Maximum performance of the traction drives system with inverter powered induction machines

Grzegorz Skarpetowski
DIMOPEQ GmbH
Untersiggenthal, Switzerland
skarpetowski@hispeed.ch

Michele K. Krättli
DIMOPEQ GmbH
Landquart, Switzerland
kraettli@dimopeq.ch

***Abstract*—The paper discusses the problems of forming an envelope of operating points in traction drive with inverter fed induction machine. Two types of three-section envelopes differing in the way of limiting the degree of freedom of the induction machine operating point in the range of the second section of this envelope are presented. It was shown that the choice of the control method not only changes the shape of the envelope, but above all has a significant influence on the dimensioning of the traction drive elements. The results of the carried out calculations were presented in the form of a comparison of the waveforms of voltage, current, torque developed by the machine and power consumption on the stator terminals.**

Keywords—Inverter-fed induction machines, traction drives, series mechanical characteristic, modified equivalent circuit, analytical description, converter, inverter, envelope of maximum performance

I. INTRODUCTION

The expected maximum performance of a traction drive system is represented in the form of a traction characteristic on a plane with coordinates (hook force, linear speed of vehicle). This curve is a graphical representation of the requirements for the traction drive and acts as an envelope of the traction drive operating area on the mechanical power plane. These requirements are transferred to the electrical space and presented in the form of an envelope of electrical power at the traction machines terminals. This envelope has a direct influence on both the parameters of the machine and the parameters of the converter feeding it. The voltage in the DC link of the converter must be matched to the phase voltage of the induction machine and the power of the converter must be matched to the power of the induction machine and include the reserve for current harmonics. The traction characteristic is an image of the data underlying the commonly used method of dimensioning the components of a traction drive system. The method requires the conversion of traction characteristics from mechanical to the electrical space and find the data needed to meet the requirements of the traction drive. The traction characteristic is an image of the data underlying the commonly used method of dimensioning the components of a traction drive system. The method requires the conversion of traction characteristics from mechanical to the electrical space and find the data needed to meet the requirements of the traction drive.

II. DESCRIPTION OF THE PROBLEM

Another designing method of power transmission system, which is technically and economically more reasonable begins with selection of induction machine or converter from among elements and subassemblies produced in mass quantities. Suitably matched electrical parameters of the induction machine and the converter enable to find the envelope of the area of the machine operating points in the stator power space. The conversion of this envelope from the electrical space to the mechanical power plane allows presenting the performance of the drive system in the form of traction characteristics.

The quality of the conversion depends on the total losses' estimation accuracy on the power transmission channel between the stator terminals and the wheel-rail contact. The search for the envelope of the controllability region in a traction drive system fed from a converter was carried out on an example using the second design method. An induction machine with fictitious equivalent parameters, pledged below, was selected, sinusoidal voltage supply was assumed, nonlinearities and frequency dependence of the equivalent parameters were neglected. The modified equivalent circuit diagram of the induction machine, all the basic relationships and simplifying assumptions used in this paper are explained in [1], [2], [3].

$P_{1n} = 1.4$	MW	Nominal electrical power
$U_{1nm} = 2040$	V	Amplitude of phase voltage
$f_{1n} = 50$	Hz	Nominal stator frequency
$f_{2n} = 0.57$	Hz	Nominal rotor frequency
$p = 2$		Number of magnetic poles
$R_1 = 0.055$	Ω	Stator resistance
$L_1 = 0.042$	H	Stator inductance
$T_1 = 0.755$	s	Stator time constant

$T_2 = 0.943$ s Rotor time constant
$\sigma = 0.071$ Inductive leakage factor
$\omega = 2 \cdot \pi \cdot f$ Relation pulse frequency to frequency

The ratio of the complex amplitude of the phase stator voltage to the complex amplitude of the phase current, is presented according to [1], [2] in the form:

$$\mathrm{Zas}(\omega_1,\omega_2) = \frac{U_1}{I_1} = \frac{1 - \sigma\cdot\omega_1\cdot T_1\cdot\omega_2\cdot T_2 + j\cdot(\omega_1\cdot T_1 + \omega_2\cdot T_2)}{1 + j\cdot\omega_2\cdot T_2}$$

The nominal value of the stator flux linkage was calculated by introducing the nominal values of the stator voltage, stator current frequency and rotor current frequency into the formula:

$$\Psi_{1n}(\omega_1,\omega_2) = U_{1nm}\cdot T_1 \frac{1 + j\cdot\sigma\cdot\omega_2\cdot T_2}{1 - \sigma\cdot\omega_1\cdot T_1\cdot\omega_2\cdot T_2 + j\cdot(\omega_1\cdot T_1 + \omega_2\cdot T_2)}$$

The modulation depth of a three-phase inverter is described by the value of the ratio between the nominal values of the stator flux and the phase voltage and by a factor depending on the machine operating point coordinates f_1 and f_2 of the form:

$$tsdvs(\omega_1,\omega_2) = \frac{\Psi_{1nm}}{U_{1nm}\cdot T_1}\left|\frac{1 - \sigma\cdot\omega_1\cdot T_1\cdot\omega_2\cdot T_2 + j\cdot(\omega_1\cdot T_1 + \omega_2\cdot T_2)}{1 + j\cdot\sigma\cdot\omega_2\cdot T_2}\right|$$

The phase voltage, which is positioned along the real axis of the complex variable plane, for a machine with star connected stator windings, without neutral conductor, is described:

$$U_1(\omega_1,\omega_2) = U_{1nm}\cdot tsdvs(\omega_1,\omega_2) = \frac{2}{\pi}\cdot \mathrm{U_{DC}}\cdot tsdvs(\omega_1,\omega_2)$$

Using this basic data, an envelope depicting the properties of the designed drive system was searched for.

Two types of the operating point area envelope for a drive system with an induction machine have been considered. Both types of envelope consist of three segments. The segmentation is the result of a different control strategy for the operating point of the machine in electrical, magnetic and mechanical space in these segments.

III. CONSTANT CURRENT ENVELOPE

The first type of envelope with a section of phase current amplitude modulus constant value is called a constant current envelope. This type of envelope results from the desire to keep the current load on the machine and converter valves at a constant rated level over the widest possible range of vehicle speeds.

A. First section of the constant current envelope

In the first control range of the constant current envelope, the drive system operates with the rated current load $|I_{1max}|$ and with the rated value of the stator flux linkage amplitude $|\Psi_{1nen}|$. These limits of freedom of the induction machine working point are due to the desire to make the best possible use of the magnetic circuit of the machine. The working point of the machine has only one degree of freedom and moves with the change of the stator frequency along the line determined by these constraints.

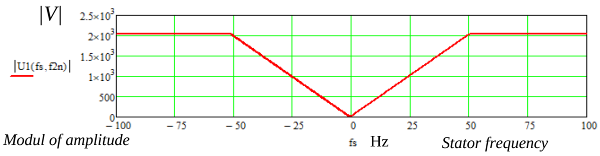

Figure 1. $|U_1| \approx f(f_1)$ Voltage-frequency characteristic curve showing the simplifications used in the converter supply of the induction machine

Each change in the stator frequency is accompanied by a corresponding change in the voltage amplitude, which takes on values that maintain the current modulus at a preset level. Keeping the stator current constant is the task of the current regulator. The observation of the value of the stator flux linkage is carried out by means of a modular or vector realization of the relationship:

$$\frac{I_1(\omega_1,\omega_2)}{\Psi_1(\omega_1,\omega_2)} = \frac{1}{L_1}\cdot\frac{1 + j\cdot\omega_2\cdot T_2}{1 + j\cdot\sigma\cdot\omega_2\cdot T_2}$$

The modular implementation of the relationship between $|I_1|$, $|\Psi_1|$ and ω_2 in the stator frequency range below the rated point is shown in Figure 2. Maintaining the rated values of the current and rotor frequency ensures that the stator flux linkage module remains still at the rated level.

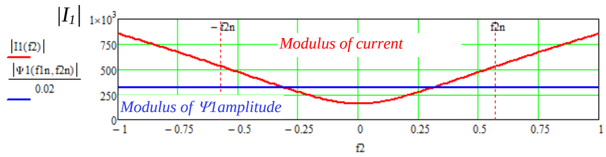

Figure 2. The ratio of the stator current amplitude modulus to the module of stator flux linkage amplitude is shown in red. In order to keep the value of the stator flux linkage constant (blue), each change in the current amplitude modulus must be accompanied by a change in the rotor frequency f_2

The first section of the operating points control area envelope ends when an increase in the stator frequency can no longer be accompanied by an increase of the machine phase voltage amplitude. As shown in Figure 3, the value of the stator frequency at which the phase voltage reaches its maximum value depends on the value of the f_2 coordinate responsible for the value of the torque produced by the machine. The envelope corresponding to the maximum performance passes through the nominal point with parameters f_{1n} and f_{2n} at the nominal value of the stator flux linkage $|\Psi_{1nen}|$. Only under these conditions the boundary of the first segment of the envelope is located exactly at the point corresponding to the rated frequency $f_{1n} = 50\,Hz$. Changing the value of f_2 induces a change in the boundary frequency of the operating point area envelope first section of the induction machine in the range $|\Psi_1| = |\Psi_{1nen}|$.

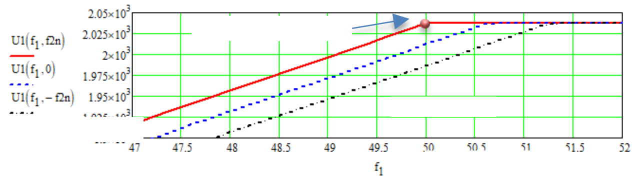

Figure 3. The end point of the first segment of the drive system operating points area envelope is placed at the rated operating point of the induction machine. The operating point of the machine has in the first segment of the envelope one degree of freedom in the space $|\Psi_1|$, f_1, f_2 and its position depends only on the frequency f_1

B. Second section of the constant current envelope

The second section of the working points envelope in the drive system with induction machine starts when the nominal operating point of the machine is reached. The converter loses the ability to further increase the phase voltage amplitude and for all higher frequencies it maintains a constant value equal to U_{1nm}. Despite this limitation, the system is able to maintain the nominal value of the phase current modulus $|I_{1nm}|$ by changing the inverter control strategy.

The analytical notation of constant machine current modulus strategy with $|I_1|$ = *const.* at constant phase voltage amplitude $|U_{1nm}|$ can be reduced to the condition imposed on the value of the ratio $|U_1|/|I_1|$ for stator frequencies higher than the rated one. The value of the modulus at frequencies higher than f_{1n} may retain its nominal value by appropriate adjustment of the rotor frequency f_2 to the stator frequency f_1.

$$|\mathrm{Zas}(\omega_1, \omega_2)| = |\mathrm{Zas}(\omega_{1n}, \omega_{2n})|$$

The solution of this equation for f_{1n} and three different rotor frequencies with $f_2 = f_{2n}$, $f_2 = -f_{2n}$ and $f_2 = 0.8{\cdot}f_{2n}$ is shown in Figure 4. Keeping the value of the ratio modulus constant with a linear increase of the stator frequency requires a non-linear adjustment of the rotor frequency. With an almost asymptotic increase of f_2 a limit of f_1 is reached, above which it is no longer possible to maintain the modulus at the preset initial value.

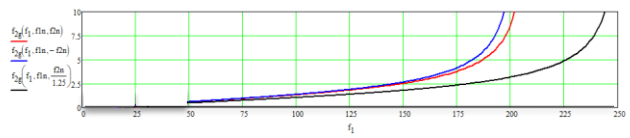

Figure 4. Adaptation of the rotor frequency to the changing value of the stator frequency in order to maintain a constant value of the $|U_1|/|I_1|$ modulus at the level determined by the initial conditions f_{2n}, $-f_{2n}$ and $0.8{\cdot}f_{2n}$. The nominal value of the modulus occurring in motoring operation can be maintained up to a frequency of $f_1>200$ Hz

However, maintaining a constant value of the current modulus only makes sense in the range of stator frequencies where an increase in the stator frequency is accompanied by an increase in the value of the torque developed by the machine. The limit of this range is the rotor frequency $f_{2u}(f_1)$ corresponding to the critical torque. Its value is represented by the formula:

$$f_{2u} = \frac{\mp 1}{2\cdot\pi\cdot T_2}\cdot\sqrt{\frac{1+(\omega_1\cdot T_1)^2}{1+(\sigma\cdot\omega_1\cdot T_1)^2}}$$

An increase in the rotor frequency above this critical value in order to maintain a constant value of the current modulus causes a decrease in the value of the torque developed by the machine. Although the controller is still able to maintain a constant current value, the drive system ceases to fulfil its purpose.

Figure 5 shows simultaneously the curve of the constant value of the $|U_1|/|I_1|$ and the curve of the critical frequency in the rotor. The point of intersection of these curves determines the value of the stator frequency which marks the end point of the second segment with $|U_1| = const$ and $|I_1| = const.$ of the investigated current envelope. Limit value of the stator frequency can also be calculated from following Eq:

$$|\mathrm{Zas}(\omega_1, \omega_{2u})| = |\mathrm{Zas}(\omega_{1n}, \omega_{2n})|$$

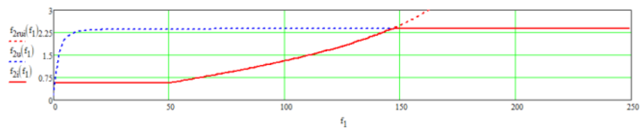

Figure 5. Curves defining the boundary of the second segment of the current envelope. The segment starts at 50 Hz and ends at the intersection of the curves at $f_1 = 146$ Hz

C. Third section of the constant current envelope

In the third section of the envelope, the rotor frequency remains below the critical value shown in blue in Figure 5. The solid red line in the figure shows the value of the rotor frequency in all three sections of the constant current envelope.

IV. DATA OF THE DRIVE SYSTEM WITH ENVELOPE OF CONSTANT CURRENT

The data of the drive system with the control algorithm leading to the formation of the constant current envelope are shown in Figure 6.

The complex amplitude of the phase current is described by the formula:

$$I_1(\omega_1, \omega_2) = \frac{U_1(\omega_1, \omega_2)}{Zas(\omega_1, \omega_2)}$$

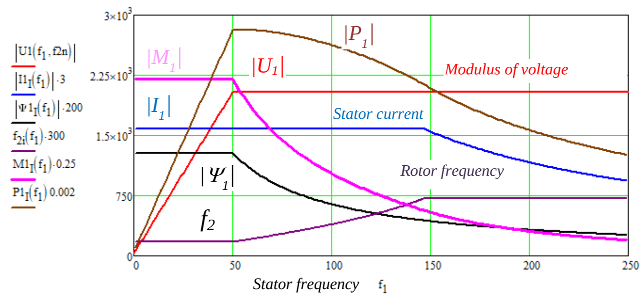

Figure 6. The drive system operating points envelope with an extended range of the constant amplitude of stator current on the mixed mechanical-electrical plane (M_1 - torque on the machine shaft and f_1 - stator frequency) is shown in pink. The figure also shows the modulus of phase voltage amplitude (red), the machine current modulus

(blue), the stator flux linkage modulus (black), the rotor current frequency (purple) and the active power at the stator terminals (brown) as a function of stator frequency. The envelope $M_{1i}(f_1)$ becomes the traction characteristic only after conversion to the plane *(F, v)*

The value of the current is determined by the phase voltage, the frequencies of the stator f_1 and rotor f_2 currents and the parameters R_1, T_1, T_2 and σ. After introducing into current equation, the values of f_1 and $f_{2i}(f_1)$ shown in Figure 5, the results presented in Figure 7 were obtained.

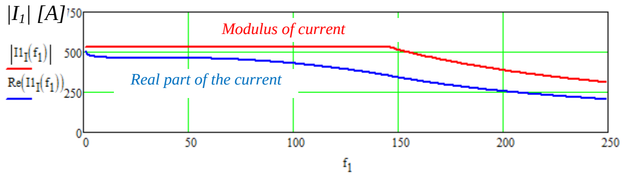

Figure 7. Modulus and the active part of the stator current realized by control method resulting in extended range of constant modulus of stator current

V. CONSTANT POWER ENVELOPE

The second type of the envelope has been named the constant power envelope.

D. First section of the constant power envelope

The first section of the constant power envelope is equal to the first section of the constant current envelope. The same method of controlling induction machine operating point is used.

E. Second segment of the constant power envelope

The difference causing the distinction between the two types of envelope occurs in the second section. The control algorithm used in the second section of the envelope maintains the rated active power at the terminals of the induction machine in the range of constant modulus of phase voltage, over the widest possible range of vehicle speed. The condition for maintaining the constant value of active power is presented in the form of relationships between machine operating points parameters:

$$\mathrm{FI}_{\mathrm{REas}}(\omega_1,\omega_2)=\frac{(1-\sigma\cdot\omega_1\cdot T_1\cdot\omega_2\cdot T_2)^2+(\omega_1\cdot T_1+\omega_2\cdot T_2)^2}{(1+(1-\sigma)\cdot\omega_1\cdot T_1\cdot\omega_2\cdot T_2+\omega_2\cdot T_2)^2}=const.$$

This relation allows to find the necessary dependence of the value of rotor frequency f_2 on the stator frequency f_1 in order to maintain the active power consumption at the constant nominal level.

$$\mathrm{FI}_{\mathrm{REas}}(\omega_1,\omega_2)=\mathrm{FI}_{\mathrm{REas}}(\omega_{1n},\omega_{2n})$$

This equation has solutions only in the range of rotor frequencies lower than the critical frequency, which means that the range of constant power always ends when the rotor frequency reaches the critical value.

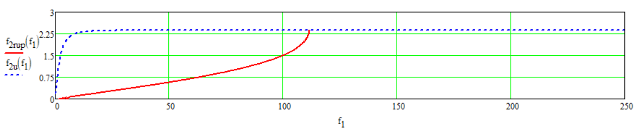

Figure 8. The figure shows the dependence of the rotor frequency on the stator frequency in the control range with a constant value of the phase voltage and a constant value of the active power at the stator terminals of an induction machine. The frequency in rotor of the machine with the equivalent data given in the introduction reaches the critical value already at the stator frequency of $f_1 = 111$ Hz

F. Third segment of the constant power envelope

The third segment of the constant power envelope is similar to the third segment of the constant current envelope but it starts already at $f_1 = 111$ Hz.

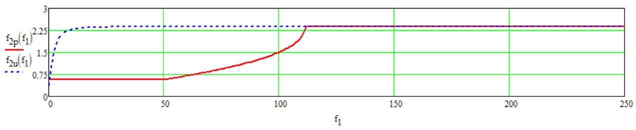

Figure 9. Frequency of current in rotor along the constant power envelope

VI. DATA OF DRIVE SYSTEM WITH ENVELOPE OF CONSTANT POWER

The data of the drive system with control leading to the formation of the constant power envelope are shown in Figure 11.

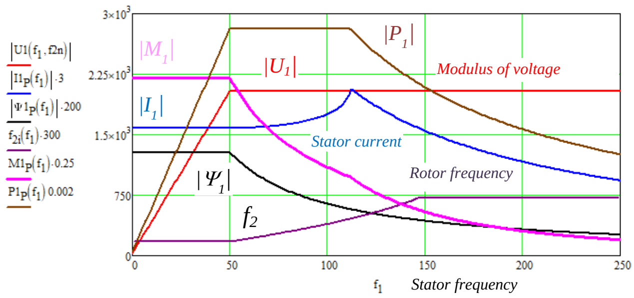

Figure 10. The envelope of the area of the drive system operating points with a section of constant active power on the mixed mechanical-electrical plane (M_{1P} - torque and f_1 - stator frequency) is shown in pink. The figure also shows the phase voltage amplitude modulus (red), the machine current modulus (blue), the stator flux linkage modulus (black), the rotor current frequency (purple) and the active power at the stator terminals as a function of stator frequency. The envelope $M_{1P}(f1)$ can be converted in traction characteristic in the plane *(F, V)*

Figure 11 shows the modulus and active component of the stator phase current along the constant power envelope.

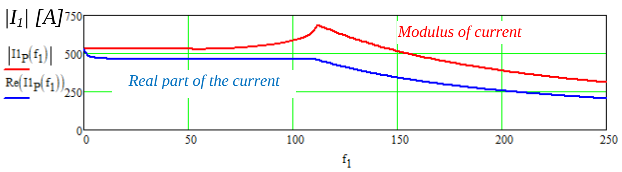

Figure 11. Modulus and active component of the machine current along envelope with constant power segment

VII. COMPARISON OF ENVELOPES

The influence of the drive system control method on the envelope of the working point area of the induction machine and the effect on the active power curves at the stator terminals is shown in Figure 12.

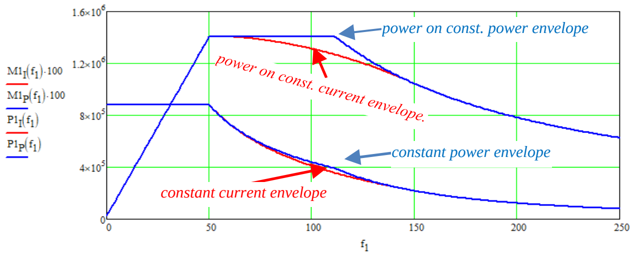

Figure 12. Comparison of power curves and envelopes of induction machines operating point areas under two traction drive control systems

Figure 13 shows the curve of the current drawn by the machine when controlling with a constant amplitude module of the stator current (red) and the curve of the current drawn by the same machine when implementing the algorithm producing a constant power range (blue) at the machine stator terminals.

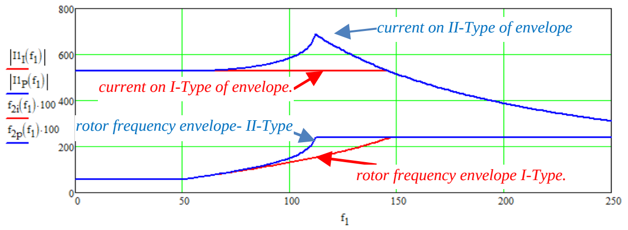

Figure 13. Influence of the traction drive control method on the value of the stator current amplitude modulus and on the value of the rotor current frequency in the whole range of stator frequencies. Control with constant power at the stator terminals of the machine causes a significant increase in the current when the machine operating point approaches the critical moment. The control with constant current does not cause an increase in the load on the converter valves.

The comparison was carried out using the same equivalent parameters of the induction machine, given in the paper, in both cases. In order to shorten and improve the clarity of the analytical description, constant values of the equivalent parameters of the machine were used in the whole range of the stator frequency. Design calculations should be carried out taking into account changes in the equivalent machine parameters $R_1(f_1)$, $T_1(f_1)$, $T_2(f_1)$, and $\sigma(f_1)$ as the stator frequency changes.

VIII. MODIFICATION OF THE ENVELOPE IN THE FIRST FREQUENCY RANGE

Fulfilment of the constant power condition in the traction characteristic causes unbeneficial current loading of the machine and the converter.

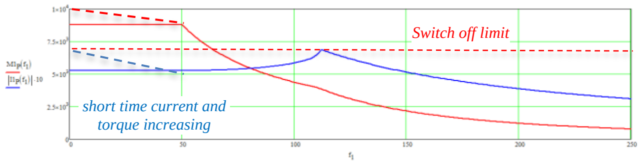

Figure 14. The use of converter current reserve and induction machine thermal reserve to increase torque values in the low stator frequencies range

Due to the significant increase of the current above the rated value, the designers are forced to increase the power of the converter and to adjust the cooling system accordingly, so that the point of the critical torque becomes point of continuous operation.

IX. CONCLUSIONS

The modelling carried out showed that when selecting the type of traction characteristics, the influence of the second section of the drive operating points area envelope on the economic and technical aspects of the design should be carefully considered. An increase in the price of the drive system due to an increase in the load on the converter valves should be compensated for by a corresponding increase in the power and torque developed by the machine.

REFERENCES

[1] Skarpetowski, G. 2017 Realisation of the mechanical characteristic of a series excited DC machine in the drive with converter – fed induction machine, MET 2017

[2] Skarpetowski, G.; Krättli, A., 2020, Modification of analytical description of the converter-fed induction machines, JMEST, Volume 7, Issue.3, March 2020

[3] Skarpetowski, G.; Krättli, M,K., 2021, Overview of control methods for inverter powered induction machines, JMEST,Volume 8 Issue 5 May 2021

[4] Skarpetowski, G., 1994, Method of Controlling Electric Vales of a converter, US Patent Nr. 5,331,537

[5] Skarpetowski, G., 2016, Przetworniki i Przekształtniki Energii, Część 1. Przetworniki ISBN 978-83-86219-86-5

[6] Skarpetowski, G., 2019, Przetworniki i Przekształtniki Energii, Część 2. Przekształtniki ISBN 978-83-956872-0-4