Losses in Sinusoidal Filter for Pulse Controlled Converters

Jaroslav Novák [1)], Jan Chyský [2)] and Petr Kořínek [3)]
[1)] Department of Instrumentation and Control Engineering, Faculty of Mechanical Engineering, CTU in Prague, Prague, Czech Republic, e-mail: *Jaroslav.Novak@fs.cvut.cz*
[2)] Department of Instrumentation and Control Engineering, Faculty of Mechanical Engineering, CTU in Prague, Prague, Czech Republic, e-mail: *Jan.Chysky@fs.cvut.cz*
[3)] Skybergtech s.r.o., Tehovec, Czech Republic, e-mail: *technology@skybergtech.com*

Abstract — **This paper presents three methods losses evaluation in magnetic circuits of sinusoidal filter chokes and their experimental verification. The attention is focused on losses caused by higher harmonics in context of frequency pulse width modulation. Methods based on the calculation of the reference loss method are described, they are based on direct measurement using an integral of instantaneous power losses and determining of them from temperature rise characteristic.**

Keywords — sinusoidal filter, dissipation losses, choke, higher harmonic components

I. INTRODUCTION

The development of power semiconductor inverters technology in electrical systems involves an increasing number of devices that operate with switching transistors and the pulse width modulation (PWM) [1] and [2]. Although the pulse width modulation is based on its principle limits of the current and voltage harmonic spectrum, it is still valid that the waveform consists of a sequence of rectangular pulses with very steep edges - to 5000 V/μs. Sinusoidal filters contribute to a positive, sometimes almost sine shape of current and voltage. Sinusoidal filters are about to become the hot topic of industrial applications. The requirements for compatibility with a large number of devices with switching transistors force the usage of sinusoidal filtering in an increasing number of cases. Sinusoidal filters are used in conjunction with electric regenerative drives, which are equipped with an input pulse rectifier, or in conjunction with network photovoltaic inverters. An example of sinusoidal filter use at the output of an inverter are electric variable speed drives where the filter is connected to the inverter output when using motor long cable.

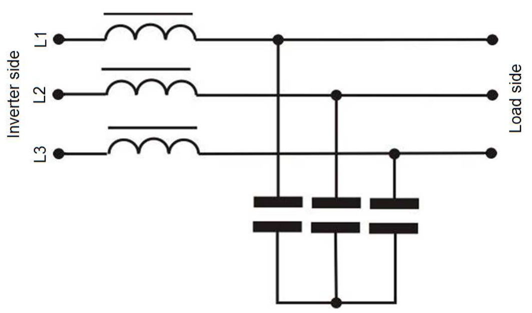

Fig. 1: Three-phases sinusoidal filter.

Sine-wave filters are often used as LC L-cells in three phase involving capacitors in star or delta. Example of an three phase sinusoidal filter is in Fig. 1.

The choke side of the sinusoidal filter is connected to a device with switching transistors. For basic harmonics the capacitors have high impedance; in a case of many times higher harmonic frequency these capacitors create in effect a short circuit. Out of necessity to increase impedance for current higher harmonics the chokes have an iron core.

The suppression effect of the sinusoidal filters is very high. The voltage formed by the PWM modulation is effectively changed to pure sinusoidal waveform. The sinusoidal filters are produced for a high current range from amperes to kiloamperes.

When the sinusoidal filters are applied some negative facts occur:

- non-neglected dimensions
- non-neglected weight
- voltage drop on the filter to 10 %
- price
- power dissipation losses

Dissipation power losses are caused first of all by losses in the choke iron magnetic circuit . Most of this power loss is caused by frequencies derived from the pulse width modulation. Power losses in filters for current of hundreds amperes are in the order of hundreds watts. These dissipation losses affect overall efficiency and simultaneously have to be included in total heat balance.

II. FINDING OF CHOKE LOSSES BY CALCULATION

A simple, partially empiric method for losses calculation in the choke iron core is below. According to [3] the losses can be expressed as

$$P_M \approx (k_H \cdot f \ + k_V \cdot f^2) \cdot B^2 \tag{1}$$

Both constants depend on geometric dimensions, weight, and ferromagnetic material properties, sometimes simplified in so called Steinmetz formula:

$$P_M \approx k \cdot B^2 \cdot f^{1,5 to 2} \tag{2}$$

Constant k depends on geometric dimensions, weight, and ferromagnetic material properties as above. As a result of (1) and (2) the losses depend on the magnetic flux density, frequency and material constant i.e. on specific losses. But these losses depend on frequency and exponent of the frequency in formulae (1) and (2) which is not constant and must be found for each relevant frequency separately. Dependence of losses in ferromagnetic material is quadratic and the density of magnetic flux in non-saturated region depends on a filter choke current. For this reason the specific losses are measured for particular frequencies of a given current. Then these losses are recalculated according to the real magnitude of relevant harmonic frequency of current and square of this current. Sum of losses of all harmonic frequencies and its multiplication by number of filter phases gives the total losses value.

First task is to find meaningful particular frequencies of the losses dominant part . The frequencies in current spectrum can be divided into frequencies derived from this base frequency and frequencies derivated from frequency of the pulse width modulation. In usual applications the basic frequency is about tens Hertz, modulation frequency for usual IGBT transistors ranges from kilohertz to tens of kilohertz. Due to the exponent of frequency in formulas (1) and/or (2) and high order modulation frequency, the basic frequency and its harmonics can be neglected, or calculated by routine methods.

It can be shown that in the filtered current spectrum multiples of PWM frequency and sums and differences with frequency of basic harmonic are present. Frequency of current components can be expressed as:

$$f_i = k \cdot f_{PWM} \pm 2 \cdot l \cdot f_1 \quad (3)$$

For the PWM odd multiples frequency f_{PWM} are (k=1, 3, 5, …), (l=1, 2, 3, 4, …). For even multiples f_{PWM} (m=2, 4, 6, …) higher harmonics components have values:

$$f_i = m \cdot f_{PWM} \pm (2 \cdot n + 1) \cdot f_1 \quad (4)$$

In formula (4) there is n=0, 1, 2, 3, …,.

E.g. for f_1 = 50Hz and f_{PWM} = 6kHz current with higher harmonic components derived from PWM frequency will have these values: 6kHz ± 100Hz, 6kHz ± 200Hz, 6kHz ± 300Hz….., 12kHz ± 50Hz, 12kHz ± 150Hz, 12kHz ± 250Hz…, 18kHz ± 100Hz, 8kHz±200Hz, 18kHz±300Hz…

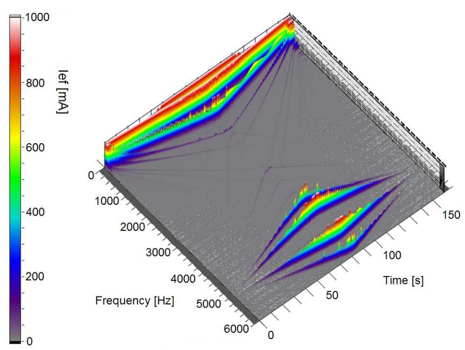

Fig.2: Current spectral map for frequency-controlled drive during run-up

With an increased multiple of frequency f_{PWM} the magnitude of the harmonic current components rapidly decreases, also the magnitude of the harmonic components with growing multiple of the basic harmonic decreases. For the practical calculation of the high frequency losses it is sufficient to limit frequencies to $f_{PW}M \pm 2f_1$ and $f_{PWM} \pm 4f_1$.

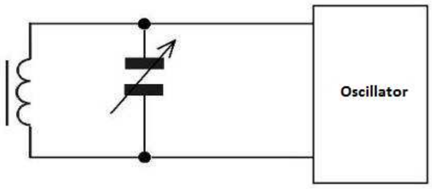

Fig.3: Ferromagnetic core specific losses measurement

TABLE I.
TECHNICAL DATA OF THE USED FILTER

Type	SKY3FSM130-400
Manufacturer	Skybergtech s.r.o. Czech Republic
Number of phases	3
Connection	L – network (see Fig. 1)
Core	Composed C - shape
Nominal phase current	130A
Nominal voltage	3x400V
Minimal PWM frequency	4kHz
One-phase inductance	0,47mH
One-phase resistance	0,93mΩ
Condenser capacity	65µF
Mass	53kg

Features of the harmonic spectrum of the output current are illustrated in Fig. 2 [4]. The basic frequency was 238 Hz and modulation frequency 5 kHz. In the figure there are visible side bands of frequency 5 kHz given with sum and difference of this frequency and multiple of 1st harmonic. Additional information dealing with this problem can be found in [5] and [6].

Core of an appropriate magnetic material is inserted into the coil and the capacitor is tuned in resonace with the circuit relative to the demand frequency. Due to this the current in the coil it is sufficient and the oscillator covers only losses in the ferromagnetic material. Joule losses in coil wires were neglected.

As next step the current magnitude for selected spectrum components must be calculated. For this we shall use simplified formula:

$$I_i = \frac{U - \Delta u_L}{i \cdot 2 \cdot PI \cdot f_1 \cdot L \cdot 4} \quad (5)$$

The dissipation power P_{Mi} of ith current harmonic component should be calculated by formula:

$$P_{Mi} = p_{Mi} \cdot \frac{I_i^{\,2}}{I_{mi}^{\,2}} \quad (6)$$

If the resonance measurement is provided at the filter choke, there is no need to do further recalculation, if not, the calculated losses must be recalculated on the choke real mass .

Total value of the power dissipation P_M of all calculated harmonic components equals:

$$P_M = j \cdot \sum P_{Mi} \quad (7)$$

As above described the losses calculation is simplified because it is usually limited to a few current components of frequencies $f_{PWM} \pm 2f_1$ and $f_{PWM} \pm 4f_1$.

Additionally, there is a neglected result of skin effect. The losses caused by skin effect grow with the square of frequency. In spite of these simplifications the method gives good results as will be introduced further.

III. REAL SINUSOIDAL FILTER MEASUREMENT

Verification of the introduced method of the HF losses calculation in sinusoidal filter chokes was carried out as a set of measurements. The dissipation losses were measured for all filter phases as an integral of instantaneous power calculated as a product of the capacitor current and choke voltage.

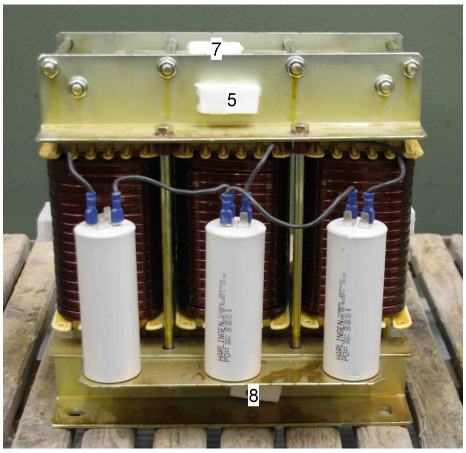

Fig. 4: Filter SKY3FSM130-400

Filter (Fig. 4) was powered by the frequency inverter Sinamics and loaded by a three-phase induction motor of 5 kW. The motor was no-loaded at the frequency 50 Hz and current of 5 A. For such low current, the losses in choke core and Joule losses in choke windings were neglected, but they can be simply evaluated.

$$P = \frac{1}{n} \sum_{1}^{n} v_i \cdot i_i \quad (8)$$

The power dissipation was measured for PWM frequencies 6, 8, 10 and 12 kHz, partially for frequency 4 kHz, which is the filter low limit .

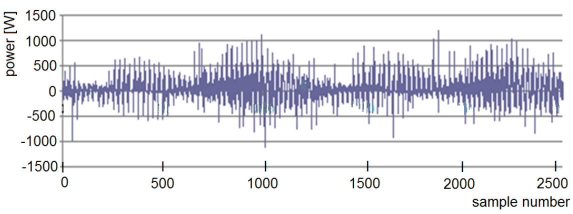

Fig. 5: Instantaneous power during two periods

In Fig. 5 there is the shape of the instantaneous power during two periods. The power dissipation is calculated from this according to formula (8).

IV. MEASURED DISSIPATION LOSSES

The power losses were measured according to the method described in chapter IV and compared with calculated losses described in chapter II. Total value of the power dissipation was the sum of losses in all three phases. The losses of phase winding on the middle leg were 10 % lower than on the two outer. It corresponds to the fact that the choke inductance on middle leg is higher than the inductances of the outer chokes and that it causes lower currents in these chokes.

Measured and calculated values are in the following table:

TABLE II.
COMPARISON OF MEASURED AND CALCULATED DATA

F_M = 6kHz		
Calculated	Measured I.	Measured II.
154 W	157 W	N/A
Max difference -1,9%		
f_m = 8kHz		
Calculated	Measured I.	Measured II.
127 W	131 W	136 W
Max difference -7,1%		
f_m = 10kHz		
Calculated	Measured I.	Measured II.
121 W	114 W	N/A
Max difference 5,9%		
f_m = 12kHz		
Calculated	Measured I.	Measured II.
112 W	100 W	108 W
Max difference -12%		

All measurements were carried out with three-phase induction motor in idle, with the 1st voltage harmonic of 50 Hz and current consumption of 5 A.

V. MEASURED DISSIPATION LOSSES USING TEMPERATURE RISE CHARACTERISTICS

The losses in the choke core are possible to find using simple method from the temperature rise characteristic. Again, the NI PXI system with special thermocouple inputs was used for the measurement. During the experiment 9 temperatures were measured at various filter locations – at the iron core, at the winding and at other parts of the construction. For the calculation it was finally used the temperature dependence of the iron core, example of the dependence is in Fig. 6.

Working parameters of the measured filter were equivalent to the measurement in chapter IV. According to Fig. 8 the temperature rise characteristic (violet curve) is equal to the first order system, the temperature rise characteristic of the winding equals to the 2nd order system. This corresponds to the fact that for the given conditions the dominant part of losses happens in the choke core and the winding is heated by heat convection from the core.

Heating process of the core is crucial for power dissipation. The temperature rise Δth is the difference between the final steady state temperature th_{max} and ambient temperature th_0 i.e. initial temperature:

$$\Delta th = th_{\max} - th_0 \quad (9)$$

In the simplest case the temperature rise characteristic, when the body is considered as homogenous with uniform heat sources distribution, can be written in the equation:

$$\Delta P \cdot dt = C_m \cdot d(\Delta th) + A \cdot \Delta th \cdot t \quad (10)$$

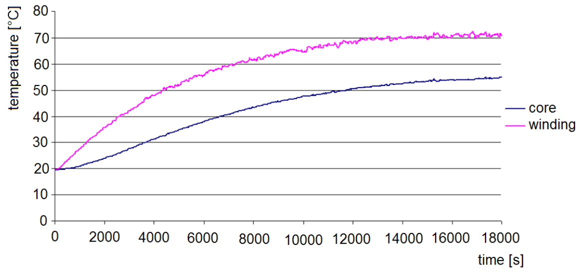

Fig. 6: Filter temperature rise characteristic

Equation (10) describes the situation, when part of the rising losses heat the filter and part passes to ambient. We shall define the temperature time constant T_{th} and final steady state temperature rise Δth_{max}:

$$T_{th} = \frac{C_m}{A} \quad (11)$$

$$\Delta th_{\max} = \frac{\Delta P}{A} \quad (12)$$

From (10), (11) and (12) we shall get:

$$T_{th} \cdot \frac{d(\Delta th)}{dt} + \Delta th = \Delta th_{\max} \quad (13)$$

This equation describes heating and its solution gives an analytic expression of - the temperature rise characteristic.

$$\Delta th = \Delta th_{\max} \cdot (1 - e^{-\frac{t}{T_{th}}}) + \Delta th_0 \cdot e^{-\frac{t}{T_{th}}} \quad (14)$$

Formula (14) is an analytic expression of an exponential function which corresponds to the measured dependence in Fig. 6. If the T_{th} and Δth_{max} are known from measurement, the dissipation power can be expressed:

$$\Delta P = \Delta th_{\max} \cdot \frac{C_m}{T_{th}} \quad (15)$$

E.g. for the measured filter (f_m = 4 kHz) the T_{th} = 5358s and Δth_{max} = 54 °C can be read in Fig. 6. According to the manufacturer's data the mass of the winding equals to 6.1 kg and the other iron parts of the filter weigh 46.9 kg. Average filter choke heat capacity is:

$$C_m = 450 \cdot 46{,}9 + 383 \cdot 6{,}1 = 23441{,}3 J / K \quad (16)$$

After substitution in (15) we shall get P_M=236 W. Results for other frequencies can be seen table II. These values suit the calculation in chapter II. With regard to the simplicity of these methods, uncertainty and simplifications very well correspond with the results for practical applications. Difference between outer limits is about 12 %. This result was also confirmed by other working parameters.

VI. Conclusions

The paper gave a summary of losses issue in ferromagnetic choke sinusoidal filters due to higher harmonics of current components. The new method using calculation was developed and it verified that the two other experimental different methods for determining the power loss provide comparable results. It can be stated that this method is possible to substitute expensive experimental tests.

An important fact which the article highlights is that the sinusoidal filters are not inconsiderable source of heat loss, especially in the case of circuits with currents of tens to hundreds of amperes.

The article maps the choke core power losses associated with the current harmonic components, which are derived from pulse width modulation inverters. In addition to determine the total power losses it is necessary to add the core choke losses induced by harmonic components of basic harmonic and losses in windings – Joule losses. The paper has not focused on these losses because for their determination standard simple formulae and catalogue choke core material data can be used.

As an example of the complexity, the total losses of a here mentioned reference filter working on the PWM modulation frequency 6 kHz are one and half times higher for the 12 kHz PWM modulation.

Acknowledgement

This research was supported by Czech ministry of education research grants No. 1M0568 and MSM6840770035.

References

[1] Chyský, J. - Novák, J. - Novák, M. - Novák, Z.: Determination of Losses in Ferromagnetic Circuit of a Sinusoidal Filter Powered with Frequency Inverter. In: Proceedings of 15th Mechatronics 2012. Praha: Czech Technical University in Prague, 2012, p. 251-256. ISBN 978-80-01-04985-3.

[2] Chapman, J.S.: Electric Machinery Fundamentals, Mc Graw Hill, 2005, ISBN 0-07-246523-9

[3] Novák, J. Doleček, R., Černý, O., Švanda, J.: Vyšetřování harmonických v trakci – 1. část, ELEKTRO 2010, roč. 20, č. 6, s. 6-8. ISSN 1210-0889

[4] Doleček, R. - Novák J. - Černý, O. - Němec, Z.: Research of Harmonic Spectrum of Currents in Traction Drive with PMSM, The 20st IEEE International Symposium on Industrial Electronics (ISIE´ 2011),pp. 710-715, Gdańsk, Poland, 37-30 June 2011, ISBN 978-1-4244-9311-1

[5] Boglietti, A.,Cavagnino, A.; Lazzari, M.; Pastorelli, M.: Predicting iron losses in soft magnetic materials with arbitrary voltage supply: an engineering approach, , IEEE Transactions on Magnetics, Vol. 39, No. 2, March 2003 ISSN: 0018-9464

[6] Christopher, O.: New Core Loss Model, Switching Power Magazine, Ridley Engineering UK, Ltd. ISSN: 1471-1176, Spring 2002