Proceedings of the International Conference on
Information Technologies (InfoTech-2018)
20-21 September 2018, Bulgaria

CONTROLLING INDUCTION MOTORS

Goran Rafajlovski, Mihail Digalovski,

University St. "Cyril and Methodius", Skopje
Faculty of Electrical Engineering and Information Technologies
goran@feit.ukim.edu.mk,
Republic of Macedonia

Abstract: This year is anniversary of 130 years induction motor (IM) invention. Today IM is the dominant motor on the market. This study attempts to give a review of the historical development of induction motor control systems, present condition as well as the future trends in the development of vector-controlled induction motors (IM) drives. The discussion focuses around various scalar systems and their characteristics, the developing stages of individual constitutive parts of the control system, as well as the domain of their application. The procedure of space vector modulation has been briefly described and its peculiarities and advantages have been discussed with regard to the classical modulation techniques. There has been given principled classification of the vector systems for controlling induction motors. By comparing the basic functional block diagrams of the direct schemes for vector control, the indirect schemes as well as the systems for direct vector control of the torque and the flux, emphasis has been put on the basic peculiarities and performances of individual systems and their application domains
Key words: induction motor, controlling scalar systems, vector systems, simulation,

1. INTRODUCTION

The induction motor (IM) compared to direct current (DC) motor, is superior in terms of largeness/power coefficient, rotor inertia, maximal possible speed, efficiency, compactness, simplicity, reliability and price [16], [26]. Up until 1972, mainly due to the non-linear highly interactive and multivariable control-dynamic structure, induction motors have been practically unfit to replace direct current motors in drives with high speed and torque control requirements. The principles of vector control were presented in 1972 in the works of Hasse [16] and Blaschke [2], [3], while the first experimental experiences have been acquired at the Darmstadt and Braunschweig Technical Universities and at the Siemens AG laboratories.

In DC motors, the reaction of the induct and excited flux has shifted by 90° el. This orthogonality between the axes of the excitation flux and the reaction of the induct does not depend on the rotor's rotation speed, whereas the developed electromagnetic torque of the motor is proportional to the product of the flux and the armature current. If a negligible small saturation is assumed, the flux is proportional to the excitation current and cannot be changed under the impact of the armature current due to the orthogonal setting of the rotor and stator field. So, in a direct current motor with independent excitation and constant excited flux, the developed electromagnetic torque is directly proportional to the armature current [2].

In induction motors, the space angle between the stator's and the rotor's flux changes with the load, causing more complex relations between the currents, the fluxes and the voltages in the machine, as well as the phenomenon of oscillatory dynamic responses. The control of this space angle could ideally be implemented by decoupling the input stator's current to d-component, responsible for the excitation flux, and q-component responsible for the developed electromagnetic torque. This can be achieved through the method of vector control enabling relatively simple solution to the problem of "coupling" between the d- and q- axes and approximating the dynamic model of the induction motor towards the model of direct current motor with independent excitation [1], [2], [3]. Furthermore, recently there have been developed more sophisticated digital dynamic models of induction motor [18], [21], [26], [29] in order to achieve certain improvements in the induction motor vector control systems.

In the last several years, a large number of studies have investigated the methods of pulse-width modulation (PWM) of the voltage invertor: sinusoidal PWM, improved sinusoidal PWM and space vector modulation [10], [11], [14], their mutual comparison and evaluation by the help of FFT, simulation and mathematical analysis etc. Some advantages of space vector modulation [26] have been emphasized, and at the same time, attempts have been made to discover uniform criteria for evaluation of space vector modulation and the classical PWM techniques. Also, intensive researches have been carried out on the influence of the so-called "blocked time" of the valves on the distortion of the space vector of the stator voltage [26], [31].

The methods for controlling the induction motor vector control systems are taking key position in many works in this area. In order to optimize the control structure, the impact of the varying parameters of the induction motor on the control quality is investigated, and new methods for adaptive control are proposed [14].. Recently, an interesting variation of the direct vector control has appeared; the so-called sliding mode control. The proposed system has a cascading structure and the controller in the sliding mode is easily adapted to various requirements of servo applications. Direct vector control [8], [10], [24], [26] shows certain advantages over the indirect vector control, above all, in simplifying the control structure. In particular, the control concepts based on the space vector of the stator flux find ever greater application in servo applications. With direct vector control of the torque and the flux [8], [9], [10], it appears that a new chapter opens up in vector control of induction motors. Here, crucial role is played by the contributions to predictive control of the torque and the trajectory of the stator flux's space vector, using only the speed as feedback information [29].

With this survey the authors intend to give a practical overview of a different control techniques for IM and assist the engineers in praxis to understand better the application performances of different variable speed drives (VSD). With an appropriate elected drive system and control technique the energy saving and efficiency of the whole control system could be improved significantly.

2. INDUCTION MOTORS CONTROL SYSTEMS

As beginnings of the more sophisticated systems for controlling induction motors (U/f systems, vector systems) are regarded the Ward-Leonhard's EMP and the so-called Kramer's EMP. Up until 1970, the controlled electromotive drives with direct current motors are predominant and represent standard industry drives. This especially refers to drives with high performances regarding controlling more variables such as speed, torque, position, acceleration etc. Typical of such applications requiring high performances of the drive is to provide: control accuracy sustenance at high speeds better than 0.5%, speed control in an 20:1 range, fast response in transient mode (for example, faster than 50rad/s for the speed control cycle) etc. Only until recently have these applications been an exceptional part of the domain of the controlled direct current drives. However, by choosing appropriate control (U/f control, vector control), with the fast development of the power semi-conducting components, and with the development of hybrid digital signal processing systems, the application of the controlled AC electromotive drives in the last decade marks a revolutionary growth. With their mass application it's been evaluated that around 10% of the generated energy can be saved. The IM control systems could be divided globally into scalar and vector control systems. The scalar control systems still find their application in general-purpose drives (circa 90%), and can be one-engined or multi-engined. Higher-capacity power drives as well as special-purpose drives usually use vector control systems. Recently, vector control systems, especially the so-called direct torque control systems, increasingly find their application in electrical traction drives.

Regarding the implementation of control cycles in the control systems, analog technology slowly but surely gives way to digital technology or the microprocessor-based control systems. Also, inevitable is the accelerated growth of application of various adaptive methods such as the variable structure systems (VSS), the self-tuning systems (STS), models of robust control, models of reference adaptive control (MRAC), and lately, and especially in the USA, Germany and Japan, expert fuzzy logic-based systems, genetic algorithms and artificial neural networks (ANN) have been intensely developed and applied.

2.1 Scalar systems: Voltage control, U/f control, PWM

The scalar IM control systems, globally, are divided into voltage-controlled IM, voltage and frequency-controlled IMs – U/f control, and PWM-controlled induction motors.

IM speed control, although accompanied with increased losses by changing the stator voltage, is attractive due to its relatively simple elements in the automated control system and its simple application in wounded rotor IMs and squirrel-cage IMs. The increased losses constrain the application of this solution to low powers, circa 250kW. Nevertheless, in this power domain, the IM drive is cheaper than the DC drive and is applied in ventilator drives, lifts, transport drives etc. To decrease losses, the so-called sub-synchronized cascade or lossless voltage control, so-called Kramer's EMD is used (Fig 1.). In the rotor's circle is embedded a converter consisting of a rectifier, damping inductance and line side controlled converter, through which the slipping power goes back in the three-phase network. The damping inductance provides continuous current, and the transformer is used to adapt the damping inductance's voltage towards the rectified voltage of the rotor. In stationary mode, these two voltages are in balance. Although this drive does not permit reversing and braking, however, since it gives constant torque in the whole speed control range (50% to 100% of the synchronous speed is recommended), it is economically and technically the most suitable for application in drives with sub-synchronized cascade (pumps, ventilators, compressors) to approximately 20MW. The dynamic characteristics of the sub-synchronized cascade are satisfactory in drives with low requirements with regard to dynamics, especially at synchronous speeds.

For controlling IM with variable voltage and frequency of the stator winding various power converters (cycle-converters, direct and indirect frequency converters) have been developed.

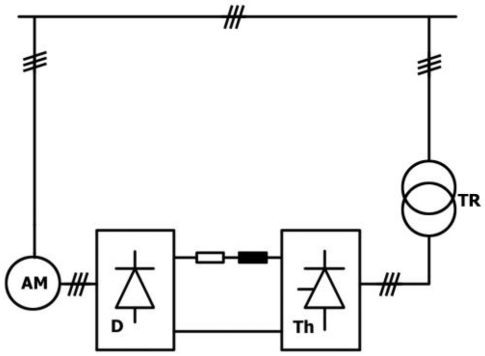
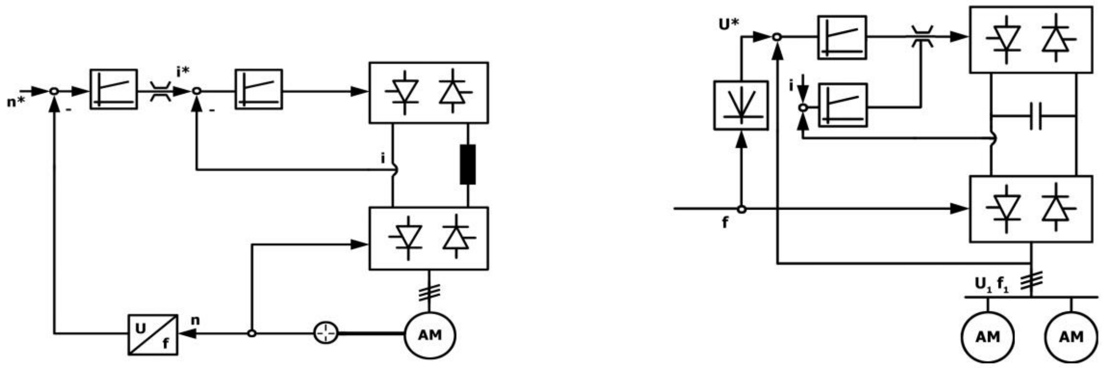


Figure 1. Principled scheme of the so-called Kramer's EMD

The cycloconverter has a simple structure composed of three line side-controlled reversible converters in anti-parallel relation without cycling currents. The controlling signals are always phase-shifted among themselves by 120 °el in order to achieve symmetric three-phase voltage at the output terminals, with 45% upper limit frequency of the powering frequency (20Hz is achieved for a network frequency of

50Hz). In particular cases, if the cycloconverter is powered by aggregates, it is possible to achieve output frequency of 400Hz. The cycloconverters are especially applicable in charging low-speed alternating high-power motors. Also, cycloconverters are applied in feeding squirrel cage IMs with multiple windings for cargo vehicles, because they ensure small pulsations in the torque (due to the approximately sinusoidal output shapes of the voltage and the current) and a wide range of speed control with minimal losses at low speed to zero.



Current source inverter *Voltage source inverter*

Figure 2. Indirect frequency converters

Indirect frequency converters on the network side have a controlled rectifier, while on the driving motor's side a controlled inverter, with its own control; while depending on the type of the DC circle they are divided into voltage source inverters and current source inverters (Figure 2).

The indirect current source frequency converters are cheaper and with dynamic performances closer to those of the direct current drives, and are applied in one-engined drives with one-square or multi-square mode, with power up to 1MW and frequencies up to 200Hz. The indirect voltage source frequency converters in practice are somewhat more expensive and are applied in charging squirrel cage IMs and synchronous motors (ventilating pumps, extruders, cranes, dredges, surface processing machines etc.) The voltage in the circulating current circuit could be constant (the output inverter has PWM and the output frequency is limited to 200Hz) or variable (the output inverter is constantly led and the output frequency goes up to 600Hz or even to 1000Hz with a reduced load).

Induction motor drives, feded with pulse-width modulated invertors (PWM invertors), are increasingly becoming a standard in the highly developed industrial countries worldwide. At the same time, various output signal modulation methods have been used as PWM inverters (sinusoidal modulation, improved sinusoidal modulation, space vector modulation).

Each of these modulations is defined by the manner of generating the switching functions of the switches s_a, s_b, s_c of the inverter (Fig. 3).The sinusoidal modulation is such technique that employs comparison between the referent sinusoidal base frequency signal and the carrying (triangle) signal with raised frequency. The improved sinusoidal and space vector modulation could be classified under the so-called programmable PWM techniques.

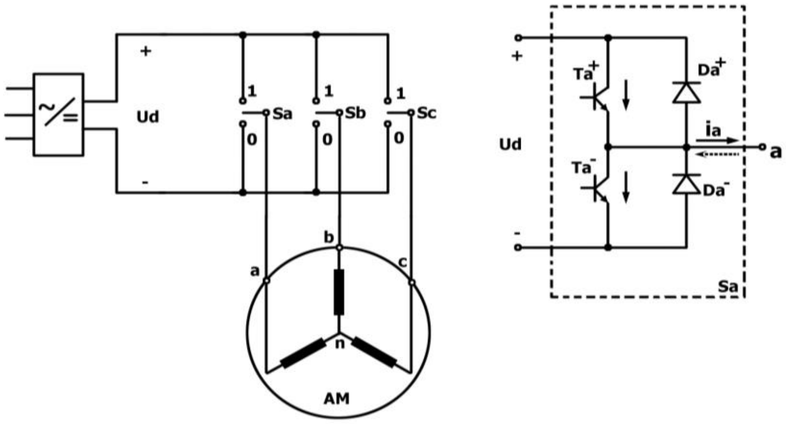


Fig. 3. Voltage inverter and the switching functions of the switches S_a, S_b, S_c

The sinusoidal modulation is considered a basic PWM technique that uses sinusoidal base frequency wave shape as referent signal, whereas triangle wave shape with increased frequency is mostly used as a signal carrier. Given that the IMs are constructed so as to work on sinusoidal voltage, it is obvious that it is necessary to use three-phase sinusoidal wave as a referent modulation signal in order to obtain PWM wave shape at the output of the inverter, in which the width of the pulses is sinusoidal modulated during in the course of one semi-period.

The practical implementation of this modulation technique demands that every inverter branch should have a comparator supplied by a referent sinusoidal voltage from its own phase and symmetrical triangle wave carrier common to all three phases. The ratio between the frequencies of the carrier and the referent wave $Z_p = \frac{f_n}{f_r}$ (carrier ratio) gives the number of output voltage pulsations from the corresponding inverter branch and this ratio must be divisible by 3 ($Z_p = 3 \cdot k, k = 1,2,3...$) in order to achieve an identical wave shape of the voltages from all three phases. The carrying triangle wave has constant amplitude and the ratio between the amplitudes of the referent sinusoidal wave and the carrying triangle wave $M = \frac{|U_r|}{|U_n|}$ is referred to as modulation index.

A disadvantage of the sinusoidal PWM is the low value of the base harmonic maximal amplitude, which for a maximal unity modulation index (M=1) amounts only to 50% of the value of the DC voltage between the converters. The simplest procedure to increase the base harmonic amplitude could be achieved by the improved sinusoidal PWM. This technique is realized by adding a third harmonic to the base referent sinusoidal signal multiplied with the so-called improvement parameter (usually amounting to 1/6) which is defined so as to obtain maximal value of the base harmonic amplitude of the output voltage.

Unlike the classical modulation techniques (sinusoidal, improved sinusoidal, etc.) space vector modulation is not oriented toward individual phase voltages but to their resulting space vector [27]. The essence of this modulation technique is to provide the voltage system required by the IM control cycles is provided through 7 (seven) different voltage vectors standing at the inverter's disposal. The objective of the procedure is to define, in each sampling period T, the given referent vector of the stator voltage $\vec{u}_1^*$ by $\alpha-\beta$ components or by a module and a space angle.

2.2 Vector systems

The current tendency of fast development in the field of power electronics and modern highly integrated electronic devices for signal processing increasingly bring about solving industrial facility situations by applying alternating current (AC) machines.

Figure 4 shows a principled block structure of a vector control system. The control system is principally divided in three sections. One of them represents the object of control, i.e. the dynamic non-linear and multi-variable mathematical model of the induction motor. The second section is the inverter, i.e. its discrete mathematical model with a variable structure, and the third section represents the DSP (Digital Signal Processor) which is to perform the function of the entire control in the closed control system. It implements the controlling algorithms, the acquisition and estimation of valid data, transformation of the coordinates, as well as the algorithms of control circuit synthesis.

Lately, there has been an ever growing substitution of scalar U/f control with vector control in the area of IM control, which assures higher dynamic performances of the drive. Main disadvantages of the U/f or scalar control in the eyes of the majority of the world's manufacturers of this kind of equipment are the limits in dynamic response (their characteristics vary with the change of the work-mode), with their extremely small number of revolutions, as well as with the possibility of high torque control dynamics.

The main reasons for these disadvantages of U/f-control, of course, are the non-linear model of the induction machine and the accompanying effect of coupling between the machine's d and q axes.

Accordingly, vector control is a method for dynamic control of the speed and the torque of the induction motor through permanent control of the intensity and the angle of the space vectors of the electromagnetic variables. One of the most important benefits of this control is energy saving, because the vector control enables dynamic control of the factor of power. With all this in mind, it can be easy to explain the common tendency of the world's highly developed countries to accept vector control as a universal method for controlling AC drives.

Basically, there are two vector control techniques: direct and indirect method. The indirect method uses the mathematical model of the induction motor, i.e. for rotor flux-oriented control it uses the corresponding slipping relation and is very dependant on the change of the machine's parameters. The direct method is based on direct measuring or estimating the space vectors of the stator's or rotor's flux.

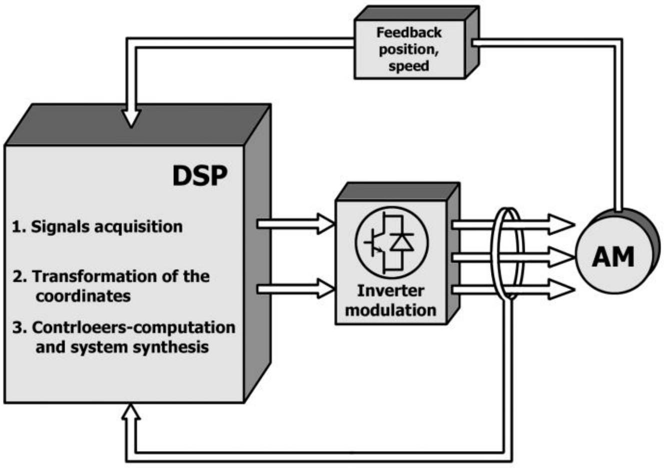


Figure 4. Principled block structure of vector control system

A basic, common characteristic to all approaches toward the different types of vector control is the dynamic equivalent scheme of the induction machine (Fig. 5) by the help of which the dynamic non-linear structure of the induction motor is transformed or approximated to the model of a DC engine with independent excitation. This results in the possibility of four-quadrant work-mode of the induction motor with full response and torque dynamics, as well as good performances of the drive down to zero-speeds. In order to provide as good overall system dynamics as possible for a broad range of speed and load, two dynamic models of induction motor so far have found practical use depending on whether the control is oriented to the vectors of the stator's current and the rotor's flux or to the vectors of the stator's and rotor's flux.

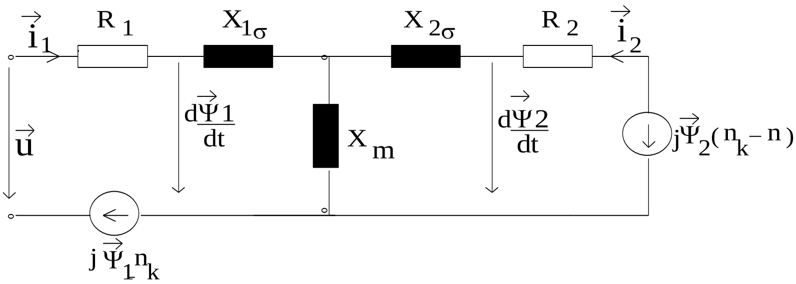


Figure 5. Dynamic equivalent scheme of the induction machine

The vector control system which is oriented to the vector of the rotor flux is intended mainly for electromotive drives in traction applications and shows relatively high sensibility with the machine's variability parameters. The vector control system of an induction motor in a stator coordinate system is oriented to the vector of the stator flux and the inverter's switching work-mode is intended almost exceptionally for servo applications. The simplicity, robustness and reliability of this relatively new control approach open up broad perspectives and new possibilities in vector-controlled servo systems with induction motors.

2.2.1 Indirect vector control systems

The indirect vector control methods with orientation on the field do not estimate or measure the space vector of the rotor flux, but use the slipping relation to calculate the output signals of the stator current's space vector (at vector control with a current inverter), or correspondingly the output signals of the stator's voltage space vector (at vector control with a voltage inverter).

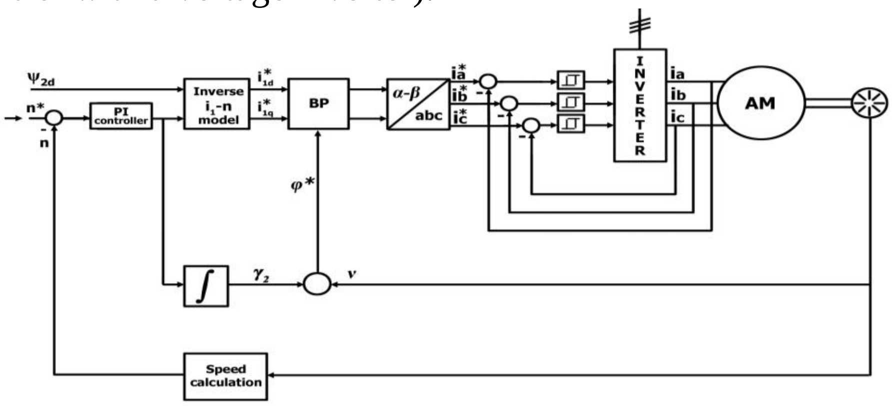


Figure 6 Principle block scheme of indirect vector control system

In order to reduce the machine parameters' dependence on heating or saturation, implementations in different coordinate systems are used. Also, there have been developed numerous numerical schemes for parameter adaptation. Well-known employed techniques are the self-tuning systems (STS), the robust control systems, model reference adaptive control systems (MRAC systems) etc. Figure 6 features a principled block scheme of an indirect vector control system. Similar variations of indirect vector control schemes have been analyzed by Flugel and Hasse [12], [16].

2.2.2Direct vector control systems

In contrast to the indirect vector control systems, the direct system is based on measurement, acquisition and (or) estimation of the space angle of the rotor's flux. In order to avoid rotor flux acquisition problems, the recent general tendency is to leave the approach of measuring the flux through additionally embedded coils or Hall's probes, and to acquire the flux through appropriately adapted mathematical models for this purpose [26]. The measurement of the rotor flux mainly has disadvantages connected with the loss of machine's simplicity due to installing additional measurement elements in the course of constructing the machine and to extra expenses for additional signal processing equipment [12], [13], thus increasing the price and reducing the need to apply such control drives. The model-based acquisition of the rotor flux has a disadvantage related to the heating sensitivity of the parameters, which is closely related to the drive's state of the motor. In this sense, long-term researches have been implemented and many models in different coordinate systems for rotor flux acquisition have been developed, as well as qualitative-quantitative evaluation and compensation of the error which is due to the temperature and magnetic variability of the parameters.

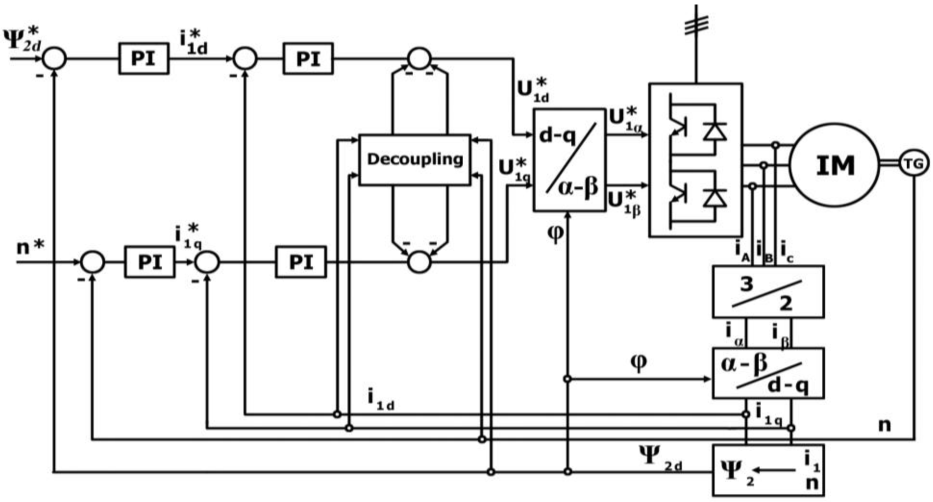


Figure 7. Principled scheme of direct vector control system

2.2.3 Direct torque control systems

According to the needs for an ever greater automation of the manufacturing processes, the servo systems most often operated by induction motors are becoming increasingly necessary for different applications, both in the field of robotics and the field of the numerically controlled machine tools. In recent years, especially in the highly developed industrial countries, a much intensified development of various concepts for IM field-oriented control can be noticed which, in a control sense, enables approximation of the induction torque to the DC motor. Unlike the control system which is oriented to the space vector of the rotor's flux $\vec{\psi}_2$, on the $\vec{i}_1 - \vec{\psi}_2$ dynamic model in a d-q coordinate system of IM and PWM of the voltage inverter, thereby using linear control technique and linear controllers, the direct torque control systems have a different concept for vector control. These systems are based on the space angle of the stator flux, on the model of the induction motor in a stationary coordinate system and on the space-vector modulation of the inverter [10], [11], [22], [27], [30], [31]. Thereby, this concept uses non-linear control techniques and non-linear controllers (Fig. 8). The orientation of the control system to the space vector $\vec{\psi}_1$, greatly reduces the control structure's dependence on the temperature variations of the parameters of the equivalent induction motor scheme.

In contrast to field-oriented IM control systems in which the precision in the estimation of the space angle of the rotor's flux $\vec{\psi}_2$ is directly dependent on the motor's parameters which determine the rotor's time-constant, in this vector control concept [27], [31], there is no need to acquire the space angle of the rotor flux $\vec{\psi}_2$. The orientation of the control structure to the $\vec{\psi}_1 - \vec{\psi}_2$ model of the induction motor in a stationary $\alpha - \beta$ coordinate system avoids the need to transform the coordinates of the machine's space angles which take part in the analysis and synthesis of the control circles [27].

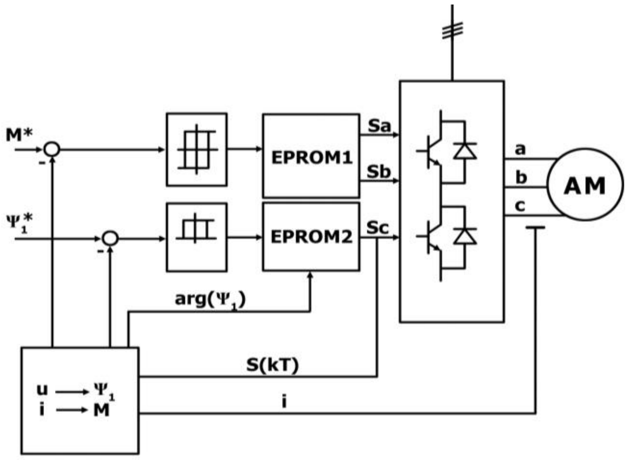


Figure 8. Direct flux and torque control

Space-vector modulation enables maximum use of the inverter’s dynamics, easy and simple optimization of the on-off frequency regarding the quality of the expected response of the controlled variables (flux, speed, torque etc.), which in the same time reduces the inverter’s on-off losses, losses introduced by higher harmonic voltage members and the current used to charge the machine, as well as the noise. The induction motor is a high level non-linear system and its vector control by means of linear techniques and controllers requires the use of complicated mathematical models. Consequently, due to the complexity of the non-linear differential equations which describe the dynamic model of the induction motor, signal processing in the control system becomes complicated. On the other hand, the power inverter is also a non-linear element, because it is composed of 6 (six) power switches (Fig. 8) which are also non-linear elements.

3. SOME TRENDS FOR THE FUTURE

Fuzzy logic-based control has aroused ever greater interest over the last few years. It is much closer to natural human reasoning and language rather than to traditional control techniques. Fuzzy logic enables effective processing and representation of real world’s inexact nature. The fuzzy logic-based control systems enable simple, fast and efficient conversion of linguistic control strategy based on expert knowledge and science in a strategy for automatic control. Experience has shown that fuzzy control could achieve better results compared to classical control, especially when applied in control systems in which the controlled object is described by a complex and difficult mathematical apparatus or when its exact mathematical description is generally impossible. The simplified three-block structure of a fuzzy logic controller is given in Figure 9.

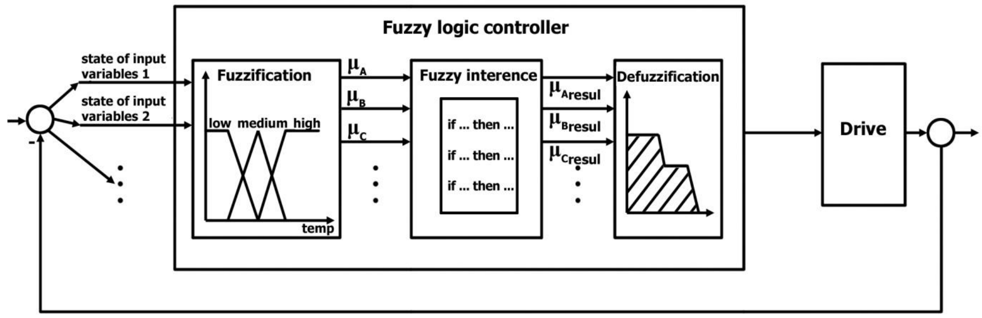


Fig. 9: Schematic block diagram of a fuzzy logic controller system

Fuzzification refers to association to a set of logic terms (variables) for describing exact states of the input variables. With this input, generalization or a logical explanation is made on the variable or the state of the input variables. For that purpose, mathematical operators based on linguistic logic are used (and a sequence of other experience rules) and mainly three asks are performed such as: Joining/associating an appropriate linguistic variable to each input variable; Determining the membership functions and Estimation of the membership coefficient

On the other hand, the Artificial neural networks-based control (ANN) finds its greatest application in non-linear systems identification and control.

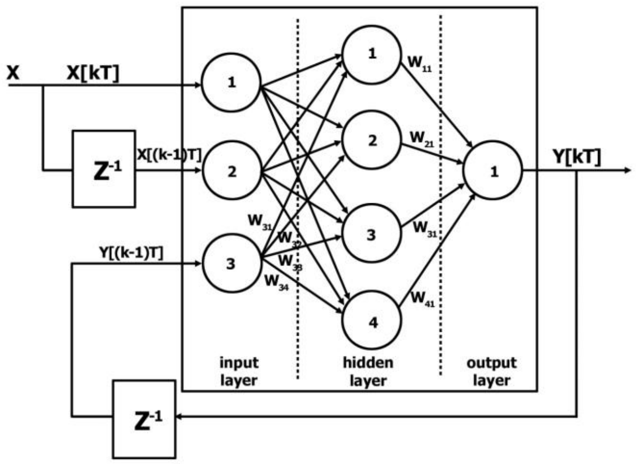


Figure 10. Principled scheme of a PI controller implemented with a three-layered ANN based on the backpropagation procedure

Artificial neural networks represent a non-linear adaptive dynamical structure containing highly interactive processing elements called neurons. Their structure is based on the neurobiological structure of the human brain. There already are many existing and developing models of neural networks, but their basic characteristic is the ability to train and adapt which makes them ideal for application in systems for automated adaptive control. The artificial neural networks-based controller (Fig.10) can be applied successfully even in cases when the parameters of the motor and the load are unknown. For that purpose, the neural networks, first, identify the unknown dynamics of the system and afterwards a thus-trained neural network can be combined with a reference model in order to reach the required control accuracy. In order to achieve more precise identification of the system, ANN is set in parallel with the unknown controlled system (for example, engine + load). The most applied method for setting the ANN's weighting factors is the so-called backpropagation procedure. A neural network consists of neural nodes interconnected with links defined by the so-called weighting factors, organized in several layers.

4. CONCLUSION

The simulation of the vector control systems becomes an increasingly attractive CAD tool especially among young researchers and engineers working on designing vector control systems. Mass application of vector control simulation packages gets this trend closer to an ever greater number of users and engineers dealing with this professional area. Many companies developing such equipment as well as many institutes for electric machines and drives at renowned universities worldwide are developing their own simulation packages to shorten the time needed to develop new more sophisticated vector control systems, to increase the effect and to reduce design costs. In that sense, this work describes a portion of the possibilities of some of the most famous simulation packages by which IM vector control systems could be designed. Future trends in the area of power converters will take place in the field of constructing smart power modules which will include protection, built-in drivers, signalization and, eventually, their being built into a low power motor, so that a so-called electronic motor would be obtained. Dominant semi-conducting valves would be IGBT thyristors and the MCT thyristors. Also, continuity is expected in the search for new materials which will combine thermal conductivity, electrical isolation and mechanical solidity. In the area of control is expected continuation and intensification of application of various adaptive methods such as the variable structure systems (VSS), the self-tuning systems (STS), models of robust control, models of reference adaptive control (MRAC), expert fuzzy logic-based systems, genetic algorithms and artificial neural networks (ANN). In future, wider choice among the DSP software tools is expected, whereby application of the DSP vector-controlled electromotive drives will be significantly increased.

REFERENCES

[1] Baader U., Depenbrock M., Gierce G.: Direct self control of inverter fed induction machine A basis of speed control without speed measurement, IAS Ann. Mtg., San Diego, 1989

[2] Blaschke F. Das Prinzip der Feldorientirerung, die Grundlage für die Transvector-Regelung von Drehfeldmaschinen, Siemens Zeitschrift 45 H.10 757-760, 1971

[3] Blaschke F.: Das Verfahren der Feldorientirung zur Regelung der Drehfeldmaschine, Diss. TU Braunschweig 1974

[4] Boglietti A., Griva G., Pastorelli M., Profumo F.: Different PWM Modulation Techniques Indexes Performance Evaluation, IEEE and ISIE Conference, Budapest 1993 Hungary

[5] Bose B. K.: Introduction to AC-Drives. Adjustable speed AC-Drive system, John Wiley and Sons, New York, 1980

[6] Bose B. K.: Power Electronic and Variable Frequency Drives, Technology and Applications. IEEE Press, 1997, New York.

[7] Bose B. K.: Technology trends in microcomputer control of electrical machines, IEEE Trans. Ind. Electr., Vol. 35, No1, 1988.
[8] Depenbrock M.: Directe Selbstregelung (DSR) für hochdynamische Drehfeldantriebe mit Stromrichterspeisung, etz Archiv Bd.7, 1985, H7 s211-218
[9] Depenbrock M.: Direct self control (DSC) of inverter fed induction machine, IEEE Power Electronics Specialists Conference 1987 pp.632-641
[10] Dote Y.: Application of modern Control Techniques to motor control, Proceedings of the IEEE, Vol.76, No.4, 1988
[11] Flöter W., Ripperger H.: Die TRANSVECTOR - Regelung für den feldorientirten Betrieb einer Asynchronmaschine, Siemens Zeitschrift 45 1971, s. 761-764
[12] Flügel W.: Drehzahlregelung umrichtergespeister Asynchronmaschinen bei Steuerungen des Flußes durch Entkoplungsnetzweke, Diss. TU Munchen 1981
[13] Gabriel R., Leonhard W., Nordby C. T.: Field oriented control of a standard AC Motor using microprocessors, IEEE Trans on Ind. Appl. Vol.IA-16, 1980, p.186-192
[14] Gastli Adel, Motsui Nobuyoki: Stator flux controlled V/f PWM inverter with identification of IM parameters, IEEE Trans. Ind. Elect., Vol. 39, No. 4, 1992
[15] IDAS SIMEC GMbH Chemnitz Germany
[16] Hasse K.: Zur Dynamikdrehzahlgeregelter Antriebe mit stromrichtergespeisten Asynchron-kurzschlusslaufermaschinen, Diss TH Darmstadt, 1979
[17] Harashima Fumio, Kondo Seiji, Ohnischi Kouhei, Kajita Masabschi, Susono Motonisa: Multimicroprocessor based control system for quick response induction motor drive IEEE Trans. Ind. Appl., Vol.IA-21, No.4, 1985
[18] Isosimov D. B., Utkin U. I. Sliding mode control of electric motors, 8th IFAC World Congr., Kyoto, Japan, 1981
[19] Jänecke M., Kremer R., Steurwald G.: Direct self control (DSC) a novel method of controling Asynchronous maschines in traction applications, EPE Aachen 1989
[20] Jotten R.,Mader G: Control methods for good dynamic performance induction motor drives based on current and voltage as measured quantities, IEEE Trans.IA 1983 No.3 pp.356
[21] Kazmierkowski M, Kasprovicz B. Andrzej: Improved Direct Torque and Flux Vector Control of PWM Inverter- Fed IM Drives, IEEE Trans. on Ind.El. Vol.42, No.4, Ag.1995, pp 344-349
[22] MATRIXx SYSTEM BULID, Integrated Systems Inc, Santa Clara, CA, USA
[23] MATLAB, The Math Works Inc., 24 Prime Park Way, Natick MA 01760
[24] Mika Aaltonen, Pekka Tiltinen, Jarkko Lalu, Samull Helkkliä ABB Industry: Direct torque control of AC motor drives, ABB Review 3/1995, pp 19-24.
[25] Rajkovic Borivoje: Tendencije u razvoju elektromotornih pogona s asinhronim motorima, AUTOMATIKA 36(1995) 1-2, pp 11-17,
[26] Schönfeld Rolf, Habiger Ernst: Automatisierte Electroantriebe, VEB Verlag, Berlin 1990
[27] Schönfeld Rolf: Digitalle Regelung elektrischer Antriebe, Verlag Technik GmbH,1990
[28] Segerer Holger: Direct control of induction motors. A time discrete strategy respecting time continuous trajectories, EPE Firenze, 1991, pp. 412-420
[29] Takahaschi I., Kanmachi T.: Ultra wide speed control with a quick torque response AC Servo by a DSP, EPE Firenze, 1991, pp.312-320.
[30] Takahaschi I., Moschikava A.: A new quick response and high efficiency control strategy of an induction motor, IEEE-IAS Annual Meeting, Toronto 1985 pp.496-502
[31] Vas Peter: Vector control of AC machines, Clarendon Press - Oxford, 1990.