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Overview Of Control Methods For 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 control method of the induction machines which allow the operation of the drive's working point along the series characteristic and the place of the series method between currently used control methods implemented in adhesion traction drives is presented. In this type of the drive system are defined extremely high requirements derived from demands on the utilization of the friction between wheel and rail. The experience and knowledge gained in the last years shows that the properties of widely used "shunt" control methods are only in limited extend suitable for adhesion traction drives and called a "nice weather" method. More suitable for this type of drive is control method that forces the induction machine to work along a series characteristic curve that is known from direct current drives.**

Keywords—Inverter–fed induction machines, traction drives, series mechanical characteristic, modified equivalent circuit, analytical description, converter, inverter

I. Introduction

To ensure clarity in the nomenclature, the difference in analytical description and graphical representation of converter and inverter is repeated and shown in figure 1 and 2. This essential difference means that both processes are named differently in this article. A device that changes the form of energy is called converter. A device that changes only values of the power coordinates, without changing the form of energy, is called inverter.

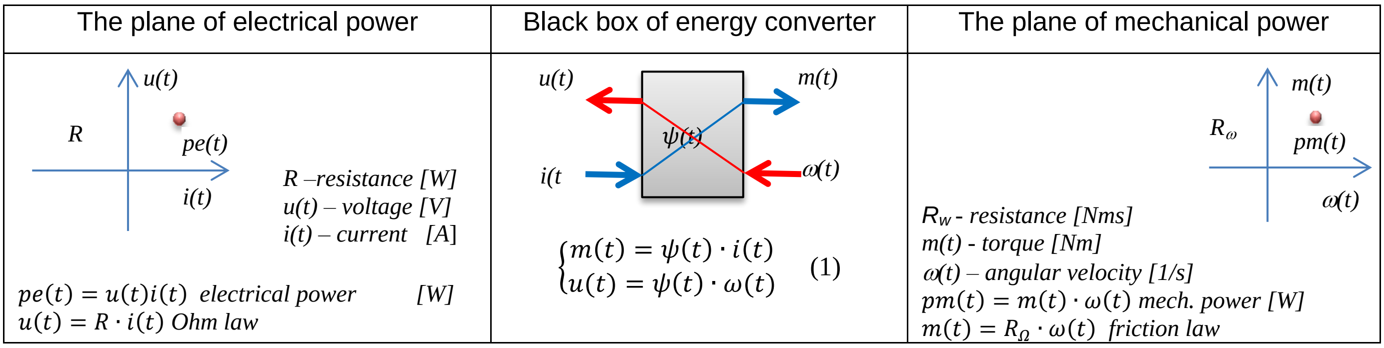

Figure 1. Illustration and analytical description of energy converter. On the left side of the converter black box, the electrical power plane is shown. On the right side of the converter black box, the mechanical power plane is shown. In the converter black box, the energy form is changed. The change of the energy form in DC machines is described by equation system (1). The conversion is represented by crossing of the symbolic transmission lines in the box. Both "speed coordinates" of the power planes (current *i(t)*, angular velocity *ω(t)*) becomes "force coordinates" (torque *m(t)*, voltage *u(t)*) by multiplying with the black box's contents. Current and angular velocity are input values while torque and voltage are outputs values of the box representing energy converter

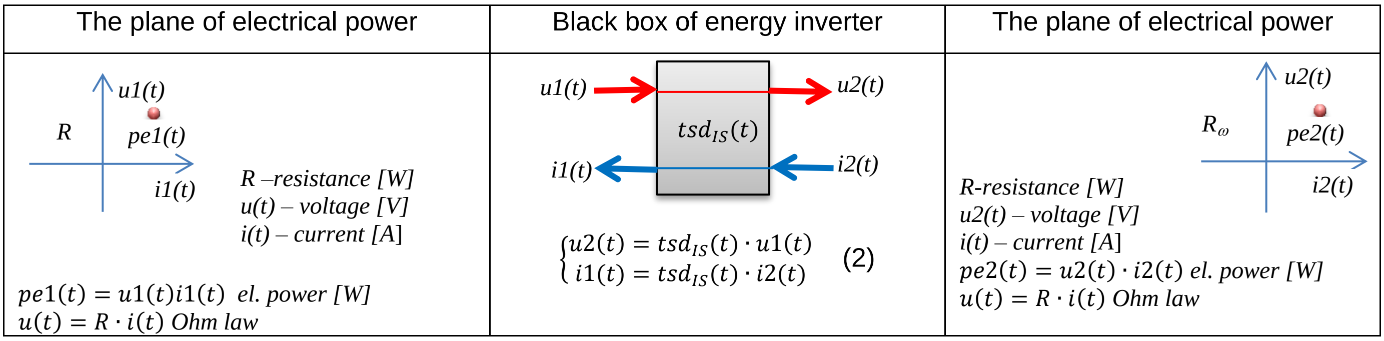

Figure 2. Illustration and analytical description of energy inverter. On the left side of the inverter black box, the electrical power plane is shown. On the right side of the inverter black box, again the electrical power plane is shown. In the black box of the inverter only the value of power coordinates is changed. The change of the power coordinates in chopper is described by equation system (2). The inversion is represented by direct transmission lines in the box. Input "force coordinate" (voltage *u1(t)*) by multiplying with the contents of the box becomes output "force coordinate" again (voltage *u2(t)*). Output "speed coordinate" (current *i2(t)*) by multiplying with the contents of the box becomes "speed coordinate" again (current *i1(t)*). There is no change in the form of energy. The basic example of energy inverter is the transformer. The transformation changes only the value of voltage and current. In the box the transformer ratio is located.

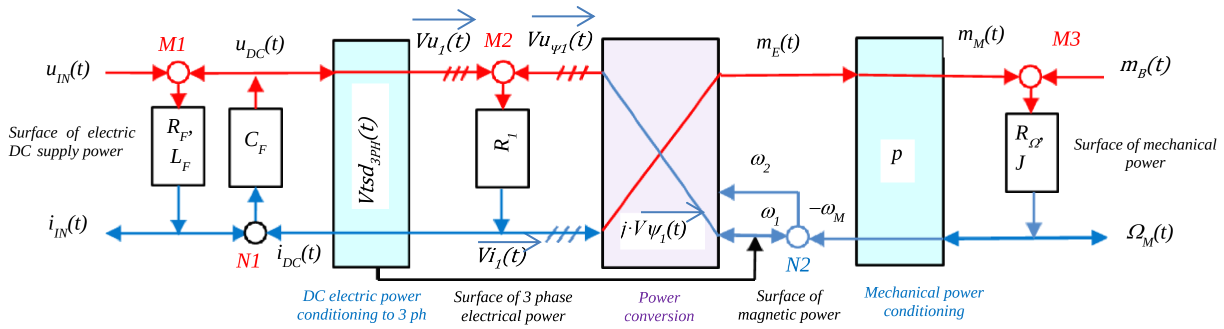

Figure 3. Block diagram of drive system with inverter-fed induction machine. Depending on implemented operating point control method, different machine characteristic can be achieved. Although only the stator voltage can be recognised as a control variable, the operating point of the machine can be controlled in different ways using measured, observed or simulated internal or external variables of the machine. External variables on the electrical side are voltage Vu1(t) and current Vi1(t), on the mechanical side torque $m_M(t)$ and angular velocity $\Omega_M(t)$ and from the internal variables $V_{\Psi1}(t)$ and $V_{\Psi2}(t)$ are often used.

II. WORKING POINT DEGREES OF FREEDOM

The degree of freedom of the induction machine's working point depends on the supply method. The operating point can be presented in several 3-dimensional spaces depending on control method used. It can be tracked in the stator electric power space, in the stator or rotor magnetic circuit or on the rotor shaft, i.e. in the plane of the mechanical power. The control method name is given by the space in which the operation point is tracked. Regardless of the name of the control method used, the direct influence on the position of the induction machine's operating point in all 3-dimentional spaces is exerted only by the voltage applied to the terminals of the stator i.e. the amplitude, frequency and phase shifting of its fundamental harmonic. The operating point of the machine can have a maximum of 3 degrees of freedom in space as shown in Figure 4.

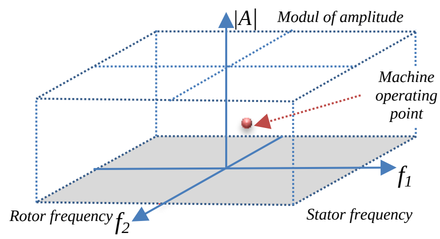

Figure 4. Space with 3 degree of freedom. The amplitude of |A| and both frequencies f_1 and f_2 can vary independently of each other

III. SUPPLY FROM INDUSTRIAL NETWORK

The classical supply method using power from industrial network introduces two restrictions in the degree of freedom of induction machine's operating point in electrical space. The amplitude and the frequency of the stator voltage are kept constant. The value of the rotor frequency is resulting from the applied shaft load . In this type of supply the operating point of the machine is not controllable.

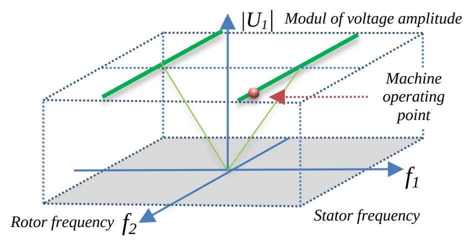

Figure 5. Trajectory of the induction machine's operating point by the supply from an industrial network. Its position is determined in electric space by constant value of stator voltage and frequency and in the mechanical space by the value of load. All the limitations of freedom mean that the machine works only along a single mechanical characteristic and the position of the operating point is determined by mechanical load

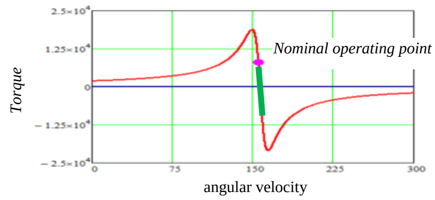

Figure 6. By the supply from industrially network the position of induction machine's operating point can move along single mechanical characteristic of induction machine. The operating point depends on the machine shaft's load. Only operating states in the green section of the characteristic are considered. Due to the comparison with the inverter supply of the induction machine, the transients are not considered.

IV. INVERTER SUPPLY

Supplying an induction machine from 3-phase voltage sourced inverter gives new possibilities of shaping the trajectory of the machine's operating point in the 3-dimensional space and allows almost any shaping of mechanical characteristic's course.

A. Control method using the properties of the space with the amplitude of the stator voltage as coordinate.

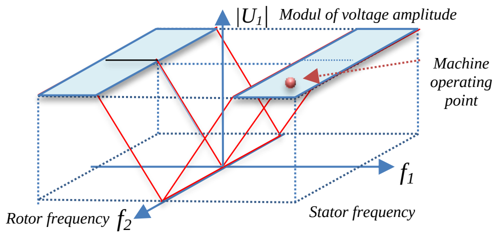

Figure 7. In the $|U_1|$=const. control method the operating point of the machine has two degrees of freedom (f_1 and f_2) and can move along the planes determined by nominal value of stator voltage in the range lying above the rated stator frequency

Average value of the mechanical power with $|U_1|$=const is described by parametric system of equation:

$$\begin{cases} M_{U1} = \frac{3}{2} \cdot p \cdot (1-\sigma) \cdot L_1 \cdot \frac{|U_1|^2}{{R_1}^2} \cdot \frac{\omega_2 \cdot T_2}{(1-\sigma \cdot \omega_1 \cdot T_1 \cdot \omega_2 \cdot T_2)^2 + (\omega_1 \cdot T_1 + \omega_2 \cdot T_2)^2} \\ \Omega_M = \frac{\omega_1 - \omega_2}{p} \end{cases}$$

B. Control method using the properties of the space with the amplitude of the stator current as coordinate.

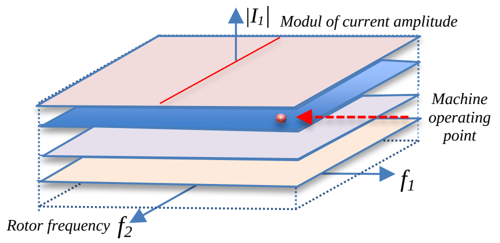

Figure 8. In the $|I_1|$=const. control method the operating point of the machine has two degrees of freedom and can move along the plane for almost all stator frequencies. The method allows the change of the current amplitude in full frequency range. The possibility of current change is demonstrated by any planes of constant value of current

Average value of the mechanical power with $|I1|$=const is described by parametric system of equation:

$$\begin{cases} M_{I1} = \frac{3}{2} \cdot p \cdot (1-\sigma) \cdot L_1 \cdot |I_1|^2 \cdot \frac{\omega_2 \cdot T_2}{1+\omega_2^2 \cdot T_2^2} \\ \Omega_M = \frac{\omega_1 - \omega_2}{p} \end{cases}$$

C. Control method using the properties of the space with the amplitude of the stator winding associated flux as coordinate

In the $|\Psi_1|$=const. control method the operating point of the machine has two degrees of freedom and can move along the planes determined by nominal value of stator flux in the range lying below the rated stator frequency.

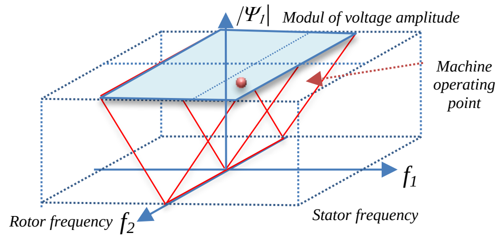

Figure 9. The plane of constant rated value of stator flux linkage introduces limitation on the freedom of the value of stator voltage amplitude making it dependent on the stator and rotor frequencies

Average value of the mechanical power with $|\Psi1|$=const is described by parametric system of equation:

$$\begin{cases} M_{\Psi1} = \frac{3}{2} \cdot p \cdot (1-\sigma) \cdot \frac{|\Psi_1|^2}{L_1} \cdot \frac{\omega_2 \cdot T_2}{1+\sigma^2 \cdot \omega_2^2 \cdot T_2^2} \\ \Omega_M = \frac{\omega_1 - \omega_2}{p} \end{cases}$$

(IV.1)

D. Control method using the properties of the space with the amplitude of the rotor flux as coordinate

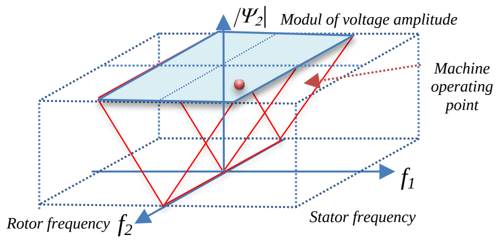

Figure 10. Rotor flux as a coordinate of the machine operating point with constant value of the flux amplitude. The control method is similar to the stator flux method, but the tracking of the operation point in that space is difficult

Average value of the mechanical power with $|\Psi2|$=const. is described by parametric system of equation:

$$\begin{cases} M_{\Psi2} = \frac{3}{2} \cdot p \cdot (1-\sigma) \cdot |\Psi_2|^2 \cdot \frac{\omega_2}{R_2} \\ \Omega_M = \frac{\omega_1 - \omega_2}{p} \end{cases}$$

(IV.2)

V. THE METHOD USED IN TRACTION DRIVES

Currently two control methods are used in traction drives. In the stator frequency range below the nominal machine frequency, the $|\Psi1|$ = const control method is applied.

The examples of the characteristics in the range of constant stator flux are presented on Figure 11. Such characteristics are called shunt characteristic. In the presented stator frequency range only $|\Psi_1|$ is kept constant. Stator and rotor frequencies are free and can be changed in any way. The stator frequency sets the idle speed value and plays a role similar to a gear box in a car. The rotor frequency sets the torque value and plays a role similar to the accelerator pedal in a car.

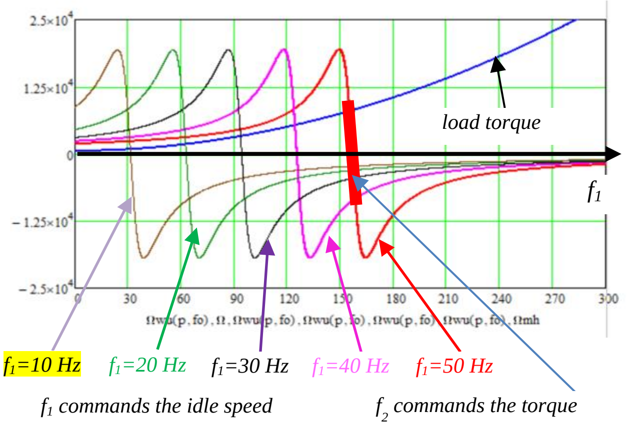

Figure 11. Characteristics of the inverter powered induction machine in the range below the nominal frequency.

Above the nominal frequency, the control method of constant stator voltage amplitude is used. In this range of stator frequency, the magnetic flux is weakened and the characteristics decrease their stiffness and have lower maximum torque values.

VI. CONTROL BY SERIES CHARACTERISTIC

Series characteristic in the inverter powered induction machine can be realised only with control method allowing completely free change of the value of all coordinates of the machine's operating point. The stator voltage amplitude, stator current, stator flux, stator and rotor frequency must be completely free and controllable. Obviously, these quantities cannot be controlled at the same time because they are related to each other by the immittance of the machine. Two of them must be used simultaneously to limit the degree of freedom of the machine's operating point. The controllability of the stator voltage amplitude is shown in Figure 12. The classical relation between voltage and stator frequency assuring the constant stator flux range is essentially changed. The most important change is the possibility to start the field weakening at any stator frequency even below its nominal value. An immediate transition to field weakening can be seen as the best reaction of the drive in case of unexpected dynamic states such as slip and slide.

A. Stator voltage amplitude, controled independently on stator frequency as the coordinate of operating point.

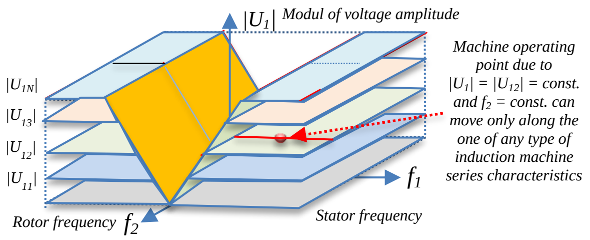

Figure 12. The amplitude of the stator voltage can be controlled independently of stator and rotor frequency. In this control space, two different limitations known as control method can simultaneously be applied. The limitation of the stator voltage |U1| = const. and limitation of the rotor frequency f2 = const. leaves the machine operating point only one degree of freedom and forces it to move with the changing stator frequency along a curve corresponding to the serial characteristic.

In case of slip and slide, the immediate change of mechanical characteristic from the shunt to series can avoid a loss of tractive force or prevent braking. The independent voltage control is necessary because all types of series characteristic can be created only in the range of field weakening.

The controllability of the stator current is discussed in Figure 8. Proper simultaneously mixing of the control principles $|U_1|$=const., $|I_1|$=const., $|\Psi_1|$=const., f_2 = const. f_2 = var. or critical value f_{2K} allow realisation of any types of series characteristic as shown in the Figure 14.

B. Modification of the control space for application using series characteristic.

In place of f_2 as the coordinate of the operating point, the stator current module |I1| is introduced and becomes a controlled quantity. Such modification recognizes quickly the beginning of the dynamic state that requires a change in the trajectory of the machine operating point. The slip and slide in motoring state causes immediately reduction of the stator current. Current regulator stops the increase of stator voltage with the stator frequency and try to maintain the original value of the machine current. This can be done by constant value of voltage by increasing of the stator frequency. The machine's torque decreases with increasing stator frequency. The machine's working point follows a series characteristic which doesn't know an idle speed value and cannot enter in the braking range in case of slip and slide.

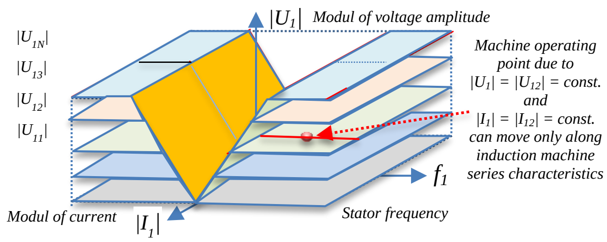

Figure 13. Replacing of the f2 coordinate of induction machine operating point by the stator current module. The operating point is now positioned in place determined by coordinates $|U_1|$=const., $|I_1|$=const., and value of f1. The trajectory of this point is similar to the series characteristic of direct current machine.

The series characteristic in an inverter-fed induction machine can be shaped in any way, by changing of f2 at Fig 12 or I1 at Figure 13. Example of characteristic are presented at Figure 14.

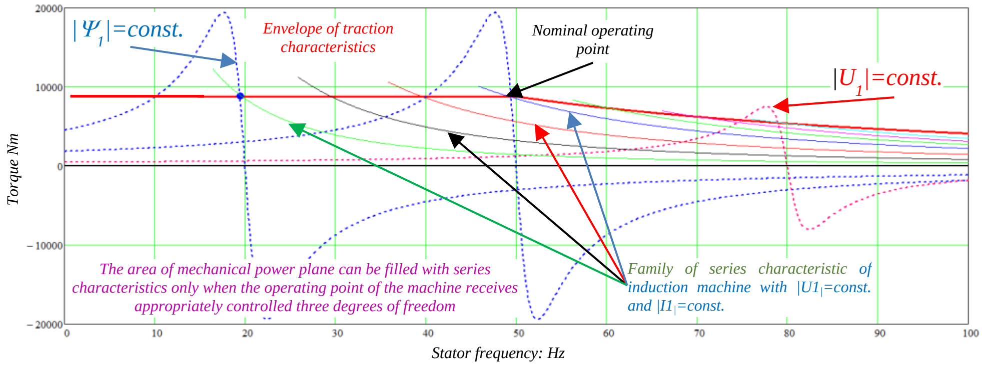

Figure 14. The area of operation of a traction drive on the mechanical power plane with the presentation of the filling this area with examples of series characteristics

References

[1] Dreszer, J., 1975 Mathematik Handbuch für Technik und Naturwissenschaft, Harri Deutsch Verlag, Thun

[2] Seely, S., 1962, Electromechanical Energy Conversion, MCGRAV-HILL BC 1962 NEW YORK

[3] Skarpetowski, G.; 1974, Przekładnia prądu przemiennego do lokomotyw spalinowo-elektrycznych, PW

[4] Skarpetowski, G., 1997, Uogólniona teoria przekształtników statycznych, ISSN 0137-2319 WPW 1997

[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

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

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

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