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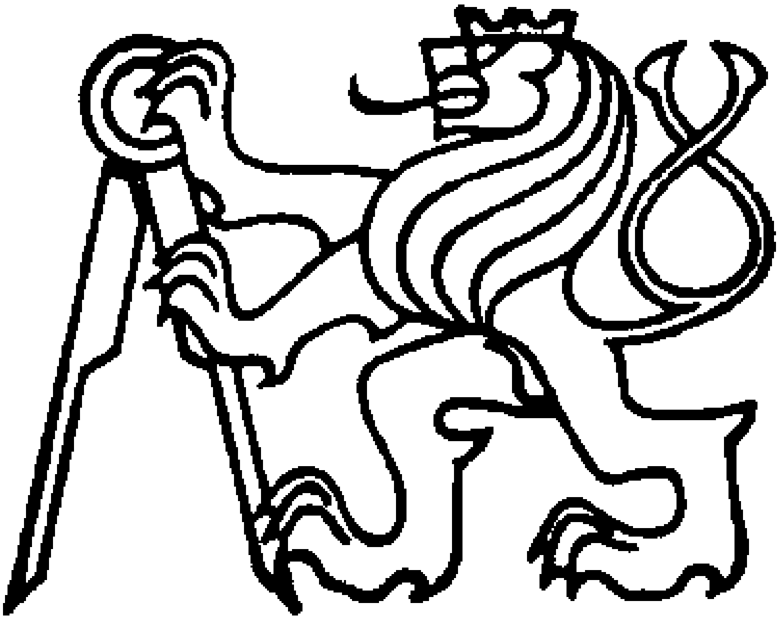

DOCTORAL THESIS STATEMENT

Czech Technical University in Prague
Faculty of Electrical Engineering
Department of Electrical Drives and Traction

New Approach to Induction Motor Drive Sensorless MRAS Control

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Ph.D. Programme: Electrical Engineering and Information Technology
Branch of Study: Electric Machines, Apparatus and Drives

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1 CURRENT SITUATION OF THE STUDIED PROBLEM

Nowadays it is possible to say that absolute majority of traction vehicles use voltage power inverter for induction machine supplying. The competitive environment in vehicle production area presses the producers to minimize costs of production and maintenance, to increase availability and to decrease time of development and introducing to the service. That means that producers are looking for the simplest solutions, from the view of production and maintenance. The speed or power are not key parameters of vehicles nowadays, because relative high amount of producers is able to fulfil requirements of customer and infrastructure. Critical parameters are reliability, reparability and delivery time. It is necessary to optimize all parts of vehicle, traction drive including, to these parameters. Main part of this job consits in technology and construction of course (modular converter conception, diagnostic, cable sets technology…), but it is possible to increase these parameters by optimization of converter control.

For example, the optimization of control through the criterion of taking-off minimal current in each operating point has been used for many years. Its principle consists in setting optimal flux in machine for each demanded torque.

Next way, how to decrease cost and increase reliability is decreasing of component number. Most often used traction drive system consists of voltage inverter, induction machine and sensors necessary for service. Phase current sensors, dc link voltage sensor and speed sensor are usually used. For control of machine it is necessary to know two of the following three quantities: terminal voltage, phase current and revolutions. Measuring of terminal voltage is difficult and unusual because it is the voltage inverter output. Current sensors are usually in converter box and are necessary for error detection to protect the converter in the case of fail. Revolution sensor has to be directly on machine in the car bogie. It means that it works in very aggressive environment: high acceleration, dust, water, temperature changes over the range from -30℃ to +220℃. In addition, the signal from revolution sensor has to be connected to the converter by relatively long cable, which is sensitive to interruption. In this point of view the revolution sensor looks to be the bottleneck of the reliability of the whole drive.

This is the reason, why it should be good to have a drive without revolution sensor.

The situation in industry drives is clear – almost each producer is able to provide the sensorless solution. But the traction drives are more complex from this point of view because these require the precise torque control in wide range of operation states.

The work on this doctoral thesis has started in 2008. Only a few trams in Germany were able to operate with sensorless traction drive. But the situation has changed since this time. The Siemens company, the world leader in this field, is able to provide sensorless solution for trams and metros, but not for locomotives.

Other big players in traction drive area (Bombardier, Alstom, Mitsubishi, …) has not used this technology in serial production yet. It is easy to predict that many companies develop it and sensorless control is going to become a standard in next years.

Many methods for induction machine sensorless control are known. The recent situation in the field of sensorless control algorithm is described in next chapter.

2 AIMS OF THE DOCTORAL THESIS

The aims of this thesis are:

- looking for possible solutions how to control the torque of induction machine without speed sensor,
- the most perspective method selection, detailed analysis of this method and detection of possible problems,
- suggestion of problem solution,
- testing of the solution by numerical simulation,
- testing of the method on a real induction machine.

3 WORKING METHODS

3.1 Induction Machine Sensorless Control Methods

3.1.1 Introduction

The target of traction drive sensorless control is to estimate mechanical speed of the machine or flux vector position. Its knowledge is important input value for vector control algorithm, because it enables current vector decomposition. The literature [1] was the main source of information for this chapter.

Estimators can be divided into several groups.

1. Estimators with machine equivalent diagram knowledge:
    - open-loop estimators with stator current and voltage monitoring,
    - MRAS (Model Reference Adaptive System) observers,
    - machine state reconstruction using observers.
2. Estimators without machine equivalent diagram knowledge:
    - stator voltage space saturation using estimators,
    - estimators based on detection of frequencies generated by machine asymmetry,
    - estimators with voltage or current signal injection,
    - artificial intelligence using estimators.

Generally we can say, that estimator is a dynamic system, the state of which is depicted by observed system. Estimator is an algorithmic block usually based on math model of the machine. Measurable values are most often input values. Knowledge of machine parameters is necessary for estimator.

Two types of estimators can be differentiated:

1. open-loop estimators,
2. closed-loop estimators.

The difference between these two types consists in feedback presence. Feedback should be used for estimator behavior correction accordingly to real system state. Closed-loop estimators are called observers.

3.1.2 Description of Current Based MRAS

Current based MRAS is the most widely used approach to sensorless inductive machine control. It uses the real machine as the reference model. Machine is supplied by the voltage. Machine stator current is a response to the terminal voltage and machine state. Getting the same current response from the adaptive model is possible, if it is in the same state as reference model. Adaptive model state is well known, because it is realized in control system. That is the main idea of the current based MRAS. The target of current based MRAS realization is to find a satisfactory adaptive model.

Realization of this solution can have some hazards:

1. The voltage for both models should be the same;
2. The reference model, including parameters, has to be very accurate to generate appropriate current response;
3. The current difference character should be independent on machine state.

Main advantage is using the real machine as the reference model. It enables real-time correction of retrieved results and it keep down the influence of machine parameters changing. It means that the current based MRAS has self-correcting character.

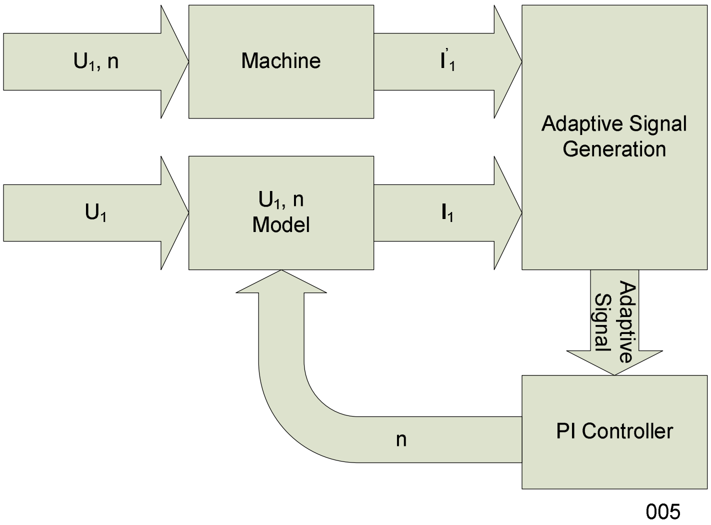

Fig 1 Current Based MRAS Scheme

3.1.3 Justification of Choice of MRAS Method

The decision of using current based MRAS method was accepted on the base of knowledge described in the thesis. Robustness, reliability and repeatability are its main properties that make this method perspective for industry traction drive using. The fact, that real machine is the significant part of estimation scheme is important, because it fulfils the self-check function of the whole algorithm. It means that the possible speed estimating error can be detected and it should not lead to any accident.

3.2 Machine Transfer Function Definition

If correct machine model parameters are available and voltage input to the model is the same as real machine terminal voltage, it can be found, that difference between measured and estimated stator current depends on difference between real and estimated speed. We can write

$$\Delta i_s = z(\Delta\omega) \qquad \textit{(Eq. 1)}$$

where

Δi_s is current difference,

$\Delta\omega$ is angular speed difference,

z should be called transfer function of the machine for purpose of current based MRAS. It can be mentioned here, that z can be called steady state impedance of the machine in some cases. Current difference can be described by the equation

$$\overset{\circ\circ}{\Delta\vec{i}} - \frac{\left(\left(j\omega_w - \frac{R_r}{L_\sigma}\right)L_\sigma - \rho R_r\right)}{L_\sigma}\overset{\circ}{\Delta\vec{i}} + \left(\frac{R_r R_s}{L_\mu L_\sigma} - \frac{\rho R_r\, j\omega_w}{L_\sigma}\right)\Delta\vec{i} = -\frac{j\Delta\omega\overset{\circ}{\vec{\psi}}_{rm}}{L_\sigma} \qquad \textit{(Eq. 2)}$$

And it can be represented by the scheme usually used for drawing of differential equation in electric drives.

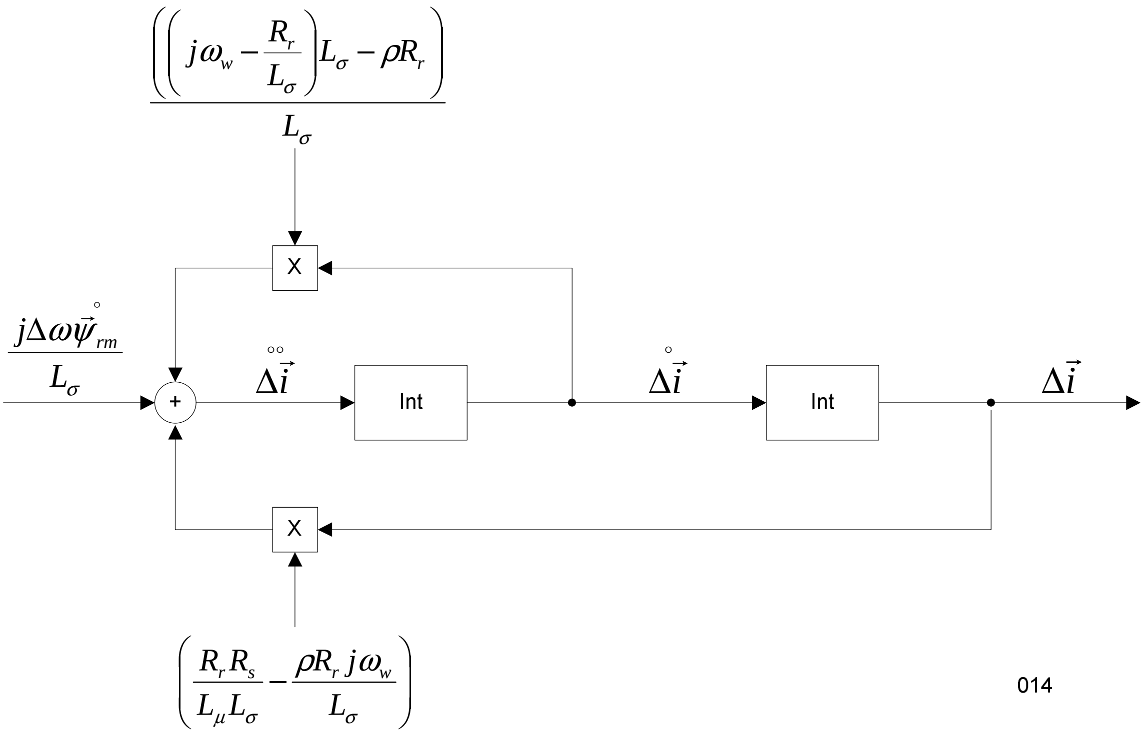

Fig 2 Transfer Function Scheme

In Fig 2 can be found the answer to the most often asked question concerning sensorless drive: “Whether is the drive able to work in zero speed area ?”

It is necessary for the speed estimation to get some difference of the current vectors ($\Delta\vec{i}$). In the figure can be found that the whole system depicted in the figure is excited by the signal $\frac{j\Delta\omega\overset{\circ}{\vec{\psi}}_{rm}}{L_\sigma}$. This signal will be called ‘excitation’ in next text. Excitation signal should be unequal to zero when current vector difference is generated.

By analysis of excitation signal we can found, that it can be equal to zero, if $\Delta\omega = 0$ or $\overset{\circ}{\vec{\psi}}_{rm} = 0$.

The condition $\Delta\omega = 0$ is fulfilled, if difference between real and model speed is equal to zero

$\Delta\omega = \omega_m - \omega_w = 0$

This is desired state of the system and principle of speed estimation.

The second condition $\overset{\circ}{\vec{\psi}}_{rm} = 0$ expresses that the vector of rotor flux is not changing during the time. This is the real limitation of sensorless speed identification. It can be found that the usually used statement, that zero speed identification is not practicable, is not correct. According to this theory, zero speed identification is possible when the system is excited by rotor flux vector changing.

Only stable harmonic operation will be considered in next part. This restriction can be accepted by supposition that the speed changing is very small during computation period. It is fulfilled always in case of traction drives.

The relation between speed difference and current difference was found. It has the following form

$$\Delta\vec{i} = \vec{\psi}_r \frac{\Delta\omega \cdot \omega_s}{L_\sigma\left(\frac{R_r j\omega_s}{L_\sigma} - \omega_r\omega_s + \frac{R_r R_s}{L_\mu L_\sigma} + \frac{\rho R_r j\omega_r}{L_\sigma}\right)} \qquad \textit{(Eq. 3)}$$

It can be adjust by multiplying $\vec{\psi}_r^{\,*}$ and dividing $\left|\vec{\psi}_r\right|^2$. We get the form

$$\Delta\vec{i}\cdot\frac{\vec{\psi}_r^{\,*}}{\left|\vec{\psi}_r\right|^2}=\Delta\omega\cdot z(\omega_r,\omega_s)$$

(Eq. 4)

where

$$z=\frac{\omega_s}{L_\sigma\left(\frac{R_r j\omega_s}{L_\sigma}-\omega_r\omega_s+\frac{R_r R_s}{L_\mu L_\sigma}+\frac{\rho R_r j\omega_r}{L_\sigma}\right)}$$

(Eq. 5)

is machine transfer function.

3.3 Transfer Function Analysis

Transfer function z is complex expression of two variables ω_s and ω_r, which can be drawn in complex space.

For analysis purpose it is the best alternative to draw graphs with constant ω_r and ω_s changing from $-\infty$ to $+\infty$. Choice of machine parameters is necessary for graph construction. The laboratory stand machine parameters were chosen, but these values are not important at this place. The graph of transfer function can be constructed on the base of information known now.

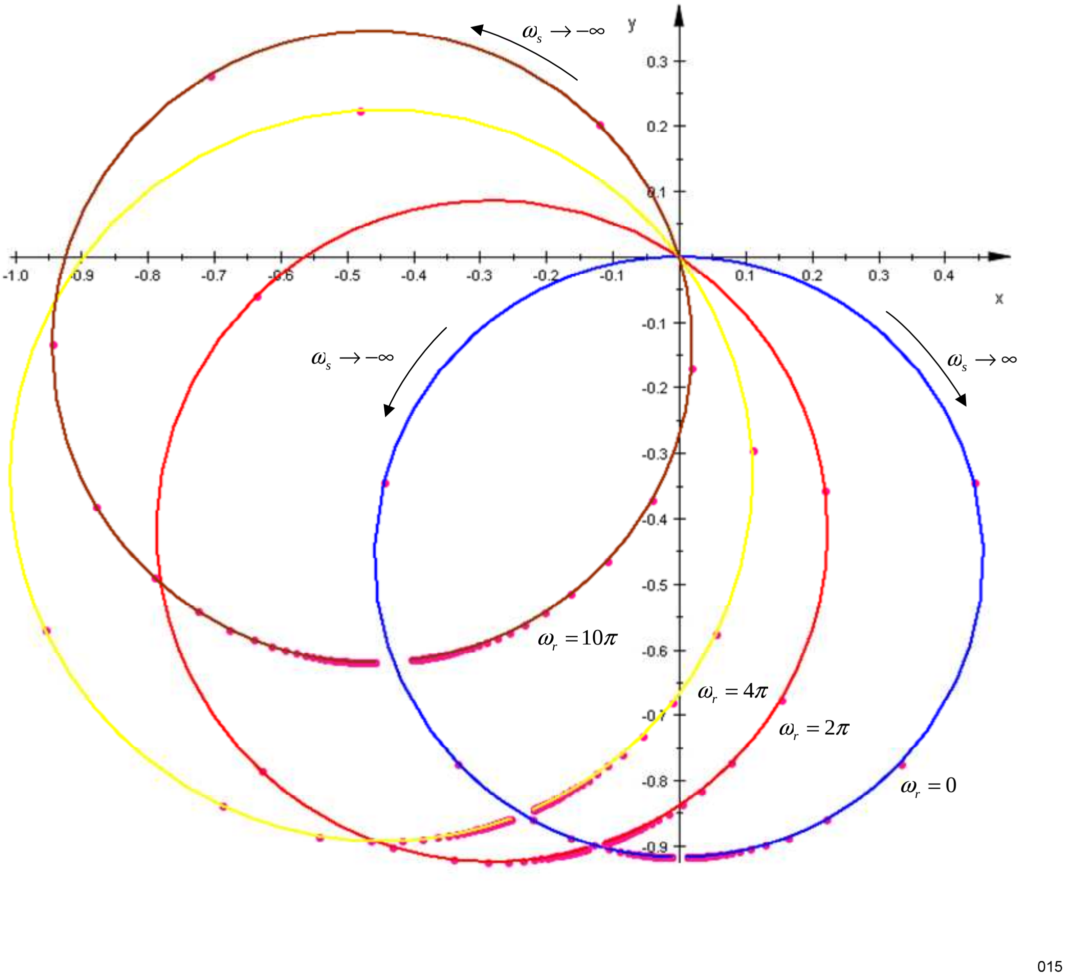

Fig 3 Transfer Function

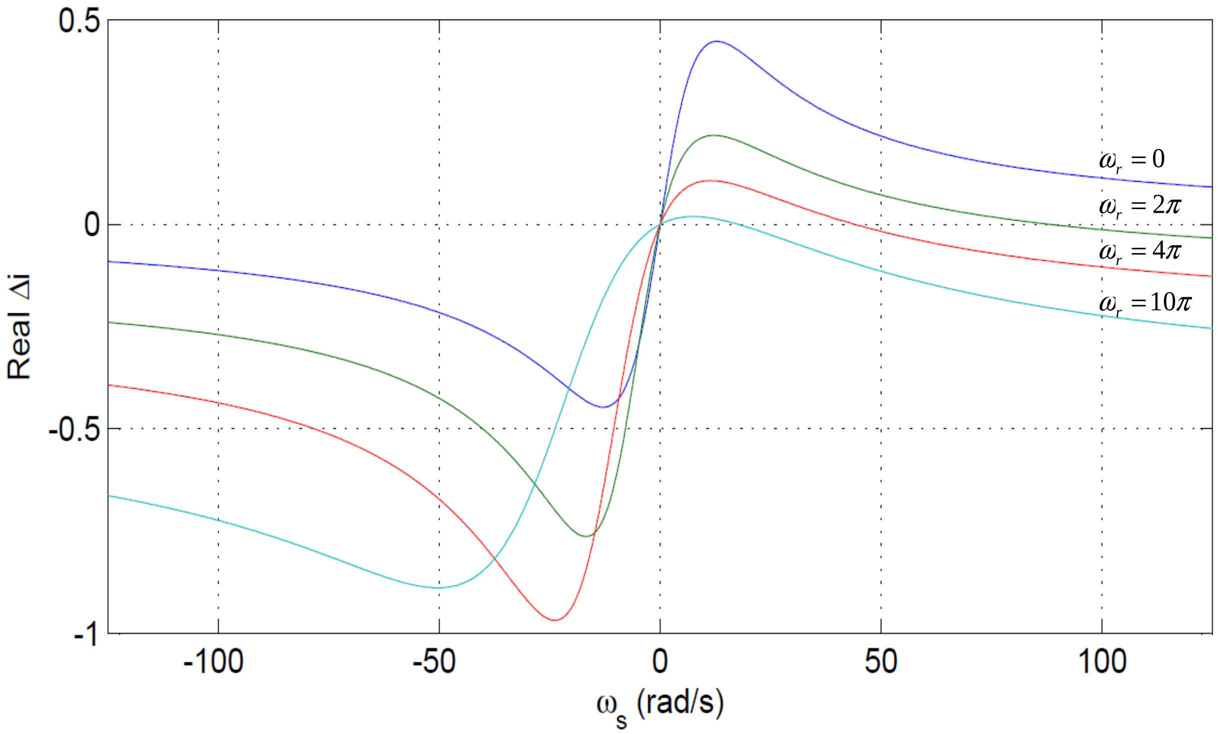

Fig 4 Real Part of Transfer Function

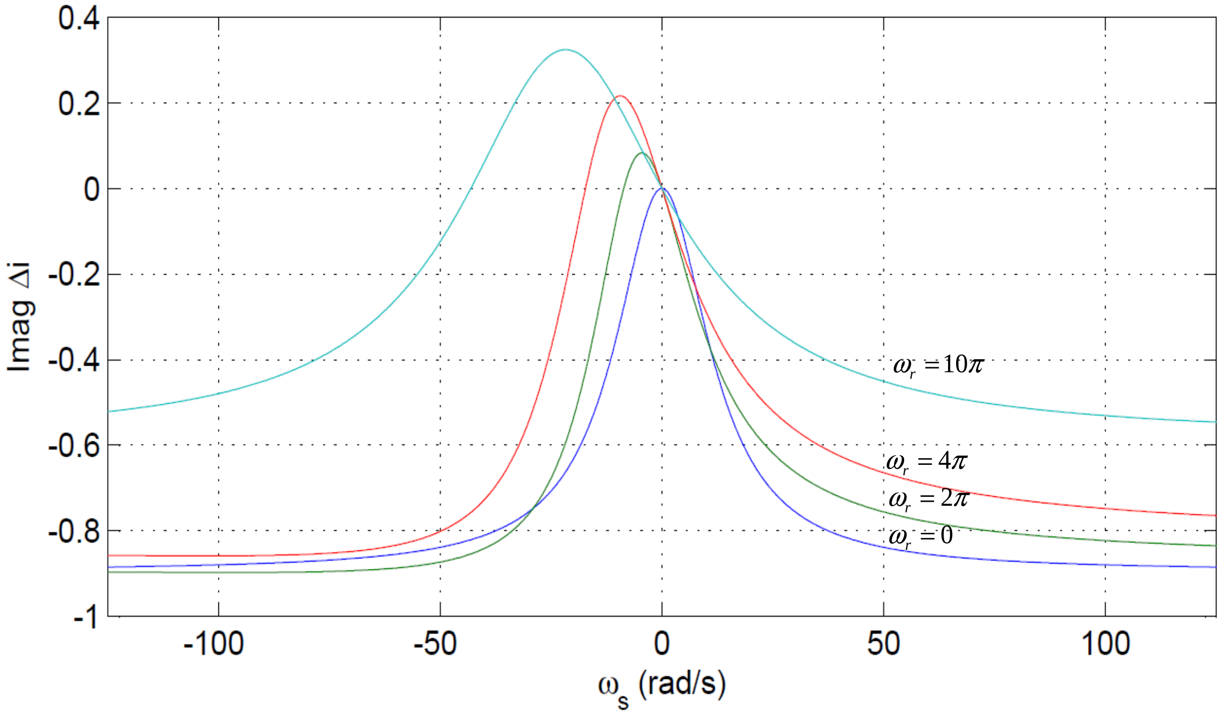

Fig 5 Imaginary Part of Transfer Function

Some interesting facts flow from Fig 3 :

1. If $\omega_s = 0$ ($\overset{\circ}{\vec{\psi}}_{rm} = 0$), then $z = 0$;
2. Sign of $(\mathrm{Re}\{z\})$ is changing in all cases;
3. If $\omega_r = 0$, then $\mathrm{Im}\{z\} < 0$ for all ω_s;

4. If $\omega_r \cdot \omega_s > 0$, then $\mathrm{Im}\{z\} < 0$;
5. If $\omega_r \cdot \omega_s < 0$, then sign of $\mathrm{Im}\{z\}$ varies;
6. Points of $\lim\limits_{\omega_s \to \infty} z$ and $\lim\limits_{\omega_s \to -\infty} z$ lie on the same circle as z for $\omega_r = 0$;
7. Behaviour of induction machine is not symmetrical in motor and generator modes.

3.3.1.1 Analysis of Points 1, 2, 3, 4

The point 1 corresponds to the assumption that exciting signal should be unequal to zero.
Points from 2 to 4 imply that $\mathrm{Im}\{z\}$ is able to generate good adaptive signal in these cases. If $\mathrm{Im}\{z\}$ would be adopted as adaptive signal, the problem appears in case described in point 5.

3.3.1.2 Analysis of Point 5

Point 5 describes the situation, when drive is in breaking mode. $\mathrm{Im}\{z\}$ has the negative polarity at high speed, but it changes the polarity in low speed area. Dependency of maximal values of $\mathrm{Im}\{z\}$ is depicted in the next figure. It seems, that the maximal value is growing with ω_r.
For adaptive signal it is necessary to have the same sign for constant $\Delta\omega$ in the whole operating area. The reason is that the feedback controller eliminating adaptive signal by its output setting can not work stable, if the sign of the adaptive signal is changing.

3.3.1.3 Analysis of Point 6

Point 6 does not take any effect to estimation algorithm, but it is possible to find its prove in the thesis.

3.3.2 Machine Transfer Function Adaptation

Requirements for adaptive signal have to be placed:

1. The sign of transfer between speed difference and current difference can not alternate according to operating mode. This condition is necessary when feedback controller is used to estimate the speed;
2. The magnitude of transfer function should be similar for all ω_r if $\omega_s \to \pm\infty$. Fulfilling of this condition makes easier setting of the feedback controller parameters. The target is to have one parameter set for large speed range (except low speed of course).

The transformation which finds the coefficient c consists of two steps:

1. The transfer function rotation in complex area;
2. Setting of transfer function magnitude to constant for $\omega_s \to \pm\infty$.

Finding of the coefficient c, which transforms transfer function z into proper adaptive signal a, is the aim the work. This situation is expressed by the next equation.

$$a = \Delta\omega \cdot c \cdot z(\omega_r, \omega_s) \qquad \textit{(Eq. 6)}$$

Coefficient c can be written as product of both transformation described in the thesis.

$$c = \frac{(R_s + j\rho L_\mu \omega_r)(R_r^2 + L_\sigma^2 \omega_r^2)}{\rho L_\mu L_\sigma \omega_r^2 + R_r R_s} \qquad \textit{(Eq. 7)}$$

Complete scheme of adaptive signal generation can be drawn at this place.

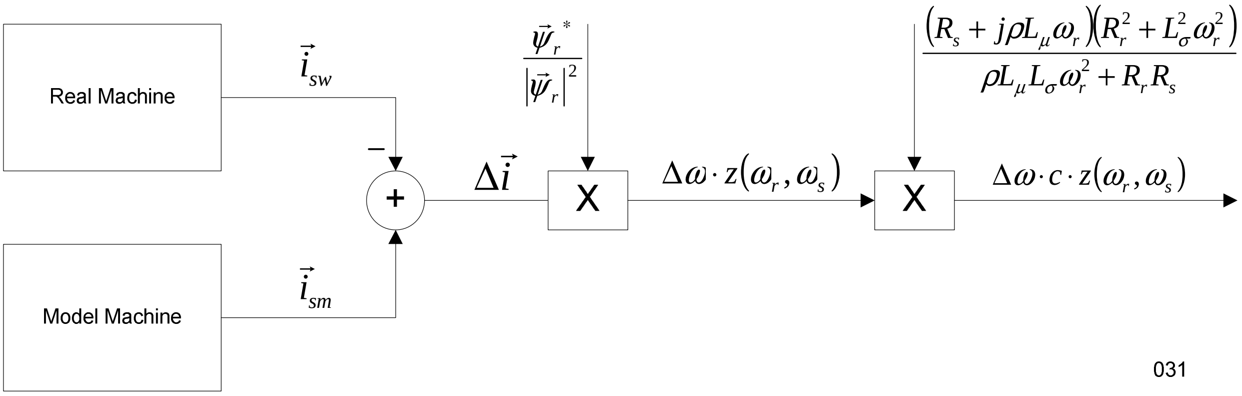

Fig 6 Complete Scheme of Adaptive Signal Generation

Transfer function waveform after transformation can be found in the next figures.

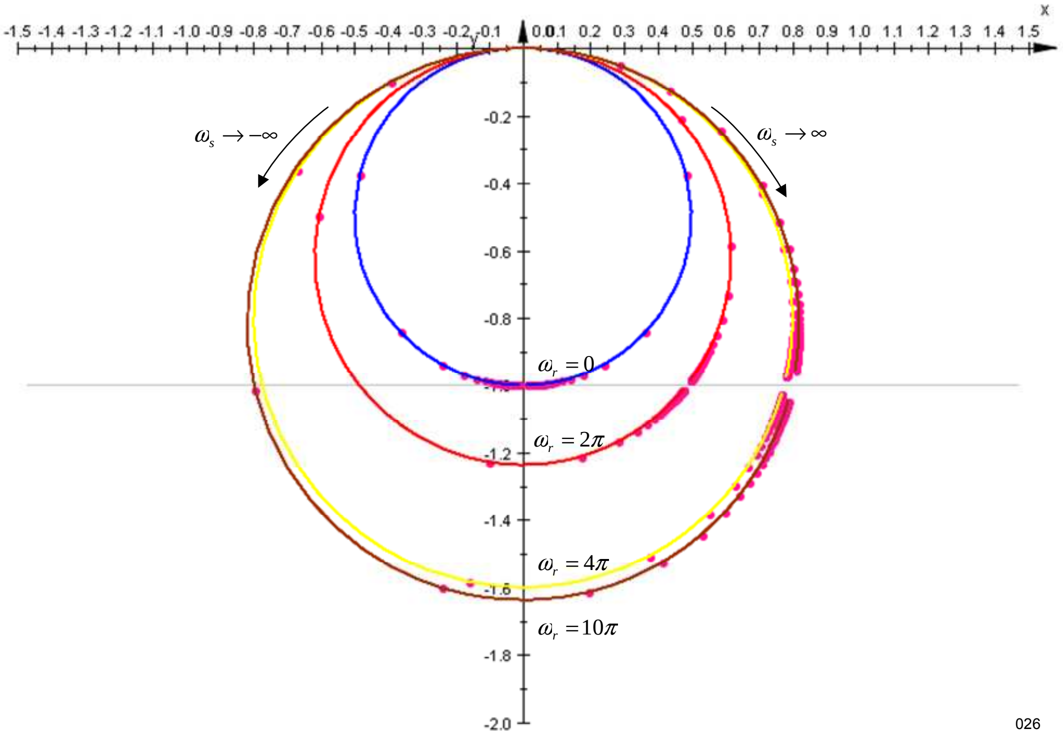

Fig 7 Transformed Transfer Function z_m

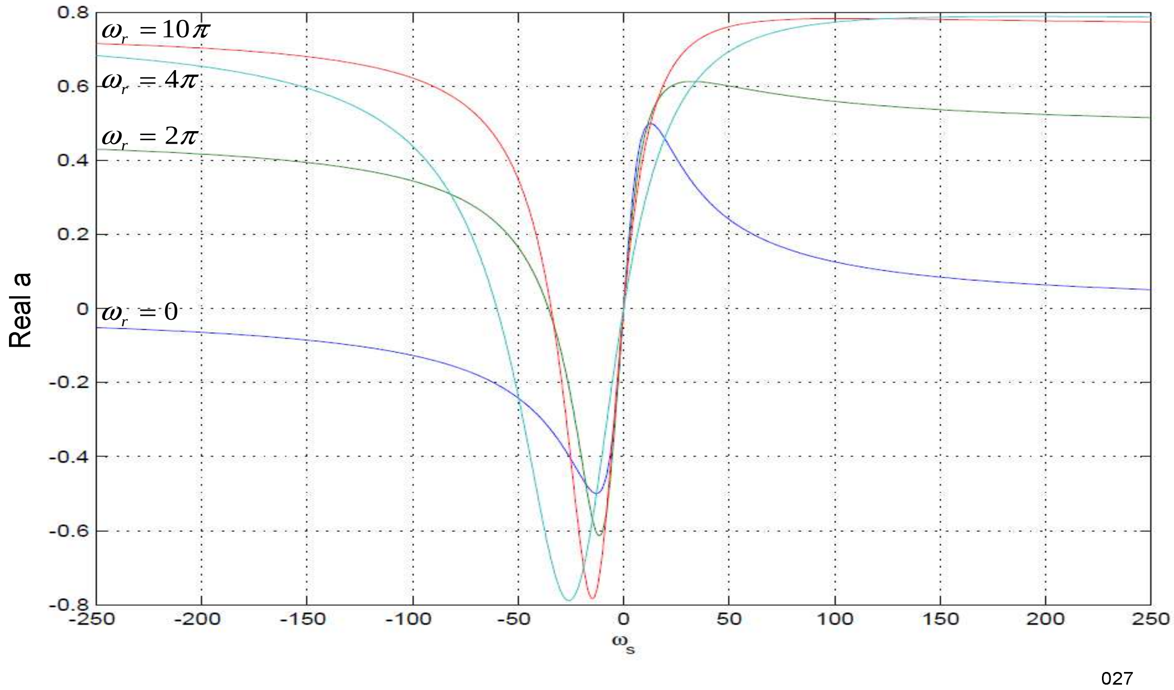

Fig 8 Real Part of Transformed Transfer Function $\mathrm{Re}\{z_m\}$

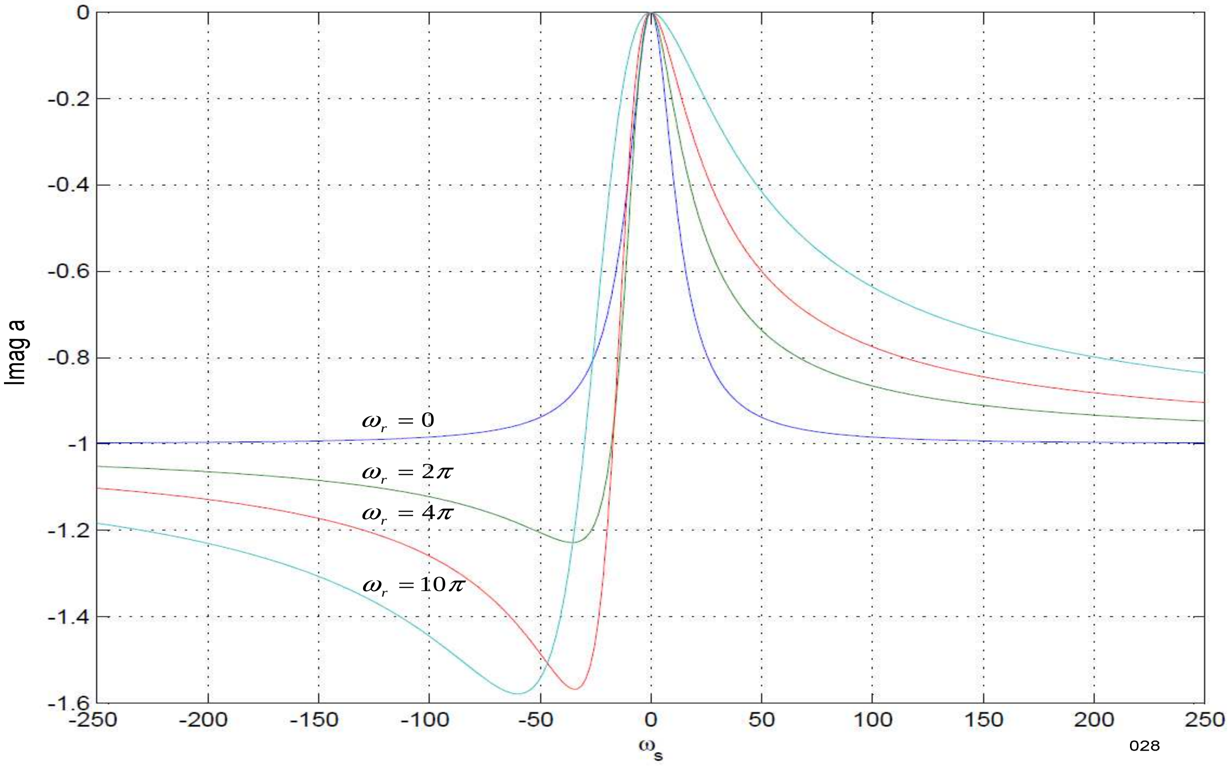

Fig 9 Imaginary Part of Transformed Transfer Function $\mathrm{Im}\{z_m\}$

As can be found in previous figures, $\mathrm{Im}\{z_m\}$ can be used as good adaptive signal, because it fulfils its requirements and enables speed identification in the whole range of drive operation area (except of the state with $\overset{\circ}{\Psi}_r = 0$).

Expression for coefficient c depends on one variable (ω_r) only and its implementation should not be complicated in drive control system.

4 RESULTS

The theory of adaptation signal transformation was successfully tested in MatLab simulation [4], [5]. It was implemented in target control hardware and tested with C-RIO system (parallel developed). The most valuable results were achieved on real laboratory inverter with induction machine.

4.1 Evaluation of Adaptive Signal on Real System

The test is designated for transfer function generation. The situation is similar to Simulink test scenario. The reference model is slowly changing the speed from -45 Hz to 45 Hz. Rotor angular speed is a constant $\omega_r = 3\pi$. The adaptive model works with continuous speed error $\Delta\omega = 2\pi$. The real and imaginary parts of transfer function and adaptive signal are saved.

4.1.1 Test Results

The format of saved data is Q13. It means that nominal value of current (1 in relative units) corresponds to 2^{13} (8192 in computer units).

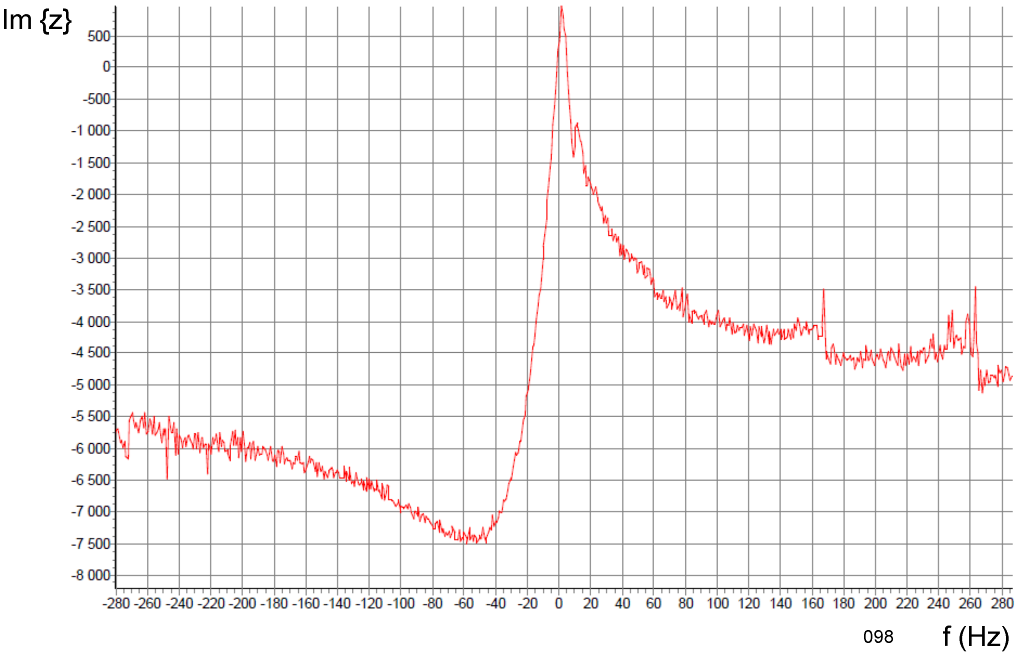

Fig 10 Imaginary Part of Transfer Function, $\omega_r = 3\pi$

The transfer function imaginary part shape for $\omega_r = 3\pi$ corresponds to theory and previous simulations.

The transformed adaptive signal for the same test is on next figure.

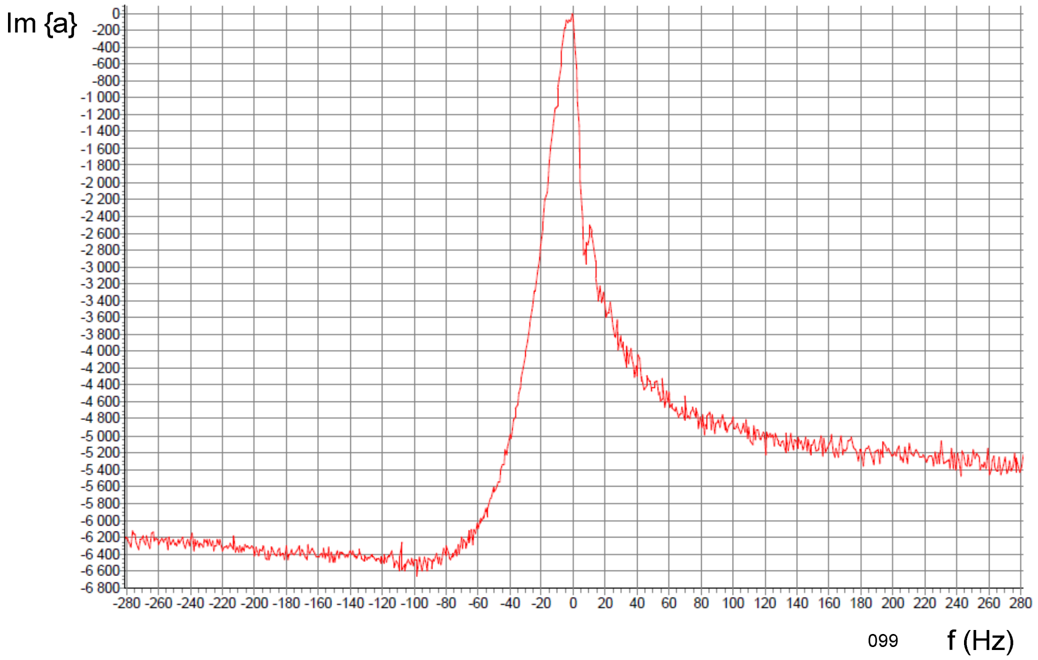

Fig 11 Imaginary Part of Transformed Adaptive Signal, $\omega_r = 3\pi$

It can be found, that transformed signal fulfils the requirements for speed adaptive signal and can be used for this purpose.

4.2 Speed Estimation Test at Real Machine

Some test scenarios were defined for examination of torque control without speed sensor.

4.2.1 Standard Acceleration Test

Normal drive start is simulated in this scenario. It simulates the situation, when the vehicle is staying and driver requires start. The nominal torque is set and speed is increasing to maximum ($\omega \approx 300 s^{-1}$).

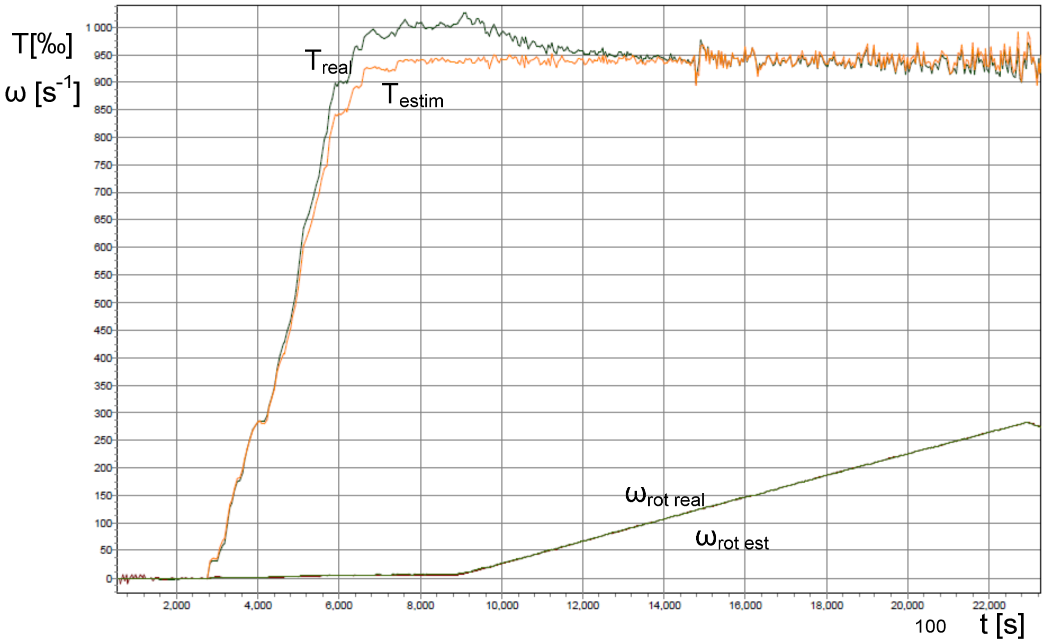

Fig 12 Acceleration Test Scenario

The worst situation is at the beginning, when the real torque is a little bit (approximately 5%) higher than the estimated one. This error is acceptable, because it is going to zero with speed rising. In real case the vehicle starts moving immediately after torque generation and the error should be quickly eliminated.

4.2.2 Whole Range of Torque

The test of torque control in the whole operating range is necessary for correct evaluation. The constant speed is set and the required torque is slowly changing between +1000‰ and -1000‰. The real and estimated torque values are checked.

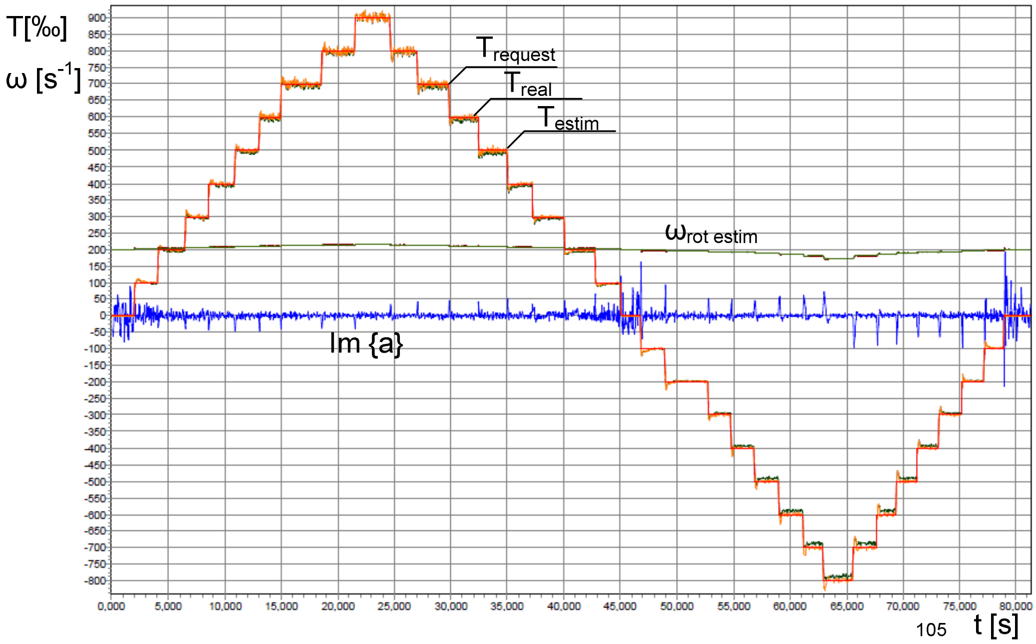

Fig 13 Whole Range of Torque

The test result is in Fig 13. It can be found that the request, real and estimated torques correspond each other. Estimated speed is correct within the whole test and adaptive signal is independent on the torque value. It changes only proportionately to real speed at torque step.

4.2.3 Very Low Speed Test

Next test shows very low speed operation. The machine generates 10% positive torque and speed is slowly changing round zero.

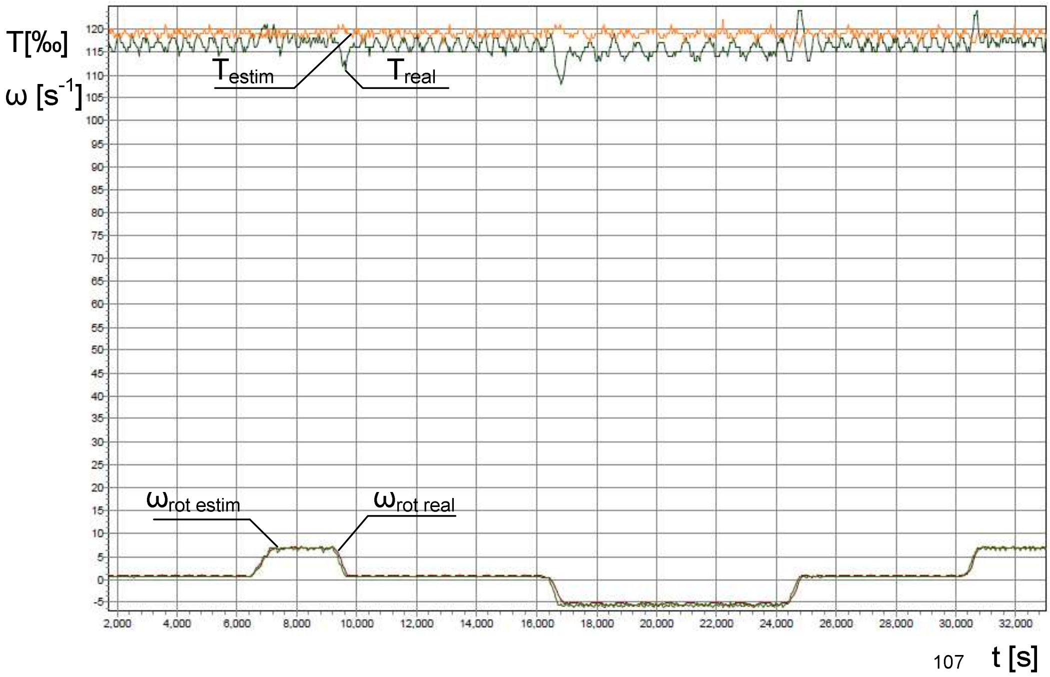

Fig 14 Zero Speed Operation

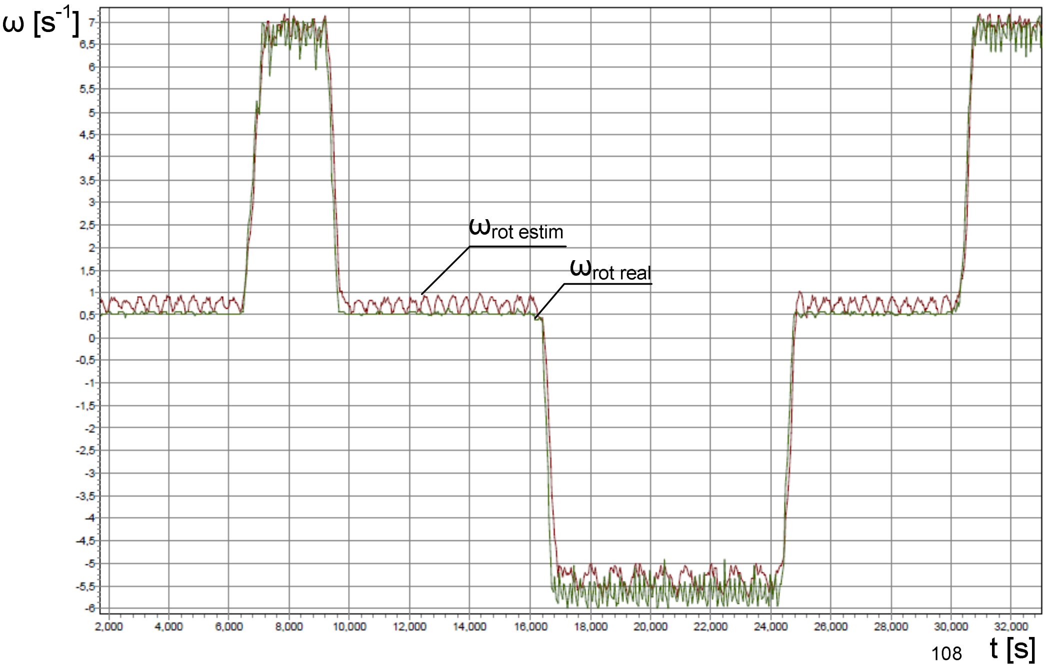

Fig 15 Zero Speed Operation (Detail)

This test proves that zero speed operation is available if the nonzero supply frequency condition is fulfilled.

5 CONCLUSION

5.1 Work Results

The aim of this work is looking for speed estimating algorithm useful for traction drive application. The MRAS method is chosen for its advantages.

The merit of the work can be found in chapter 3 of the thesis. The detail MRAS analysis is introduced. U1, n model and transfer function deductions are necessary for understanding next theory. Deductions are inspired by literature [2], [3]. The most important and original part of this work is chapter 3.2 Adaptive Signal Deduction. This part looks for feedback adaptive signal which can be useful for MRAS algorithm. The transformation of transfer function was found.

Chapter 4 brings the invented theory evaluation. The evaluation process starts with modelling of mathematically described system in MatLab Simulink [6]. The deducted equation has been programmed and their behaviour was checked at first.

Subsequently the system with two induction machines (reference, adaptive) was simulated to check that it works in the same way as deducted equations. After that the MRAS system was implemented into the model. The speed estimation was possible in the simulation.

Next step of evaluation was the implementation of all described algorithms to hardware which enables the proving of introduced theory in the real world. The hardware was shortly presented in one subchapter. The problem of equation discretization is very important for successful solution of MRAS task. That is why it was tested and detail described in one part of this work.

The implementation was tested by using a new device called C-RIO simulator [9]. It was very important moment in development of speed estimating system because it allows comfortable debugging of machine models. The development of C-RIO simulator was done by another team. But it was under way parallel with my work and cooperation was useful for both sides. The result beyond this work is fully operational system for traction drive simulations.

The validity of the theory has been proved on this system. The transfer function shape was found and checked. The transfer function transformation to adaptive signal was successfully tested. And at the end the speed estimation was prepared and checked at C-RIO system.

The last step of work evaluation was testing on real machine. The procedure was the same as in previous chapter. The main difference was in using the machine supplied by voltage inverter. The transfer function shape was saved. The adaptive signal generation was checked. The last step was testing of speed estimation. The estimation worked properly in the whole speed range in both (traction, brake) modes [10, what was the main target of this work.

5.2 Recommendation for Next Development

Next development in induction machine sensorless control should lead to practical realization of sensorless drive in some traction application. The algorithm for online machine parameter adaptation, such as temperature, is needed. Elimination of zero frequency of supply voltage needs to be examined. Improvement of inverter model would be useful. This could be matter for some other work.

6 LIST OF LITERATURE USED IN THE THESIS STATEMENT

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7.2 Works in Reviewed Magazines

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7.3 Patents

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8 RESPONSE AND REVIEWS

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9 SUMMARY

The aim of this thesis is looking for the algorithm which is able to identify the rotational speed of asynchronous machine and which can be used for traction vehicle (such as a metro).

The possible algorithms are overviewed and evaluated in the first part of the thesis. The Model Reference Adaptive System (MRAS) was chosen because it has the most important properties required for traction drive: robustness, repeatability by using on different vehicle types and self-controllability, which is required for safety reasons.

The part of work looks for feedback signal which fulfils all specified requirements. The influence of speed error to current difference between reference and adaptive model was deduced at first. This signal is called transfer function for using in the MRAS. It flows from the detailed analysis, that one part of this vector is good candidate to become an adaptive signal. But it does not fulfill all requirements in low speed area in braking mode.

The analysis of the transfer function gives the response to the question, why is it not possible to estimate the speed by zero input frequency. DC supply is not able to excite the system to generate the adaptive signal. It implies that the problem is not in zero speed but in zero supply frequency. If the control system eliminates the state of DC supply, it should be possible to identify the zero speed.

The most important part of this thesis consists in looking for the adaptive signal which does not change the polarity in different operation areas, and has the constant magnitude in the high speed operation area. The coefficient that changed the transfer function in to the suitable form was found. The feedback signal received this way corresponds to the requirements.

Next parts of the thesis concern to the confirmation of the theory. The feedback signal was analyzed by computer simulation of the drive in the first step. The whole MRAS system was implemented in the control system of power converter. It was useful to test the implementation by next simulation tool (hardware in the loop system - C-RIO) before deployment to the real power system. The main advantage of this approach is elimination of external influences caused by parameters or measurement inaccuracy.

If the theory was successfully verified on C-RIO the developed algorithms were used to identify the speed of the real machine supplied by voltage inverter.

The test results correspond to the theory and confirm its validity.

10 RÉSUMÉ

Práce se zabývá hledáním takového algoritmu identifikace otáček asynchronního stroje, který by byl použitelný pro aplikaci na trakčním vozidle.

První část práce obsahuje přehled a hodnocení algoritmů připadajících v úvahu. Jako nejvhodnější byl nakonec vybrán Model Reference Adaptive System (MRAS), a to pro svou robustnost, reprodukovatelnost při nasazování na různé typy vozidel a samokontrolovatelnost požadovanou především z důvodu bezpečnosti provozu.

Další část práce se zabývá hledáním zpětnovazebního signálu, který by splňoval všechny požadavky na něj kladené. Jako první je odvozen vliv chyby otáček na odchylku proudu mezi referenčním a adaptivním modelem. Pro účely MRAS je tento signál nazýván přenosovou funkcí. Podrobná analýza takto získaného signálu ukazuje, že jedna jeho složka vykazuje potenciál pro použití jako zpětnovazební signál. Avšak nevyhovuje všem požadavků v oblasti malých otáček při generátorickém chodu.

Z vlastností odvozeného signálu je rovněž patrné, kde vznikají obecně známé problémy identifikace velmi malých otáček – nulová frekvence statorového napětí nedokáže excitovat systém pozorovatele tak, aby generoval chybový signál. Z toho však plyne, že problém není v malých otáčkách stroje, ale v nulové napájecí frekvenci. Pokud se tedy podaří eliminovat stejnosměrné napájení, je možné identifikovat i nulové otáčky stroje.

Hlavní část práce spočívá v hledání zpětnovazebního signálu, který vyhoví jednak požadavku na neměnnou polaritu v závislosti na pracovním bodu a zároveň splní podmínku konstantní amplitudy pro velké rychlosti. Byl nalezen koeficient, kterým lze násobit přenosovou funkci tak, aby takto vzniklý adaptační signál splnil všechny požadavky.

Následující části práce popisují proces ověřování představené teorie a prostředky k tomu potřebné. V prvním kroku byl generovaný adaptační signál podroben analýze v počítačové simulaci pohonu. Následně byl celý systém MRAS implementován do systému používaného k řízení výkonových měničů. Před nasazením na skutečný asynchronní stroj se ukázalo jako velmi výhodné použít další simulační nástroj C-RIO. Jedná se v podstatě o hardware-in-the-loop (HIL) emulátor pohonu. Tedy zařízení, které snímá pulzy ze řídicího systému, modeluje jeho odezvu a řídicímu systému poskytuje vypočtené zpětnovazební signály. Hlavní výhodou tohoto přístupu je eliminace nepříznivých vlivů vznikajících například nepřesností parametrů náhradního schématu silového obvodu nebo nepřesností senzorů.

Teprve poté, co byla teorie úspěšně ověřena na C-RIO, byly vyvinuté algoritmy nasazeny na identifikaci otáček skutečného stroje napájeného z napěťového střídače. Pro testování byly použity podobné scénáře, jako na C-RIO. Výsledky testů odpovídali dříve představené teorii a potvrdily tak její platnost.