FREQUENCY RESPONSE OF SELECTED CURRENT TRANSFORMES AND HALL-EFFECT CURRENT SENSORS

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Abstract − This paper is dealing with the comparison of isolated current sensors of nominal value up to 200 A. Emphasis is placed on the operation of the sensors at very low frequencies, where the amplitude and phase error is evaluated. This research was needed for the choice of an optimal current sensor for the development of a diagnostic system for induction motors. The most suitable sensors in the terms of performance and cost are selected in accordance with the application.

Keywords: current sensors, current transformer, hall-effect current sensor, transfer function measurement, comparison

1. NOMENCLATURE

Tf	Current transfer ratio
I_p	Primary RMS current
I_s	Secondary RMS current
R_s	Secondary coil resistance
L_s	Secondary coil inductance
I_{max}	Maximum primary current
R_2	Resistance of load + secondary
R_{Fe}	Eq. resistance of iron losses
δ_{Fe}	Static error of current transformer
f_d	Lower cut-off frequency
R_{load}	Load resistance
R_{sense}	Primary current sensing resistor
k	Discrete spectral line
H1(k), H2(k), H3(k)	Frequency response function
$G_{XX}(k)$, $G_{YY}(k)$	Input, output autospectrum
$G_{XY}(k)$	Cross-spectrum
γ_{XY}^2	Coherence function
I_p	RMS Primary current
U_{sns}	RMS Voltage on R_{sense}

2. INTRODUCTION

Electric currents can be principally measured using two methods − direct and indirect. For direct measurement a simple sensing resistance is used, but the disadvantage is that the measuring circuit is galvanically connected to the device which is measured. The developed induction motor diagnostic system needs to measure three-phase current and convert it to a 0–10 V signal. Galvanic separation is also needed, so the direct measurement is not suitable. Here, the indirect method has its advantages. With current transformers or hall-effect sensors low and also very high currents can be measured, and the measuring circuit is isolated. Current transformers are simple in design, but work only for AC. Hall-effect sensors can measure current from DC like current sensing resistors, but are more complicated and expensive.

3. FREQUENCY RESPONSE MEASUREMENT

3.1. Method selection

For the measurement of the frequency response of a system generally two approaches are used. In the first the measurement is made point after point for defined input parameters and the output values (amplitude, phase) are measured. This is a lengthy process because large number of points is needed to measure, which is the main disadvantage of this method. The advantage is that we can specify the input in highest detail − for this application the RMS current and the waveform can be specified; also more waveforms can be combined. The excitation signal can also be based on real-world waveforms.

The other approach uses a wideband input signal. White noise is usually used as an excitation signal, because of its uniform spectral density. The frequency response of the whole spectrum (0–f_{max}) is measured at once, the resulting output amplitude and phase is computed using FFT. Averaging is used to cancel out random errors and noise and also to improve amplitude resolution. The frequency resolution of the measurement depends on the selected FFT parameters. Two measurement ranges which are described in Table 1 were used.

Table 1. Frequency ranges.

	Low	*High*
Bandwith [Hz]	0-200	0-25600
FFT Resolution [Hz]	0.125	4
Single measurement time [s]	8	0.25
Number of averages (minimum)	10	200
Driving signal	white noise	white noise
Window for measured data	Hamming	Hamming

The B&K PULSE LabShop software computes the frequency response as described in (1)–(3). For our measurement the H3 function was used for the calculation.

$$H1(k) = \frac{G_{XY}(k)}{G_{XX}(k)} \qquad (1)$$

$$H2(k) = \frac{G_{YY}(k)}{G_{XY}^{*}(k)} \qquad (2)$$

$$H3(k) = \sqrt{H1(k) \cdot H2(k)} \qquad (3)$$

$$\gamma_{XY}^{2} = \frac{\left|G_{XY}(k)\right|^{2}}{G_{XX}(k) \cdot G_{YY}(k)} \qquad (4)$$

$G_{XX}(k)$, $G_{YY}(k)$ are the autospectra of the measured input and output, $G_{XY}(k)$ is the cross-spectrum [1].

The outputs of the calculations done in the software are the amplitude and phase response of the measured system and also the coherence value. This coherence value (4) quantifies the linear relationship between the input and output signal and is used to detect errors in measurements. In the ideal case it should be 1 for the whole frequency range. A lower coherence value at 50 Hz indicates that some noise from the mains is present in the input signal. Low coherence at very low frequencies (up to three frequency lines from zero, caused by the used FFT window function) is present because the current transformer has a minimal frequency below which it cannot operate. For sensors operating from DC, the coherence value at 0 Hz is low if the sensors has a DC offset. A separate measurement using a zero and a defined DC current is needed to determine the transfer function of the sensor for DC signals.

Note the disadvantage of this method: the shape of the input signal for the measured system. The wideband noise is different from the real signal which the sensor is designed for, and because the energy of the whole spectrum is limited, each frequency line has low amplitude. But the results obtained show that this method is suitable and produces valid results, which were confirmed at selected points with the single-point measurement approach.

3.2. Measurement setup

The primary winding of the current sensor was connected to a power amplifier. This amplifier consists of a power operational amplifier in the voltage follower circuit. The current is sensed with a 1.1 Ω current sensing resistor, which is connected in series with the device under test. The secondary coils of the current transformers were loaded with a resistor. The circuit is depicted on Fig. 1.

Measurements of transfer functions were made using the B&K Pulse multi-analyzer type 3109 and 7533. This device has two analog outputs and four analog inputs. One generator for supplying the driving signal to the amplifier was used; one input was used for the current sensing resistor voltage measurement (reference signal) and another three inputs for the simultaneous measurement of the output signal of three sensors. The use of the reference signal (primary current sense) eliminated the effect of the amplifier on the measured transfer function. The maximum bandwidth range is DC–25.6 kHz. The supplied software program Pulse LabShop v.17 was used for all subsequent measurements and transfer function calculations. The calculated frequency

characteristics were exported to the Matlab software package for visualization.

The load resistance R_{load} was selected from the values of 1; 10; 100 and 1000 Ω. Because the amplifier output current was limited to about 1 A by its design, the primary coil had Np=1; 2; 5 or 10 turns to achieve higher primary currents (by lowering the P:S turns ratio). At high values of Np the maximum primary current was also limited by the resulting large inductance of the primary coil.

DC resistance was measured with a HP 34401A multimeter using four-wire method. Inductance was measured using HP 4263B LCR meter, also with four-wire connection.
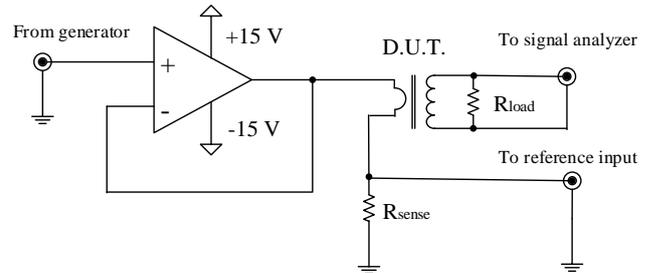

Fig. 1 Measuring circuit with amplifier

4. CURRENT TRANSFORMERS

4.1. Principle of operation

The most common used indirect AC current sensors are current transformers. Their operating principle (equivalent circuit) is illustrated below and consists essentially of a transformer with a defined turns ratio, which operates into near short-circuit load. The transfer of an ideal current transformer is given by the turn ratio. In reality, the amplitude transfer is always lower. Due to currents flowing which do not pass through RL, e.g. core losses, capacitive losses.
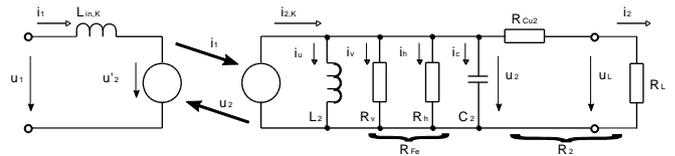

Fig. 2 Current transformer equivalent circuit.

The load resistance consists of the used load resistor and also the secondary winding resistance, which is fixed. The measurement with this transformer has an amplitude and phase error [2]. The amplitude error is never zero, because of iron core losses (hysteresis losses and eddy currents):

$$\delta_{Fe} = 1 - \frac{R_{Fe}}{R_2 + R_{Fe}} \qquad (5)$$

The bandwidth of the current transformer is limited by its design, where the simplified equation for the lower cut-off frequency (-3 dB amplitude error) is:

$$f_d \cong \frac{R_2}{2\pi L_2} \qquad (6)$$

4.2. Measurement results

All current transformers except one were manufactured by HQ Sensing [4], [5]. For comparison, one low-cost current transformer type SCT013 [6] from manufacturer YHDC was measured too. In the Table 2 is a summary of transformer types and their properties.

Table 2. Current transformers measured

Type	Datasheet values		Measured values				
			DC	@100Hz		@1kHz	
	Turns ratio	I_{max} [A]	Rs [Ω]	Ls [H]	Rs [Ω]	Ls [H]	Rs [Ω]
JC16F[a]	1:3k	200	296	65.2	983.7	82.6	5.8k
JC24F[a]	1:3k	300	170	38.5	526.3	46.5	2.1k
JP3W[b]	1:2.5k	6	143	241.4	3.6k	-164.5	60.9k
JN1V[b]	1:1.5k	6	47	53.8	10.5k	41.7	36.6k
SCT013[a]	1:2k	100	99.8	5.7	257.5	6.1	695.3

a.   Split core design
b.   Toroidal core design

For the following measurements R_{load} was 10 Ω. The frequency range of the current transfer function and phase is defined by its upper and lower frequency, where the error compared to the frequency of 50 Hz is not exceeded by a defined percentage or value, as seen in the following tables.

Table 3. Current transformer high frequency response

Type	Measured values							
	@50Hz				Tf ±1%		Ph. err ±1°	
	I_p [A]	U_{sns} [mV]	Tf [mA/A]	$Phase$ [°]	f_l [Hz]	f_u [kHz]	f_l [Hz]	f_u [kHz]
JC16F[a]	4.46	14.8	0.333	0.79	8	25.6	8	25.6
JC24F[a]	4.27	14.1	0.330	0.79	8	25.6	24	25.6
JP3W[b]	2.59	8.6	0.401	0.12	8	25.6	8	25.6
JN1V[b]	0.95	5.3	0.669	0.30	8	25.6	8	25.6
SCT013	0.72	30.1	0.507	3.47	24	25.6	48	0.052

Measured low-frequency response of one selected transformer with different load resistances are in the next table.

Table 4. Current transformer low. frequency response

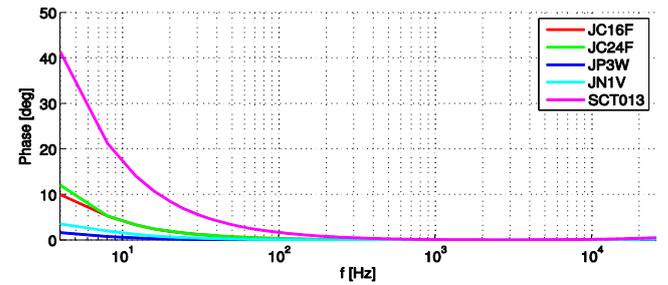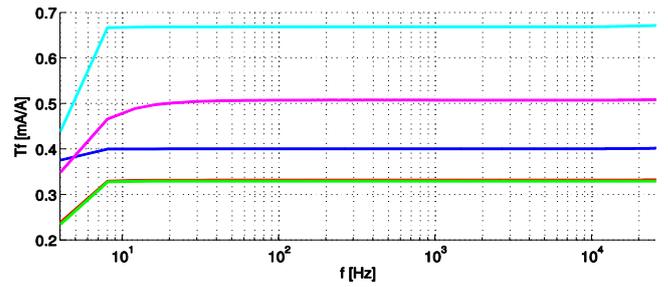| Type	Measured values							
	@50Hz				Tf ±1%		Ph. Err ±1°	
	R_L [Ω]	Ip [A]	Tf [mA/A]	$Phase$ [°]	f_l [Hz]	f_u [Hz]	f_l [Hz]	f_u [Hz]
JP3W	1	1.46	0.404	0.616	1	200	3.75	200
	10	1.47	0.402	0.15	0.88	200	5	200
	100	1.46	0.408	0.73	1	200	4.38	199.75
	1k	1.45	0.391	4.4	5.13	200	9.63	198.75

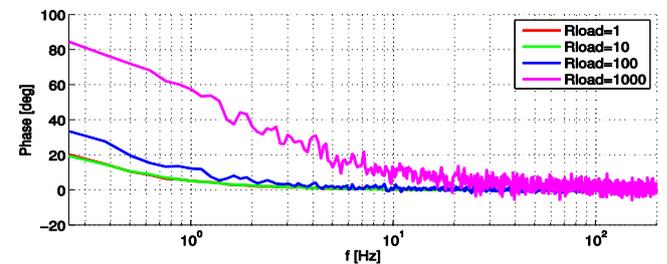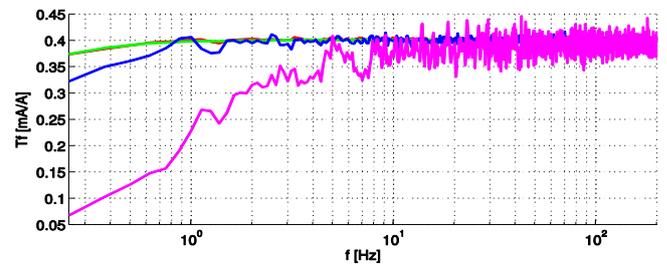Fig. 3 Current transformer high frequency response

Fig. 4 Low frequency response of a JP3W current transformer.

4.3. Result discussion

The SCT013 current transformer has the core made from a ferrite material with good high-frequency properties. The frequency response at low frequencies is poor. All other transformers were made from iron laminations and their error at very low frequencies is significantly lower. Transformers with a whole core had a remarkable better performance than split-core types.

The effect of the load resistance on the transfer function was observed as expected, the higher the RL, the larger is the amplitude and phase error. From our measurements, the RL = 10 Ω is the best compromise between desired low resistance and a reasonable voltage drop at the resistor (to achieve good signal to noise ratio). Smaller values can be used, but the connection between the RL and the subsequent amplifier should be as short as possible. With an RL of 1000 Ω the transformer is operated far away from ideal conditions and the appropriate line in the plot shows this behaviour.

5. HALL-EFFECT CURRENT SENSORS

5.1. Principle of operation

Current sensors measuring from zero frequency obviously cannot be based on transformer designs, but direct measurement of magnetic flux can be used. The core (same as in the current transformer) has an air gap, and the measured current creates a magnetic flux through the core. In the gap, the magnetic field intensity is measured by a hall-effect sensor. This intensity is proportional to the measured current, and the hall voltage is proportional to this magnetic field intensity. The sensor is, in the designed range, therefore also linear. This simple arrangement, which only measures the magnetic flux intensity, is called an open-loop sensor. It is simple, but can be influenced by temperature changes and external magnetic fields and the linearity depends on core design. The main limiting factor is the saturation of the core. The output of this sensor type is the amplified hall voltage [3].

The so called closed-loop or compensation design has a compensation coil wound on the measuring core. A loop amplifier sets the current to this coil so that the resulting magnetic flux in the core is always zero. The advantage is that the core flux is always zero and cannot reach saturation, the core can be smaller. On the other side, the greater the measured current, the greater must be the compensation current, so the current consumption varies with the measured current and can be quite large. The output from this sensor is derived from the compensation current, which is sensed [2].
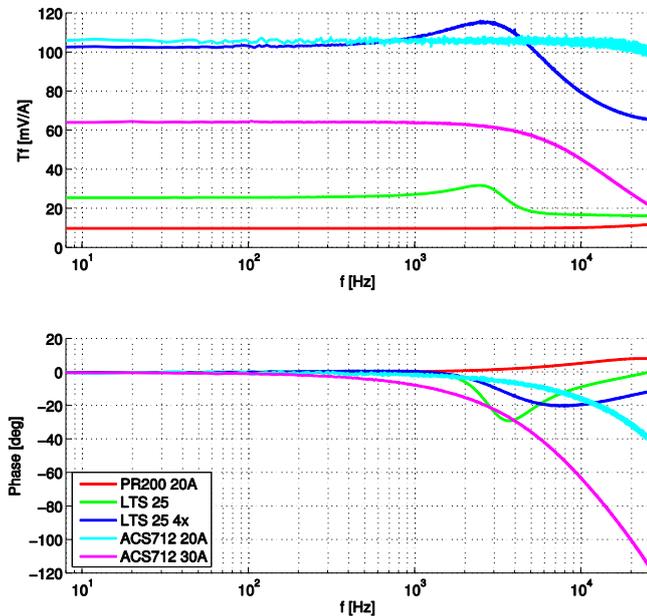
5.2. Measurement results

Fig. 5 Hall-effect sensor high frequency response.

Two sensor types were measured. The closed-loop sensor were the split-core sensor type LEM PR200 [7] with 20 A and 200 A ranges and a small sensor module type LEM LTS-25 [8], without and with a buffer amplifier stage with gain of 4. Open-loop sensors were represented by small modules with the monolithic sensor ACS712 [9] with 20 A

and 30 A current rating. The device package limits its use on high-voltage applications. The parameters of this sensor make it more suitable to measure currents in low voltage application with a need for a low-cost, low-loss solution. For some circuits without the need for high precision measurements those monolithic open-loop current sensors can replace other sensor types.
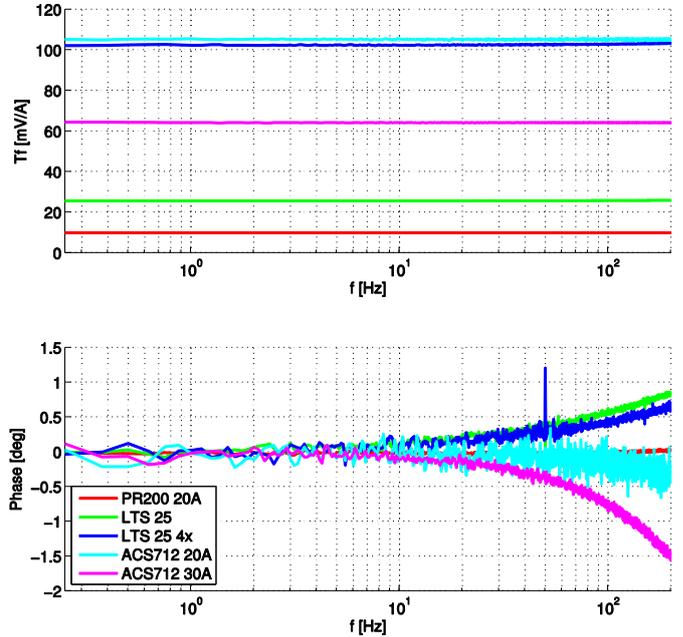
Fig. 6 . Hall-effect sensor low frequency response.

Table 5. Hall-effect current sensor high frequency response.

Type	Measured values						
	@50Hz			Tf ±1%		Ph. Err ±1°	
	I_p [A]	T_f [mV/A]	Phase [°]	f_l [Hz]	f_u [kHz]	f_l [Hz]	f_u [kHz]
PR200 20A	5.44	10.123	-0.002	8	5.6	8	1.73
LEM LTS-25	2.84	25.877	0.254	8	3.46	8	1.4
LTS-25 4x amp.	0.66	102.86	-0.156	8	5.11	8	1.6
ACS712T-20A	0.77	105.62	-0.39	8	16	8	1.14
ACS712T-30A	0.77	64.54	-0.39	8	1.62	8	0.18

Table 6. Hall-effect current sensor low frequency response.

Type	Measured values						
	@50Hz			Tf ±1%		Ph. Err ±1°	
	I_p [A]	T_f [mV/A]	Phase [°]	f_l [Hz]	f_u [Hz]	f_l [Hz]	f_u [Hz]
PR200 20A	7.75	9.99	-0.028	0	200	0	200
LEM LTS-25	3.1	25.77	0.07	0	200	0.125	200
LTS-25 4x amp.	0.735	102.1	0.349	0	200	0.25	131
ACS712T-20A	0.82	105.59	0.059	0	200	0.25	200
ACS712T-30A	0.82	64.29	-0.361	0	200	0.25	120

The frequency range of the current transfer function and phase is defined by its upper and lower frequency, where the error compared to the frequency of 50 Hz is not exceeded by a defined percentage or value, in this case 1% difference from the transfer amplitude at 50 Hz and an absolute phase error of 1° compared to the measured phase at 50 Hz. The upper frequency is limited by the equipment used to 25.6 kHz.

5.3 Result discussion

Closed-loop type current sensors have generally better properties, but at the cost of relatively large and variable power consumption. From Fig. 5 is seen, that the LTS 25 sensor has a significant amplitude error at 2 to 3 kHz. It could be the effect from too large capacitive loading of the output. But the same phenomenon appears also on the plot of the transfer function of the sensor connected to a buffer amplifier with a gain of 4. No deeper research was made, and therefore this problem was closed with the following result. The anomaly is probably caused by the sensor itself, or some measurement error is the cause of this result, which is outside the LTS-25 sensor specifications.

6. CONCLUSIONS

Several current sensors were measured, and their frequency response was compared. Especially the response at low frequencies was explored, because the diagnostic system has to measure currents with frequency as low as 1 Hz.

It was found that current transformers operate with an acceptable error also at very low frequencies, and some types are usable with an amplitude error of 1 % down to about 1 Hz. But the phase error at these frequencies is very large (in the order of tens of degrees); this is not acceptable for our application (induction motor diagnostic system). For applications with low demands on minimum phase error,

current transformers should be considered as suitable sensors.

As expected, hall-effect type sensors have good performance over the whole frequency range and the phase and amplitude error is low and constant. Their superior properties are outweighed by higher cost, but for our application they were chosen as a good compromise.

For the applications with highest demands, a current sensing resistor (shunt) has to be used. With a good design, a very large bandwidth can be achieved.

For our application, sensing of stator currents of induction motors, finally the LTS 25 sensor was chosen because it turned out to be the most suitable sensor for this purpose in all cases.

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