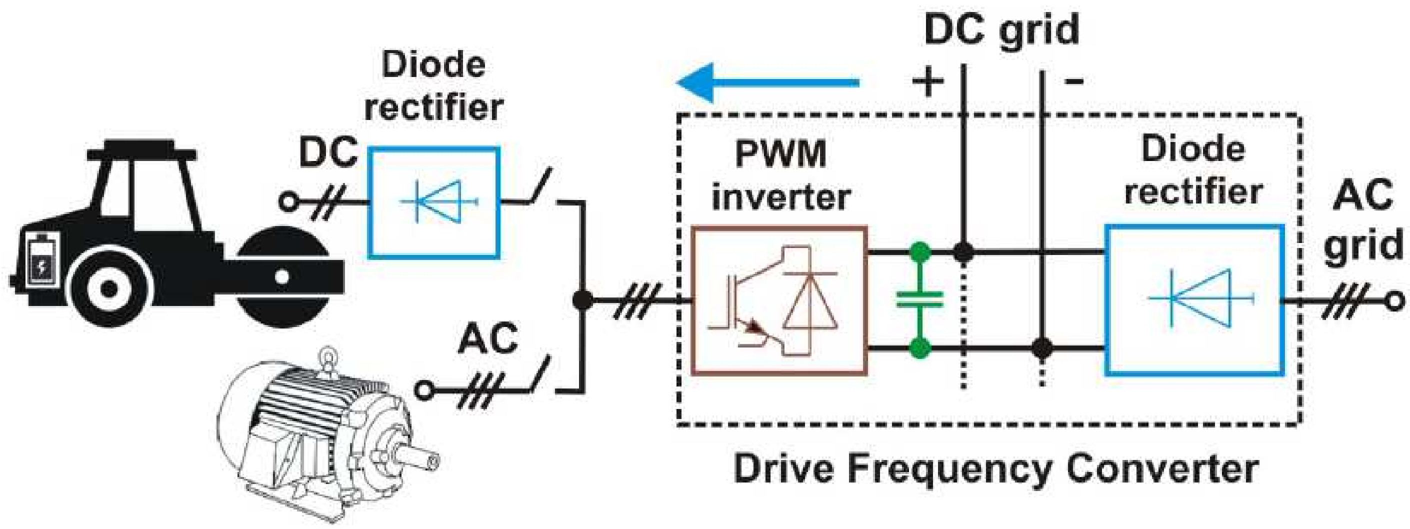

Figure 1

Proposed solution of the double function in the drive frequency converter1.

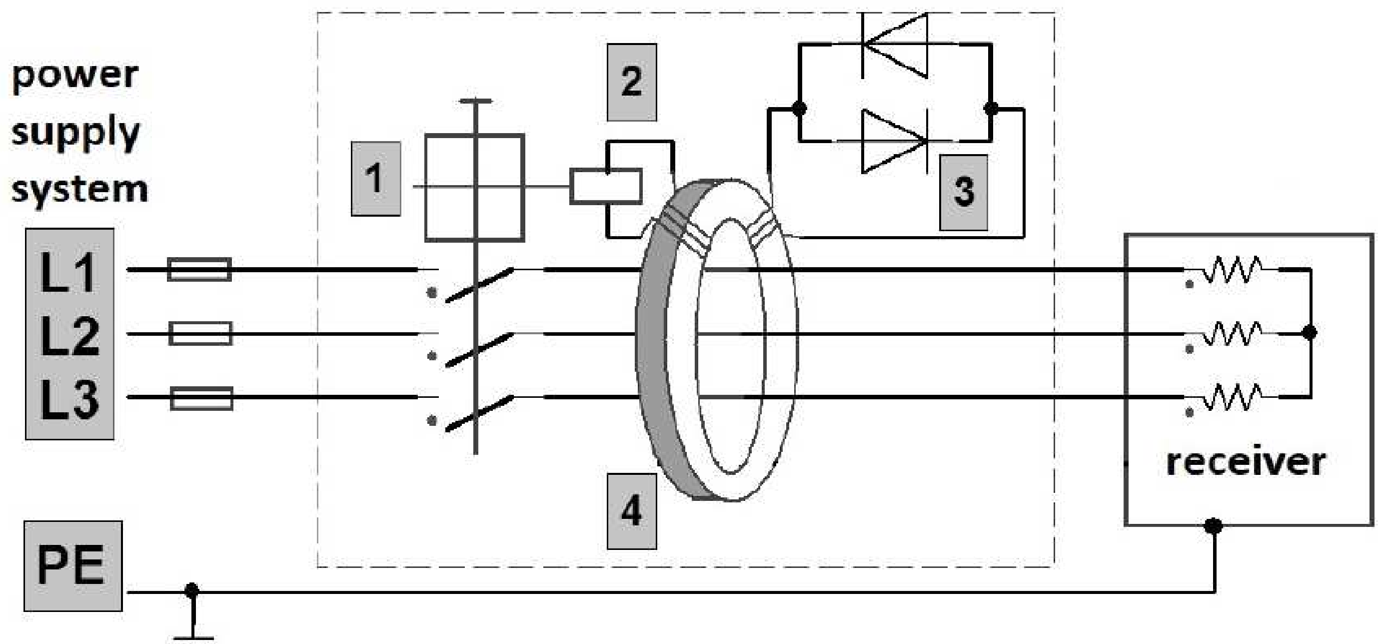

Figure 2

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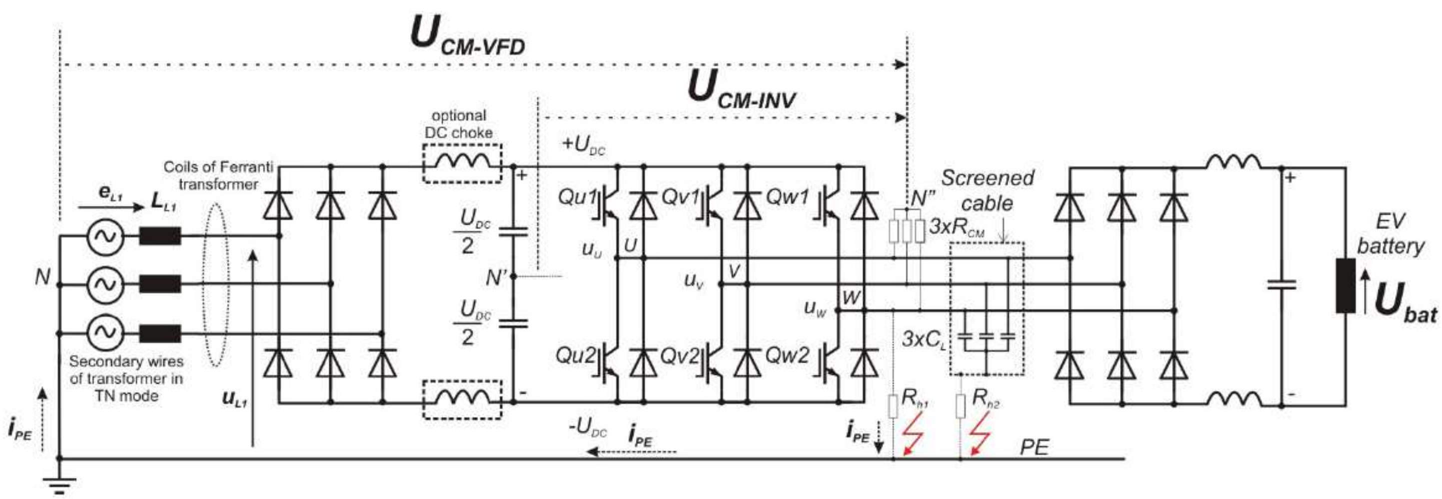

Figure 3

The model of the EV charging system with the frequency converter and the residual current device for protection against earth fault.

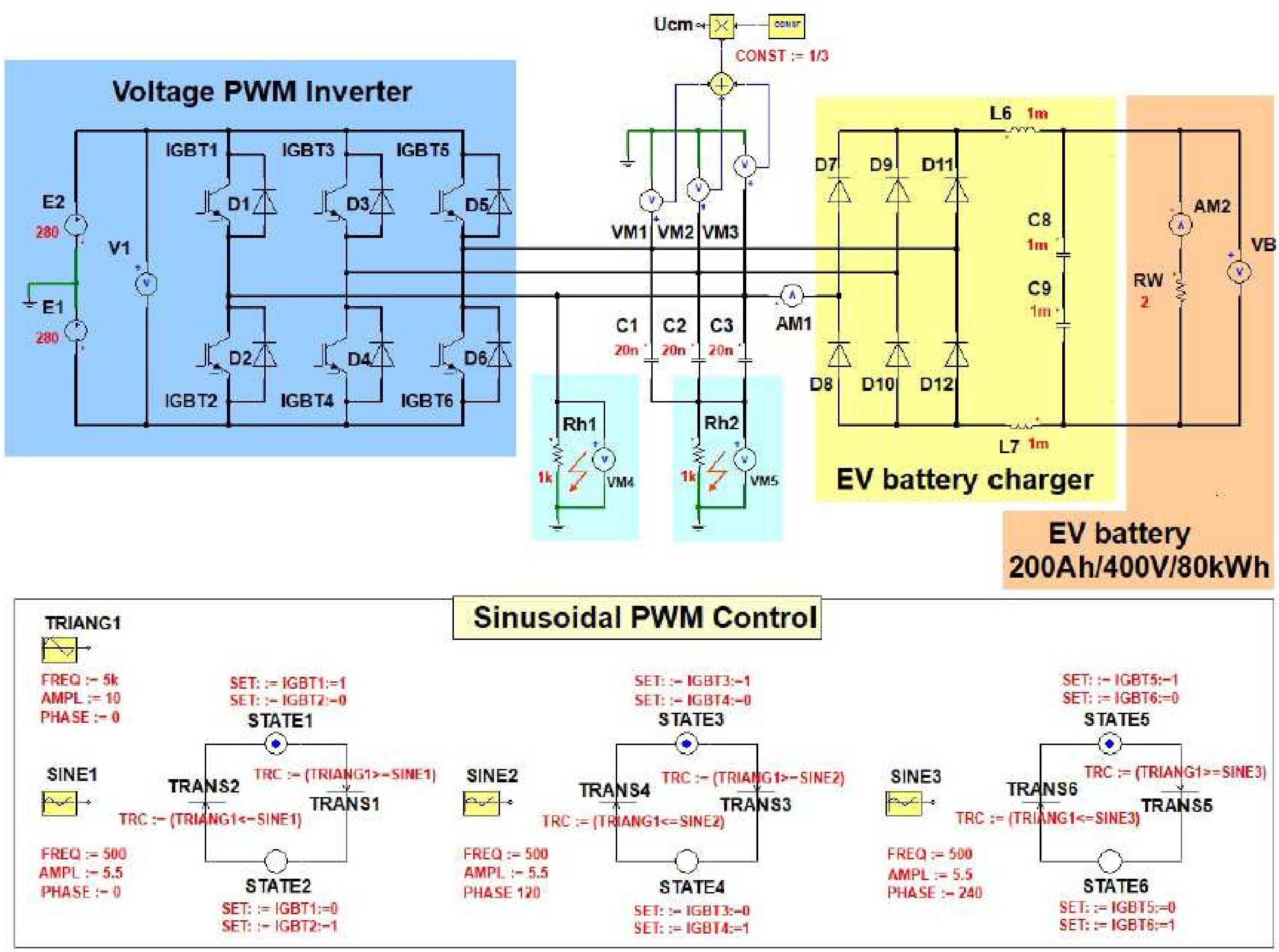

Figure 4

The model of the EV battery charging system with a voltage inverter.

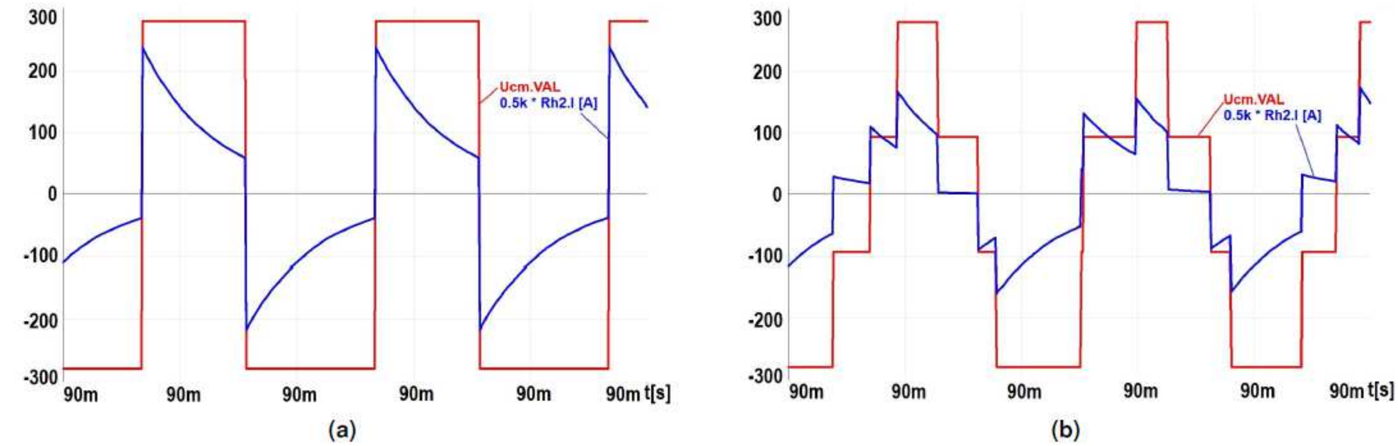

Figure 5

Waveforms of CM voltage and ground current with 1kW resistance for modulation factor: a) M=0, b) M=0.55.

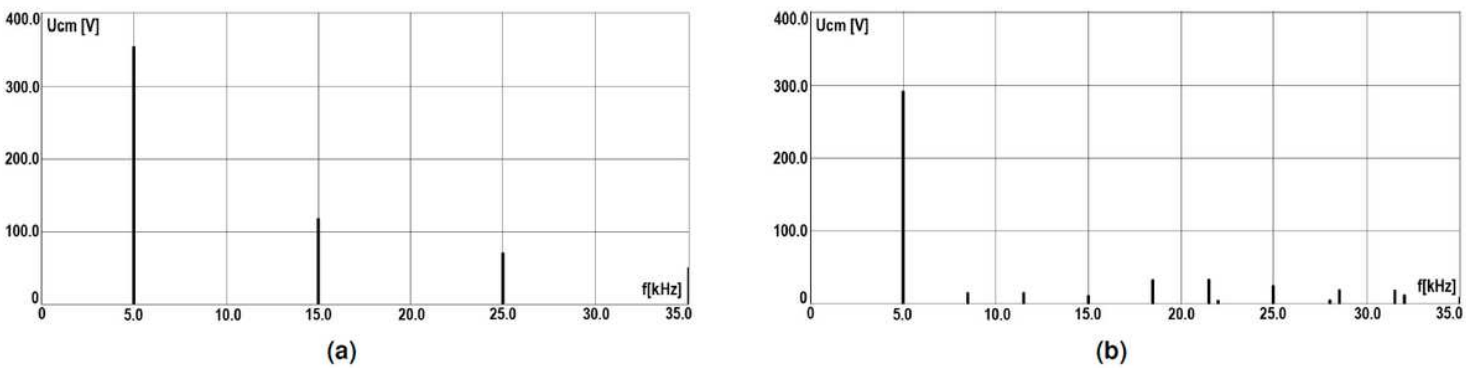

Figure 6

Amplitude spectrum of common-mode voltage for modulation factor: a) M=0, b) M=0.55.

(a) (b)

Figure 7

Laboratory stand for short ground current flowing via the human body caused by inverter phase voltage and common-mode voltage: a) current probe measure of leakage current in PE wire in RCD protection of drive VFC’s power system, b) measuring of leakage current on an equivalent resistance of the human body 1kΩ.

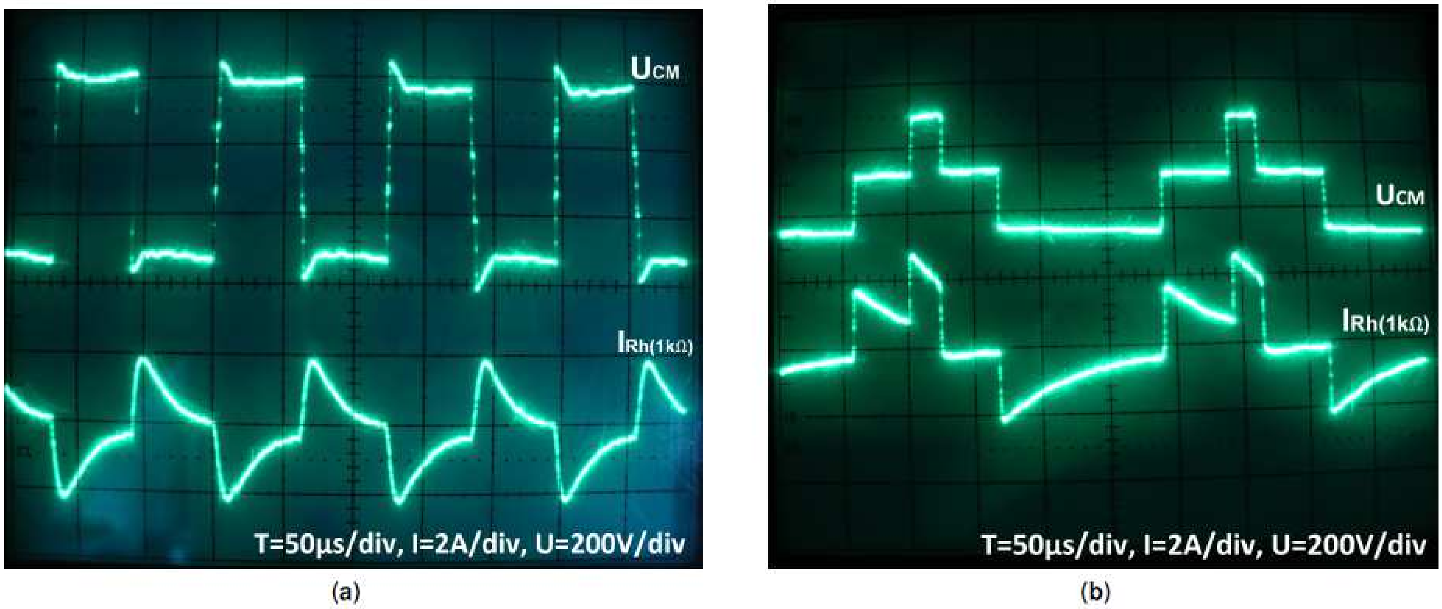

Figure 8

Waveforms of earth fault currents at ground resistance 1kΩ while: a) common-mode voltage UCM is for M≈0, b) UCM is for M=0.55 (inverter output basic harmonic frequency is 35Hz)

Figure 9

Scheme of special nanocrystalline magnetic cores as a common-mode filter.

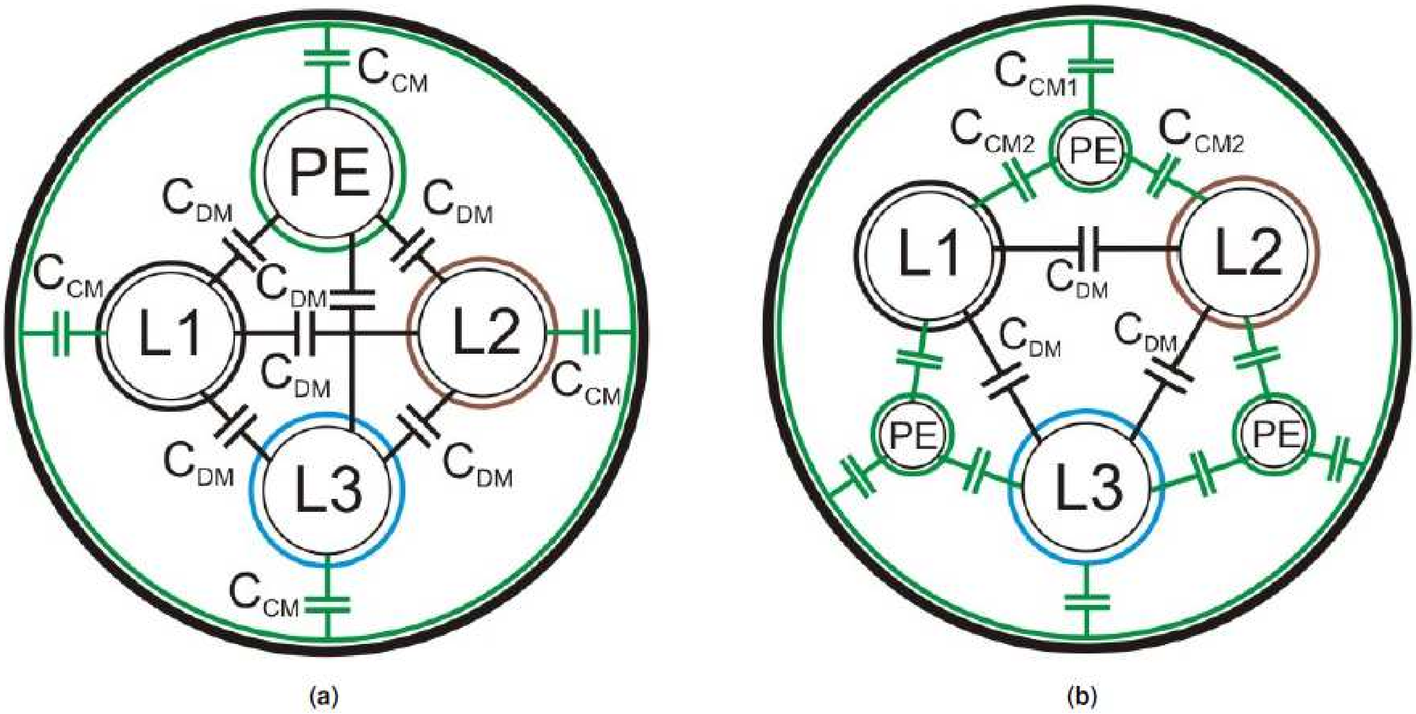

Figure 10

Cross-section of 3-phase screened cables with green marked parasitic line-to-line capacities CDM and parasitic ground leakage capacities CCM in: a) with 1 PE wire b) with 3 PE wires.