

# The effect of the motor filters on earth fault current waveform in circuits with variable speed drives

**Abstract.** In circuits with variable speed drives distorted earth fault current flows. Earth fault current distortion influences the threshold of ventricular fibrillation. This paper presents earth fault current distortion in circuits with variable speed drives when motor filter is used. Two types of motor filter are analyzed. For every type of filter the effect of earth fault current distortion on ventricular fibrillation is evaluated.

**Streszczenie.** W układach napędowych z przemiennikami częstotliwości płynie odkształcony prąd ziemnozwarciowy. Odkształcenie tego prądu wpływa na próg fibrylacji. W artykule analizowano prądy ziemnozwarciowe w układach z filtrami silnikowymi. Rozpatrywano dwa typy filtrów silnikowych. Dla każdego przypadku przeprowadzono analizę prądu odkształconego i określono jego wpływ na próg fibrylacji. (Wpływ filtrów silnikowych na kształt przebiegu prądu ziemnozwarciowego w obwodach z napędami o regulowanej prędkości obrotowej).

**Keywords:** variable speed drives, earth fault currents, protection against electric shock.

**Słowa kluczowe:** napędy o regulowanej prędkości obrotowej, prądy ziemnozwarciowe, ochrona przeciwporażeniowa.

## Introduction

Variable speed drives are commonly used in low voltage systems. In such motor circuits automatic disconnection of supply – as means of protection against electric shock [1] – is used. However, these types of circuits are very difficult for evaluation the effectiveness of protection against electric shock [2 - 4]. The earth fault current is distorted and waveform shape of this current depends on the point of fault, actual motor speed and PWM frequency. Additionally, input and/or output (motor) filters can be applied. Motor filters modify the waveform shape of earth fault current. It is necessary to recognize the effect of motor filters on earth fault current waveform for wide range of motor speed. Such recognition can show the threshold of ventricular fibrillation in relationship to the arrangement of the variable speed drive circuit (no filter, type of motor filter). It is important for proper selection of protective devices and evaluation of persons safety in circuits with variable speed drives.

## Analyzed Variable Speed Drive Circuit

The nowadays converters are built with the use of insulated gate bipolar transistors IGBT, whose dynamic parameters are very high, i.e. the on- and off-switch times are extremely short. Fast switching of power devices causes high  $dv/dt$  at the rising and falling edges of the inverter output waveform. High  $dv/dt$  in modern inverters is the source of numerous disadvantageous effects in the electric drives [5-7]. The main negative effects are faster motor bearings degradation, overvoltages on motor terminals, failure or degradation of the motor winding insulation due to partial discharges, increase of motor losses, and a higher electromagnetic interference level. Some listed negative effects are emphasized in the case of long cables used to connect the inverter and the motor.

The use of inverter output filters is common in modern electric drives to improve the electromagnetic compatibility and motor supply condition. With the filter the motor is protected against bearing and insulation degradation, the motor efficiency is increased and the motor noise is decreased. Passive filters used in induction motor driver are called inverter output filters or motor filters. Depending on filter structures and their parameters, the following filters are specified [8-10]:

- differential mode filters (LC filters, sine-wave filters),
- common mode filters, and
- $dv/dt$  filters.

With differential mode filters, the motor supply voltage is smoothed to almost a sinusoidal shape in contrary to the

inverter output voltage, which is composed of series of short rectangular pulses. The common mode filters are used mainly to limit the motor leakage current which flows through motor parasitic capacitances. The major part of that current flows through the motor bearing to the motor case and to the ground. The role of  $dv/dt$  filters is to eliminate the wave reflection effect in long cables to avoid overvoltages on the motor terminal as well as to secure the motor windings insulation from failure. The wave reflects are produced because of incompatibility of the cable and motor wave impedances. In extreme conditions, the peak of the motor terminal overvoltages can reach twice the value of the inverter supply voltage. The structure of  $dv/dt$  filter is similar as differential mode filter, the difference is in smaller values of the  $L$  and  $C$  elements.

The structures of the filters used in the investigations are presented in Fig. 1.

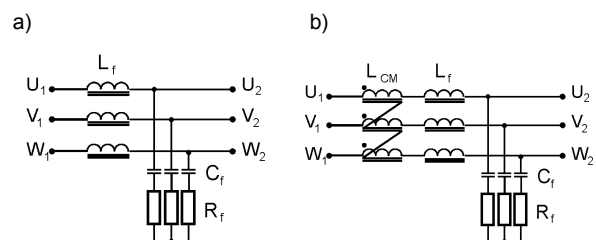


Fig.1. The structures of the filters used in the investigations: a) type 1 (FT-1) differential mode ( $L_f = 9$  mH,  $C_f = 8$   $\mu$ F,  $R_f = 2,2$   $\Omega$ ) b) type 2 (FT-2) common mode and differential mode ( $L_{CM} = 14$  mH,  $L_f = 5,6$  mH,  $C_f = 10$   $\mu$ F,  $R_f = 1$   $\Omega$ )

In Fig. 1 filter structures the parameters  $L_f$ ,  $C_f$  and  $R_f$  are for differential mode operation. Inductors and capacitors create low pass filter with cut-off frequency below the inverter switching frequency. The resistor is for damping the resonance oscillation. The inductor  $L_{CM}$  is for common mode operation. It is constructed with three symmetrical coils wound on a toroidal core. The mutual inductance between the coils is identical. The  $L_{CM}$  inductor is negligible for differential mode current because the total flux in the core is zero for three-phase symmetrical currents. However, the inductance  $L_{CM}$  is significant for the common mode circuit.

The circuit of the analyzed variable speed drive is presented in Fig. 2. A converter is a type widely used in the industry. It has input rectifier, dc link and voltage inverter. PWM frequency is equal to 3,3 kHz. On the inverter output a filter is installed and induction motor is supplied with

variable voltage and frequency. One of the motor supply wire could be line-to-earth short-circuited by low inductance resistor  $1\text{ k}\Omega$ .

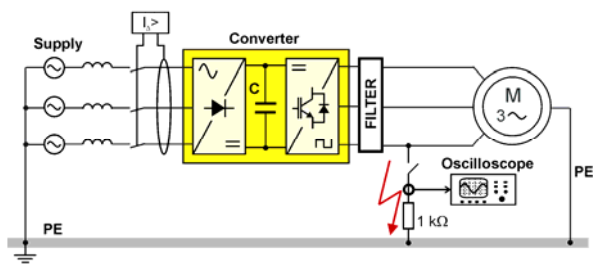


Fig.2. The structure of the analyzed variable speed drive circuit

The resistor  $1\text{ k}\Omega$  emulates the human body resistance. When short-circuited the earth fault current was measured by wideband current probe TCP0030 and digital oscilloscope DPO4034. The same equipment was used to observe motor leakage current, and differential probe P5205 for line-to-line voltage observation.

The waveforms showing the differential mode filters operations without short-circuiting are presented in Fig. 3 – 4.

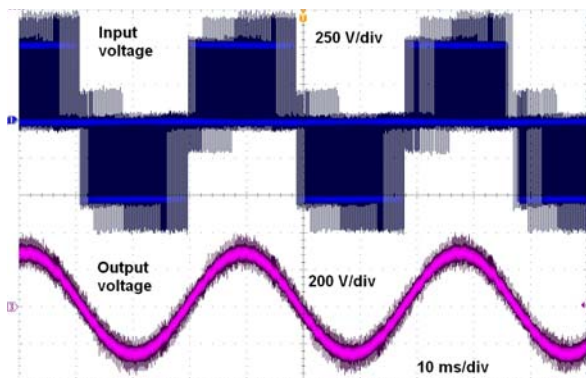


Fig.3. The waveforms for FT-1 filter: line-to-line input and output voltage under normal operation – no earth fault,  $f_{\text{thar}} = 25\text{ Hz}$

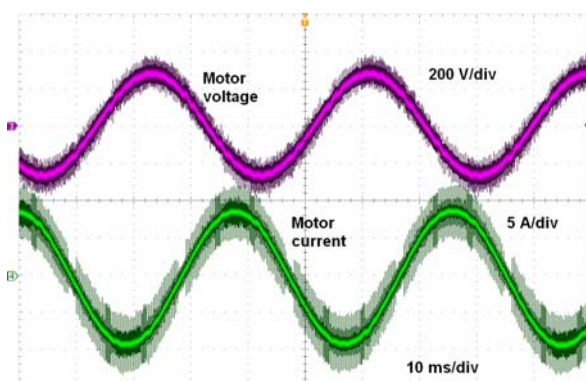


Fig.4. The waveforms for FT-1 filter: motor current and voltage under normal operation – no earth fault,  $f_{\text{thar}} = 25\text{ Hz}$

Figure 5 is showing an influence of the filter on motor leakage current under normal operation. Very high value of leakage current (measured in PE conductor) occurs in the arrangement without motor filter (Fig. 5a). Peak value of this current exceeds  $1\text{ A}$ . Such value may cause nuisance tripping of residual current protective devices. Significant

reducing of leakage current is observed in the arrangement with FT-2 filter (differential & common mode filter).

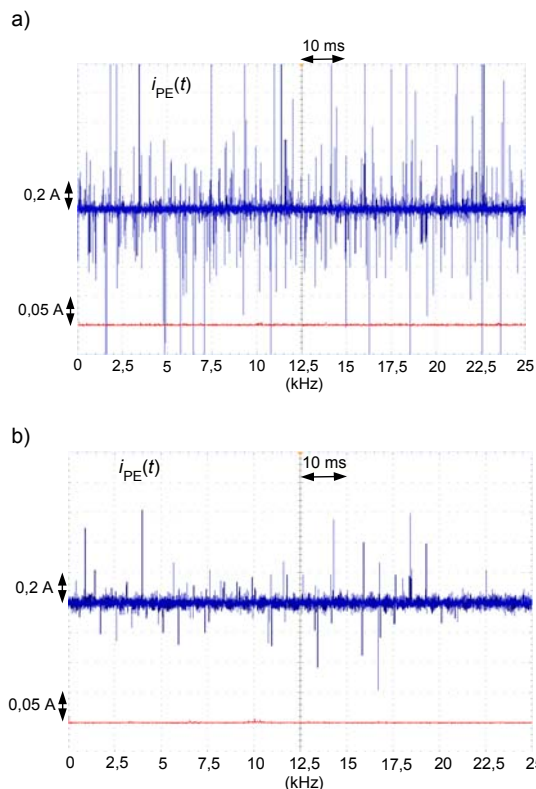


Fig.5. Leakage current waveform  $i_{PE}(t)$  (no earth fault) and its spectrum in circuit with variable speed drive; motor frequency  $50\text{ Hz}$ ; a) without motor filter, b) with FT-2 filter

### Earth Fault Current – Laboratory Test

In order to evaluate shock hazard in motor circuit spectral analysis of the earth fault current should be performed. The analysis was performed for the following variations of the circuit:

- without motor filter,
- FT-1 motor filter is applied (differential mode),
- FT-2 motor filter is applied (differential & common mode).

Earth fault current was measured in the structure presented in Fig. 2. The example results of the measurement are presented in Fig. 6 and Fig. 7. The earth fault current comprises a low frequency component which depends on the desired motor speed, a constant  $150\text{ Hz}$  component as well as a component at the PWM frequency and its multiple and also its interharmonics. The amplitude of the low frequency component and the PWM component changes as a function of the motor speed and reference frequency.

For the  $50\text{ Hz}$  operating frequency the amplitude of  $50\text{ Hz}$  component exceeds the amplitude of PWM component (Fig. 6). For very low motor frequency ( $1\text{ Hz}$ ) the amplitude of PWM component significantly exceeds the amplitude of current of motor frequency and the  $150\text{ Hz}$  component (Fig. 7). However, comparing Fig. 7b to Fig. 7a one can see that for FT-2 filter the PWM component is significantly lower than for the arrangements without filter.

Figure 8 presents variation of the earth fault current main components ( $50\text{ Hz}$  component,  $150\text{ Hz}$  component and PWM component) and total r.m.s. value as a function of motor frequency. For  $50\text{ Hz}$  component (Fig. 8a) the all traces have similar characteristics. The same conclusion flows from the Fig. 8b – value of  $150\text{ Hz}$  component.

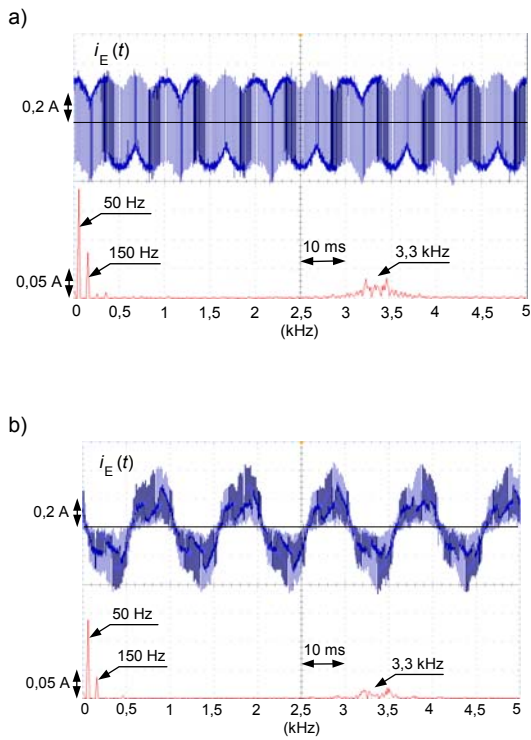


Fig.6. Earth fault current waveform  $i_E(t)$  and its spectrum in circuit with variable speed drive; motor frequency 50 Hz; a) without motor filter, b) with FT-2 filter

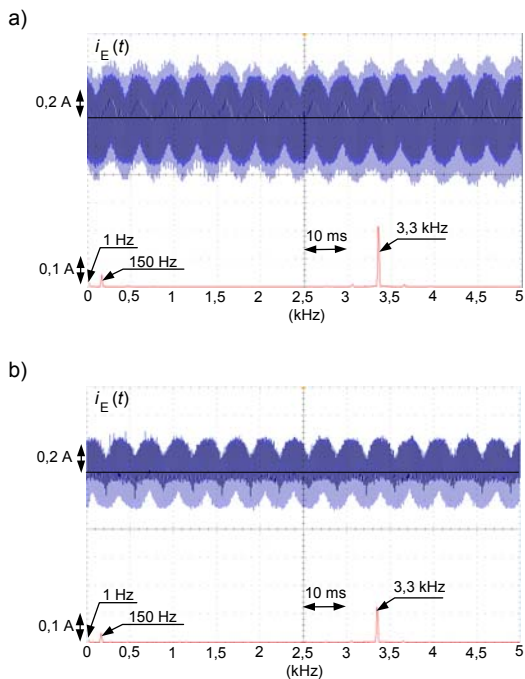


Fig.7. Earth fault current waveform  $i_E(t)$  and its spectrum in circuit with variable speed drive; motor frequency 1 Hz; a) without motor filter, b) with FT-2 filter

Motor filter (both FT-1 and FT-2) has slight impact on 50 Hz and 150 Hz components in the earth fault currents. The effect of the motor filter on reducing of the earth fault current component is noticeable with reference to PWM component – especially when FT-2 filter (differential &

common mode filter) is used (Fig. 8c). When this filter is used, for the whole range of motor frequency (1÷50 Hz) PWM component is reduced to about 50% value of the arrangement without filter. Such reducing of PWM component has impact on total r.m.s. value of the earth fault current. The lowest value of the total earth fault current is for the arrangement with FT-2 filter (Fig. 8d).

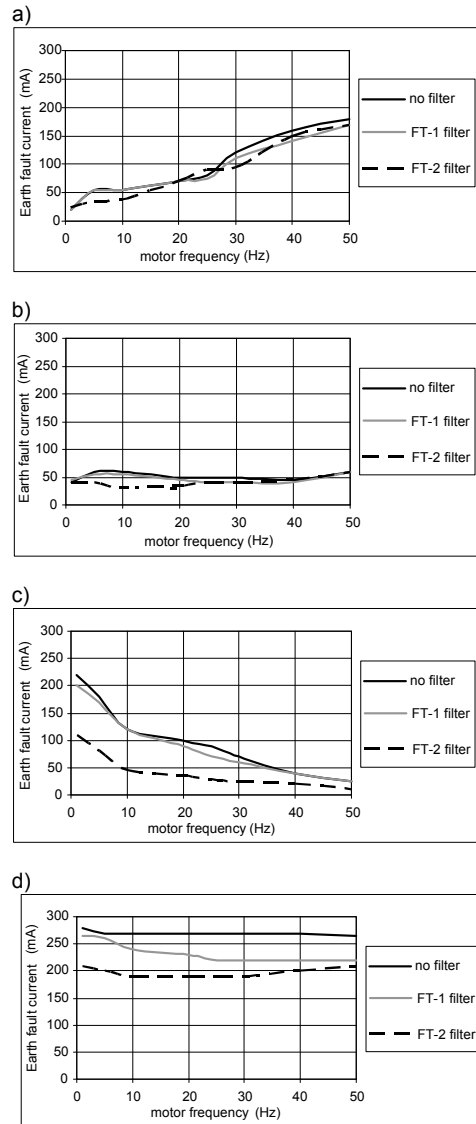


Fig.8. Earth fault current components: 50 Hz (a), 150 Hz (b), PWM (c) and total r.m.s. value (d) as a function of motor frequency

### Shock Hazard For Distorted Current

Technical specification [11] determines basic guidance of the effects of touch current on the human beings and livestock. Figure 9 presents conventional time-current zones of effect of a.c. current on person according to this technical specification. The most important is the threshold of ventricular fibrillation. For the current frequency 15÷100 Hz dangerous is touch current higher than 30÷40 mA.

For the touch current of higher frequency, the threshold of perception, threshold of let-go and threshold of ventricular fibrillation move to a higher value. For frequency equal to 1000 Hz the threshold of ventricular fibrillation is 14 times higher than for frequency equal to 50 Hz (420 mA instead of 30 mA) – Fig. 10.

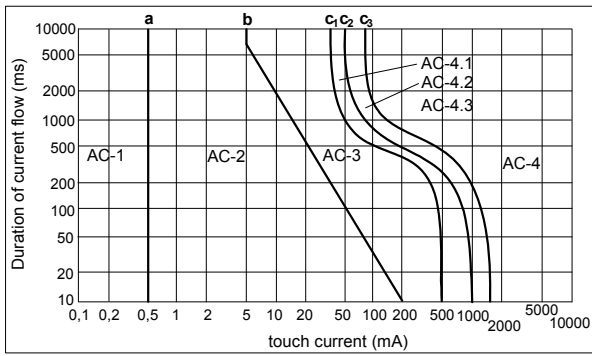


Fig.9. Conventional time-current zones of effect of a.c. current (15-100 Hz) on person [11]; Probability of ventricular fibrillation: increasing up to about 5%  $\Rightarrow$  area  $c_1 - c_2$ , increasing up to about 50%  $\Rightarrow$  area  $c_2 - c_3$ , higher than 50%  $\Rightarrow$  beyond curve  $c_3$

The ventricular fibrillation hazard caused by a current with harmonics may only be estimated (rough approximation) as equivalent to the hazard caused by a pure sinusoidal current having the following characteristics [12] – the fundamental frequency with an amplitude  $I_{ev}$  equivalent to the quadratic summation of all component amplitudes  $I_h$  individually affected by the appropriate frequency factor  $F_f$  as shown in Fig. 10.

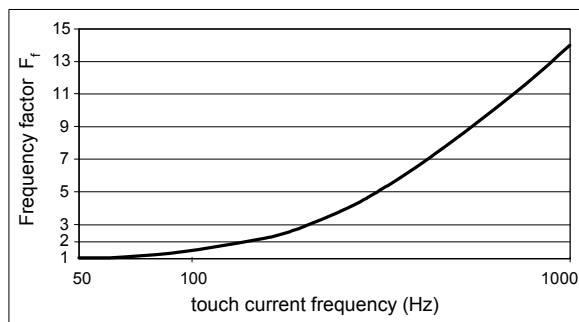


Fig.10. Variation of the threshold of ventricular fibrillation within the 50 Hz to 1000 Hz frequency range

Results of calculation of the equivalent current  $I_{ev}$  are presented in Fig. 11. Equivalent earth current was estimated for every analyzed motor frequency (1, 5, 10, 20, 25, 30, 40, 50 Hz) and three motor filter arrangements (without filter, FT-1 filter, FT-2 filter). Results of calculation are compared with three horizontal traces ( $c_1$ ,  $c_2$ ,  $c_3$ ) indicating various probability of ventricular fibrillation. In low voltage system traces  $c_1$  should not be exceeded.

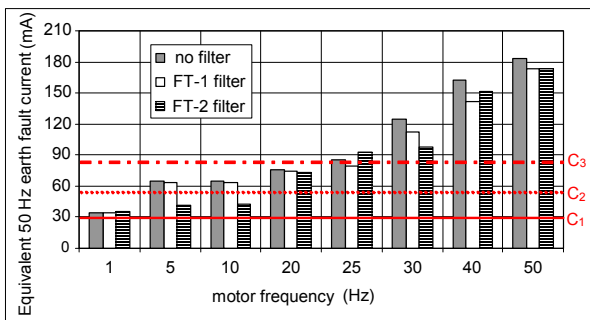


Fig.11. Equivalent 50 Hz earth fault current in terms of ventricular fibrillation effect;  $c_1$ ,  $c_2$ ,  $c_3$  – probability of ventricular fibrillation (see Fig.9)

The lower is motor frequency (in consequence motor speed) the lower is shock hazard. This is the effect of high frequency components. High frequency current is less dangerous than current of fundamental frequency. For majority of the motor frequencies, motor filters – especially FT-2 filter – give positive effect. Equivalent earth fault current is then relatively low and probability of ventricular fibrillation can be decreased.

Unfortunately, in all cases, the value of equivalent earth fault current is higher than value represented by trace  $c_1$ . This is because of that the motor filter reduces high frequency current components which are less dangerous for human than other current components.

## Conclusions

In variable speed drives with output filter, motor is protected against bearing and insulation degradation, the motor efficiency is increased and the motor noise is decreased. Common mode filters influences the reducing high frequency components in leakage current. It enables to install high sensitivity residual current devices. This type of filter also reduces high frequency components in earth fault current. For the arrangement with such type of filter, in case of direct contact or in case of fault, probability of ventricular fibrillation can be decreased.

## REFERENCES

- [1] HD 60364-4-41:2007 Low-voltage electrical installations – Part 4-41: Protection for safety – Protection against electric shock
- [2] Czapp S., Włas M., Działanie wyłączników różnicowoprądowych przy doziemieniu silnika zasilanego z przemiennika częstotliwości, *Przegląd Elektrotechniczny*, 86 (2010), nr4, 296-301
- [3] Czapp S., The impact of higher-order harmonics on tripping of residual current devices, *Proc. of the 13<sup>th</sup> Int. Power Electronics and Motion Control Conf. EPE-PEMC 2008*, Poznań, Poland, 1-3 September (2008), 2082-2088
- [4] Czapp S., Guzinski J., The effect of the motor filters on earth fault current waveform in circuits with variable speed drives, *Proc. of the 11<sup>th</sup> Conf.-Seminar Int. School on Nonsinusoidal Currents and Compensation ISNCC 2013*, Zielona Góra, Poland, 20-21 June (2013)
- [5] Erdman J., Kerkman R., Schlegel D., Skibinski G., Effect of PWM Inverters on AC Motor Bearing Currents and Shaft Voltages, *IEEE APEC Conference*, Dallas, USA, (1995)
- [6] Muetze A., Binder A., High frequency stator ground currents of inverter-fed squirrel-cage induction motors up to 500 kW, *EPE Conference*, Toulouse, France, (2003)
- [7] Abu-Rub H., Iqbal A., Guzinski J., *High Performance Control of AC Drives with Matlab/Simulink Models*, A John Wiley & Sons, (2012)
- [8] Akagi H., Prospects and Expectations of Power Electronics in The 21st Century. *Power Conversion Conference, PCC'2002*, Osaka, Japan (2002)
- [9] Akagi H., Hasegawa H., Doumoto T., Design and Performance of a Passive EMI Filter for Use With a Voltage-Source PWM Inverter Having Sinusoidal Output Voltage and Zero Common-Mode Voltage, *IEEE Trans. on Power Electronics*, vol. 19 July (2004), n.4
- [10] Bose B.K., Power electronics and motor drives recent progress and perspective, *IEEE Trans. on Industrial Electronics*, vol. 56 February (2009), n.2
- [11] IEC/TS 60479-1:2005 Effects of current on human beings and livestock. Part 1: General aspects
- [12] IEC/TS 60479-2:2007 Effects of current on human beings and livestock. Part 2: Special aspects

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