Predictive Control for Electrical Drives – A Survey

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Abstract — During the last decades several proposals have been made in literature to use predictive control for inverter control – especially in electrical drives. These algorithms are completely different to the recursive but linear predictive algorithms known from information theory, where closed mathematical equations are used (e.g. Kalman-filters).
Only few of the presented schemes have been realized in industrial applications so far. After some further progress, however, the advantage of predictive algorithms might lead to an increased number of industrial implementations in the future.
Besides the common basic idea – to use the well-known but strongly non-linear behaviour of inverters to precalculate the best switching times – there are many differences in the details of these proposals. This contribution shows similarities and differences and attempts to design a "family tree" of predictive control algorithms. This might grow to a first step to a theoretical approach to deal with predictive control schemes in a more generalised way.

I. Introduction

First ideas of predictive control have already been proposed in the 1960s [1]. Meanwhile lots of papers on predictive control have been published [2-10]. Nevertheless field oriented control still is state-of-the-art in industrial drive applications.

Behind the simple expression "predictive control" there is a variety of different control methods. Most of these methods have been proposed by different authors independent from each other. Having a closer look, it is clear, that in spite of their individual developments there are many similarities between the different algorithms. For a more generalized way to deal with predictive control it is useful to design a "family-tree" of the different control methods. A first attempt of designing this kind of "family-tree" has been made on the IEEE pesc'00 conference in Galway [11].

This paper gives a classification for different predictive control algorithms dividing them into classes of predictive control. After explaining the general idea of predictive control, the different classes will be illustrated and a family-tree will be designed.

II. Predictive Control – What is that?

As the expression "predictive control" can be understood differently and is already used by information technology in different ways, a short definition of "predictive control" is useful. Predictive control means, that the behaviour of the controlled system is precalculated by a model of the process. This model is mostly based on differential equations or equivalent circuits, but could also be very simple as in the case of so-called "predictive PID-controllers" according to [52], that predict the future error with a simple linear interpolation – in this case the model is just a linear curve.

The main principle of most predictive control schemes is illustrated in fig. 1. Since the inverter has only a finite number of switching elements, the number of possible switching states is limited as well. For each of these switching states an equivalent circuit of the drive system *without* switching elements can be defined. Therefore the behaviour of inverter and machine can be calculated separately and in advance for each of the switching states. Comparing the results of the calculation with the desired behaviour of the system, the optimal switching state of the inverter can be derived. Then the next switching state and switching time will be calculated using the corrected values.

State-of-the-art in most drive applications is the field oriented control. Basically there is a threefold cascade structure consisting of current/torque control, speed control and position control. Consequently, there are three different controllers: position, speed and current/torque controller.

The major problem of cascaded control structures is the limitation of the dynamic behaviour caused by the cascaded structure itself. The inner loop must be as fast as possible to reach an acceptable dynamic be-

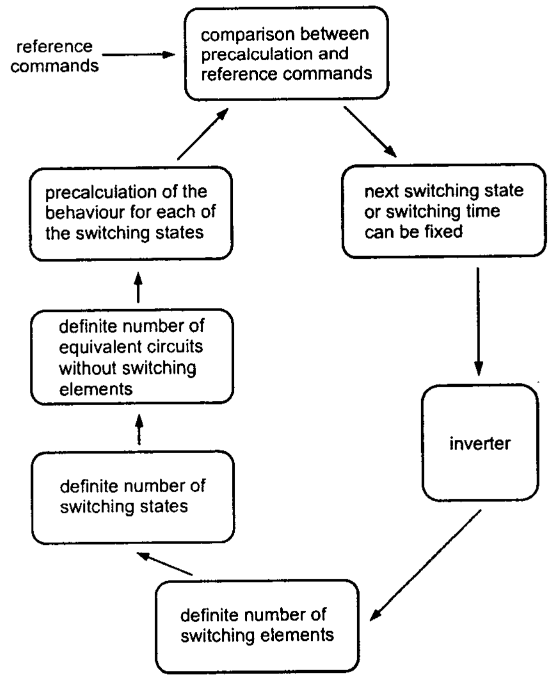

Fig. 1. Basic principle of Predictive Control

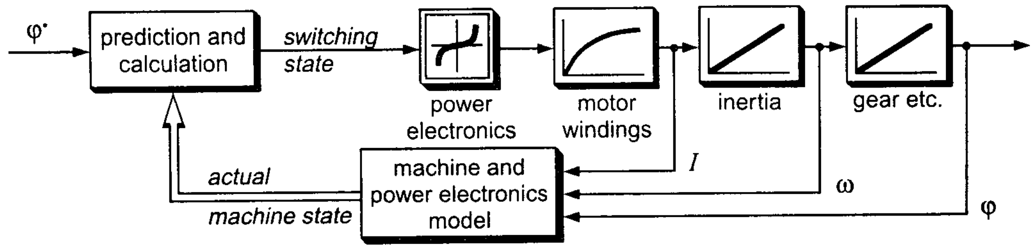

Fig. 2. Basic structure of a Predictive Controller

haviour of the whole cascaded system. This requires the use of high performance controllers only to deal with the inner control loops in acceptable calculation times (e.g. several microseconds).

The non-linear characteristic of inverters, which is usually considered by linearization, represents another problem. Linearization, however, leads to inaccuracies in the description of the inverter and drive characteristics. In spite of many adaptation circuits, a non-optimal behaviour of the whole drive system and more side effects are the result.

The typical structure of a predictive controller is shown in fig. 2. This example shows a position control system. The state variables of the drive are fed into a model of the machine and the power electronics. The information derived from the model is transferred to a unit called "prediction and calculation". This unit can be regarded as the heart of a predictive control system. Comparing the actual machine state with the reference value of the drive position, the correct switching state of the inverter will be chosen corresponding to the implemented optimizing criteria, which for example can be the minimum switching frequency, the minimum current distortion or the minimum torque ripple.

In contrast to standard closed loop controls, predictive control uses the fact, that the switching behaviour of an inverter can be calculated and therefore predicted. The response of the drive to a certain switching state can be described by mathematical equations. The cascade structure disappears, because *all* measured system variables will be considered by only *one* controller. Since there are no cascaded control loops any more, the dynamic of the control system is improved.

Non-linear characteristics of the inverter and drive can be considered in the model and the predictive controller. As the behaviour of the controlled system is described by models considering non-linearities (e.g. by non-linear mathematical equations), predictive control is a possibility to control an inverter supplied drive with high dynamic and sufficent accuracy in spite of the non-linear characteristics of inverter and drive.

III. Predictive Control Strategies

It is possible to separate the different predictive control strategies published so far, into three families: Hysteresis based, trajectory based and model based predictive control. These "classes" of predictive control will be explained in the following paragraphs.

A. Hysteresis Based Predictive Control schemes

Hysteresis based predictive control strategies keep the controlled system variables between the boundaries of a hysteresis area or space. The most simple form of this principle is a so called "bang-bang-controller". Although bang-bang controllers usually are not considered as predictive controllers in literature, they clearly show the characteristics of a typical predictive controller. An improved form of a multi-dimensional bang-bang controller is the predictive current controller proposed by Holtz and Stadtfeld [3].

Using predictive current control, the switching instants are determined by predefined error boundaries. As an example fig. 3 shows a circular boundary, the position of which is controlled by the current reference vector $\underline{i}_s{}^*$. When the current vector $\underline{i}_s$ touches the boundary line, the next switching state vector is determined by prediction and optimization, which in this case is a mimimum switching frequency.

Since 1983, when the algorithm was published, the demand for low switching frequency has decreased. Today different optimizing criteria have more importance, e.g. low current distortion or low electromagnetic inferences (EMI). Modifications of the predictive current control are consequently under consideration.

B. Trajectory Based Predictive Control schemes

The principle of trajectory based predictive control strategies is to force the system's variables onto pre-calculated trajectories. The first trajectory based predictive control schemes have been published in 1983 [6] – at that time, however, the application was a line commutated converter. Some time later control algo-

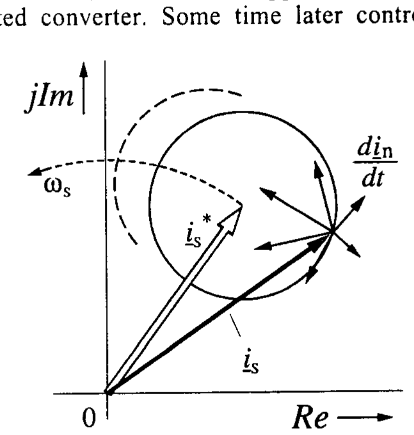

Fig. 3. Predictive current control, boundary circle and space vectors [3]

rithms according to this strategy like Direct Self Control (DSC) by Depenbrock [13] or Direct Mean Torque Control (DMTC) by Flach, Hoffmann and Mutschler [9] were published for asynchronous drives. Some more methods like Sliding Mode Control [1] or Direct Torque Control (DTC) [2] are a combination of hysteresis- and trajectory-based strategies, whereas Direct Speed Control (DSPC) by Mutschler [14] can be identified as a trajectory-based control system, though it also has a few hysteresis-based aspects. DSPC is explained here as an example of trajectory-based predictive controllers.

The initial state of the system is assumed being e_k/a_k. Now, "torque increasing" and "torque decreasing" voltage vectors are switched in a way, that in steady state, the system state moves along the path $+Hy$–e_{k+2}/a_{k+2}–$-Hy$–e_{k+3}/a_{k+3}–$+Hy$ (fig. 4). Hence the speed error e is kept within the hysteresis band between $-Hy$ and $+Hy$.

The algorithm of DSPC clearly shows the main principle of trajectory based predictive control. Foreknowledge of the drive system is used to precalculate the optimal switching states instead of trying to linearize the nonlinear parts of the system and then control them by PI-controllers. The speed can be controlled direcly without and cascaded structure.

C. Model Based Predictive Control schemes

Whereas there seems to be a kind of relationship between hysteresis based and trajectory based predictive control strategies, model based predictive control (MBPC) is founded on completely different ideas. Hysteresis and trajectory based algorithms only use the actual system values to calculate the next switching state of the inverter. MBPC also takes into account the past and searches for the best switching state not only concerning the next cycle but up to a specified horizon in the future. Clarke [15] gives a good survey on model based or adaptive predictive control and its historical development.

Fig. 5 shows the typical structure of Model Based Predictive Control. Its central part is the model, which is used to predict the future behaviour of the system. This "total respose" is calculated up to a finite *prediction horizon*. The difference between the future reference and the total response results in the future errors

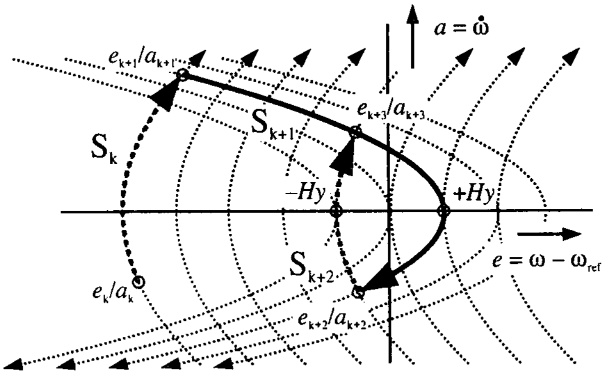

Fig. 4. DSPC: Trajectories in the e/a-state plane [14]

of the system enabling an optimizer to determine the best set of future controls $u(t+j)$.

A problem of MPBC is the high demand for calculation performance. Due to the precalculation of all system states up to the prediction horizon huge matrices must be calculated. As a result of this, almost all applications have been made in the field of chemical engineering, where the sample rates are much lower than in drive systems [16,17]. Papers presenting MBPC used for controlling inverter supplied drives (e.g. [18]), only use it as speed controller.

Several proposals have been made to cope with this disadvantage of MBPC [19,20]. Nevertheless the applicability of MBPC was recently proved by implementing a cascaded GPC-controller using a Pentium-Processor with 233 MHz clock rate [21]. A sample time of 125 µs could be achieved.

IV. Summary

A family tree of predictive control can be designed. As shown in fig. 6, control methods with trajectory or hysteresis based algorithms are intensively interlinked and therefore related to each other. Model based control is founded on completely different strategies and forms a family of its own. Since the individual algorithms of MBPC only differ in the model of the system and the type of the objective function, but *not* in their basic structure, they are not all included in the family tree of fig. 6.

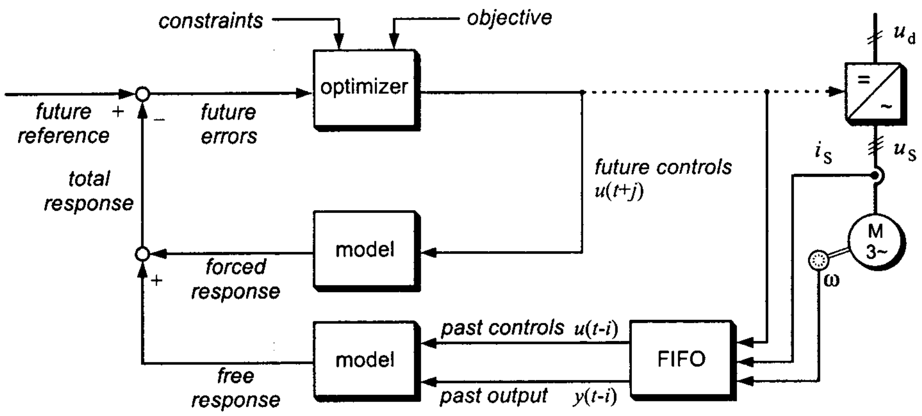

Fig. 5. Typical structure of MBPC [15]

The examples presented in this paper show, that predictive control is an interesting alternative in comparison to conventional cascaded control. The advantages of predictive control are a better representation of non-linear systems, the possibility to use the foreknowlegde of the drive system and – in many cases – no need for a cascaded structure.

Predictive control cannot be compared with Fuzzy control as some authors try to do, because it is something completely different. Fuzzy control is especially suited for controlled systems, where the physical background is completely unknown or very difficult to be described mathematically. Using Fuzzy control for electrical drives would mean to ignore totally all foreknowledge of the system and therefore stands in direct contrast to the basic principles of predictive control.

The same situation (all foreknowledge of the drive system is completely neglected), arises using Neuronal-Network schemes or Genetic Algorithms. Control schemes taking care of any foreknowledge, like real predictive controllers, must be superior to those not using it.

Although predictive control has been known for more than 15 years, industrial applications are still very rare. Almost all implementations have been made only for research investigations, except for Direct Self Control [13] and its derivates like e.g. Direct Torque Control [2,22]. The challenge is the commissioning of a predictively controlled drive. Since there is no cascaded structure, a step-by-step procedure as used in cascaded structures is not applicable. The nonlinearities must be implemented into the control structure and the parameters of the model must be determined. For an easy-to-do starting process a self-commissioning feature is necessary to increase the number of industrial applications.

V. References

[1] S. V. Emeljanov, *Automatic control systems with variable structure (Automatische Regelsysteme mit veränderlicher Struktur)*, Munich, Vienna: R. Oldenbourg Verlag, 1969

[2] I. Takahashi, T. Noguchi, "A new quick response and high efficiency control strategy of an induction motor", in *Conf. Record IEEE IAS Annual Meeting 1985*, pp. 496-502

[3] J. Holtz, S. Stadtfeld, "A predictive controller for the stator current vector of AC-machines fed from a switched voltage source", in *Conf. Record IPEC Tokyo 1983*, Vol. 2, pp. 1665-1675

[4] D. W. Clarke, C. Mohtadi, P. S. Tuffs, "Generalized Predictive Control. Part I. The basic algorithm", *Automatica*, Vol. 23, No. 2, pp. 137-148, 1987 and "Generalized Predictive Control. Part II. Extensions and interpretations", *Automatica*, Vol. 23, No. 2, pp. 149-160, 1987

[5] J. Holtz, U. Schwellenberg, "A new fast-response current control scheme for line controlled converters", in *Conf. Record International Semiconductor Power Converter Conference Orlando 1982*, pp. 175-183

[6] R. Kennel, D. Schröder, "Predictive control strategy for converters", *Proc. of the third IFAC Symposium 1983*, pp. 415-422, Lausanne 1983

[7] H. Warmer, D. Schröder, "An improved method of predictive control for line-commutated DC-drives", in *Conf. Record ICEM Munich 1987*, pp. 566-571

[8] A. Purcell, P. Acarnley, "Multilevel hysteresis comparator forms for direct torque control schemes", *Electronic Letters*, Vol. 34, No. 6, pp. 601-603, March 1998

[9] E. Flach, R. Hoffmann, P. Mutschler, "Direct Mean Torque Control of an induction motor", in *Conf. Record EPE'97*, Vol. 3, pp. 672-677, Trondheim 1997

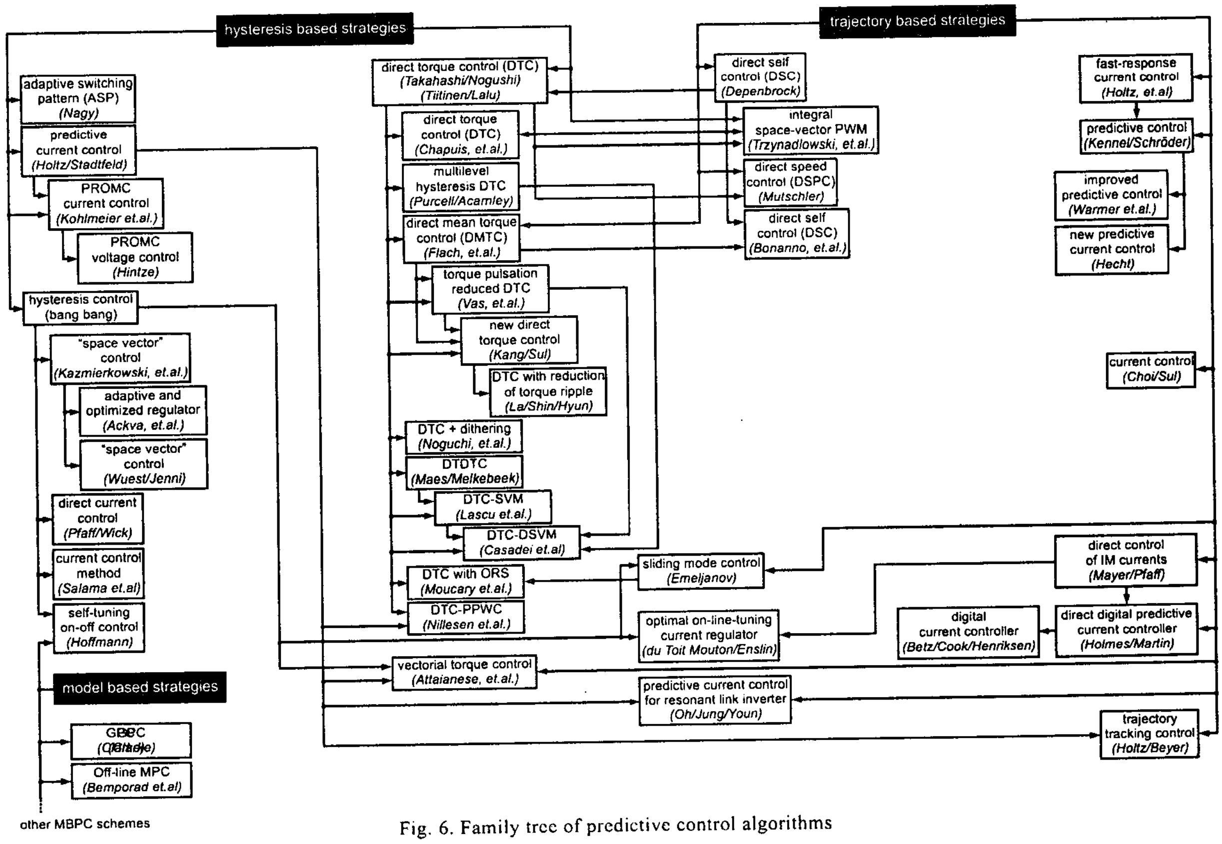

Fig. 6. Family tree of predictive control algorithms

[10] A. M. Trzynadlowski, M. M. Bech, F. Blaabjerg, J. K. Pedersen, "An integral space-vector PWM technique for DSP-controlled voltage-source-inverters", *IEEE Transactions on Industry Applications*, Vol. 35, No. 5, pp. 1091-1097, Sept./Oct. 1999
[11] R. Kennel, A. Linder, "Predictive control of inverter supplied electrical drives", in *Conf. Record PESC'00*, Vol. 2, pp. 761-766, Galway 2000
[12] A. Khambadkone, J. Holtz, "Low switching frequency high-power inverter drive based on field-oriented pulsewidth modulation", in *Conf. Record EPE'91*, Vol. 4, pp. 672-677, Firenze 1991
[13] M. Depenbrock, "Direct Self-Control (DSC) of an inverter-fed induction machine", *IEEE Transactions on Power Electronics*, Vol. 3, No. 4, pp. 420-429, Oct. 1988
[14] P. Mutschler, "A new speed-control method for induction motors", in *Conf. Record of PCIM'98*, pp. 131-136, Nuremberg, May 1998
[15] D. W. Clarke, "Adaptive Predictive Control", *Annual Review in Automatic Programming*, Vol. 20, pp. 83-94, 1996
[16] P. Boucher, D. Dumur, P. Raguenaud, C. Rougebief, "Multivariable Generalised Predictive Control for cognac distillation", in *Conf. Record European Control Conference ECC'99*, Karlsruhe 1999
[17] J. Yamamoto, K. Nakane, T. Tani, K. Takahashi, T. Inoue, "Application of a cooperative control system to residue fluid catalytic cracking plant using a knowledge based system and Model Predictive Multivariable Control", in *Conf. Record IECON 2000*, pp. 1056-1061, Nagoya 2000
[18] M. Tonnes, H. Rasmussen, "Robust self-tuning control of AC-servo drive", in *Conf. Record EPE'91*, Vol. 3, pp. 48-49, Firenze 1991
[19] C. Bordons, E. F. Camacho, "A Generalized Predictive Controller for a wide class of industrial processes", *IEEE Transactions on Control Systems Technology*, Vol. 6, No. 3, pp. 372-387, May 1998
[20] A. Bemporad, M. Morari, V. Dua, E. N. Pistikopoulos, "The explicit solution of Model Predictive Control via multiparametric quadratic programming", in *Conf. Record American Control Conference ACC 2000*, pp. 872-876, Chicago 2000
[21] R. Kennel, A. Linder, M. Linke, "Generalized Predictive Control (GPC) – Ready for use in drive applications?", in *Conf. Record PESC 2001*, Vol. 4, pp. 1839-1844, Vancouver 2001
[22] A. de Bok, B. Fälth, "High torque at zero speed", *AMD&C International Magazine*, Issue 7/8 '99, 1999, pp. 19-21
[23] G. Pfaff, A. Wick, "Direct current control of AC-drives by PWM inverters (Direkte Stromregelung bei Drehstromantrieben mit Pulswechselrichter)", *rtp – Regelungstechnische Praxis*, Vol. 24, No. 11, pp. 472-477, 1983
[24] U. Hoffmann, "Adaptive bang-bang-control for processes containig switching actuators (Eine adaptive Zweipunktregelung für Prozesse mit schaltenden Stellgliedern)", *at – Automatisierungstechnik*, Vol. 35, No. 5, pp. 184-191, 1987
[25] D. Wuest, F. Jenni, "Space vector based current control schemes for voltage source inverters", in *Conf. Record PESC'93*, pp. 986-992, Seattle 1993
[26] Nagy, I, "Novel adaptive tolerance band based PWM for field-oriented control of induction machine", *IEEE Transactions on Industrial Electronics*, Vol. 41, No. 4, pp. 406-417, August 1994
[27] M. Aaltonen, P. Tiitinen, J. Lalu, S. Heikkilä, "Direct Torque Control of AC-drives (Direkte Drehmomentregelung von Drehstromantrieben)", *ABB Technik 3/1995*, pp. 19-24
[28] Y. A. Chapuis, C. Pelissou, D. Roye, "Direct Torque Control of induction machine under square wave conditions", in *Conf. Record IEEE IAS Annual Meeting 1995*, Vol. 1, pp. 343-349, Orlando 1995
[29] J. Holtz, B. Beyer, "Optimal synchronous pulsewidth modulation with a trajectory-tracking scheme for high-dynamic-performance", *IEEE Transactions on Industry Applications*, Vol. 29, No. 6, pp. 1098-1105, November/December 1993
[30] J.-W. Choi, S.-K. Sul, "New current control concept – Minimum time current control in the three-phase PWM converter", *IEEE Transactions on Power Electronics*, Vol. 12, No. 1, pp. 124-131, January 1997
[31] F. Bonanno, A. Consoli, A. Raciti, A. Testa, "An innovative Direct Self-Control scheme for induction motor drives", *IEEE Transactions on Power Electronics*, Vol. 12, No. 5, pp. 800-806, September 1997
[32] H. Kohlmeier, O. Niermeyer, D. Schröder, "High dynamic four-quadrant AC-motor drive with improved power-factor and on-line optimized pulse pattern with PROMC (precalculation of reference for optimal model control)", in *Conf. Record EPE'85*, Vol. 3, pp. 3.173-3.178, Brussels 1985
[33] D. Hintze, *Current source inverter fed induction machine drive with four-quadrant operation and low ripple (Asynchroner Vierquadranten-Drehstromantrieb mit Stromzwischenkreisumrichter und oberschwingungsarmen Maschinengrößen)*, Dissertation, TU Munich, 1993
[34] M. P. Kazmierkowski, M. A. Dzieniakowski, W. Sulkowski, "Novel Space Vector Based Current Controllers for PWM-Inverters", *IEEE Transactions on Power Electronics*, Vol. 6, No. 1, pp. 158-166, January 1991
[35] A. Ackva, H. Reinold, R. Olesinski, "A Simple and Self-Adapting High-Performance Current Control Scheme for Three Phase Voltage Source Inverters", in *Conf. Record PESC'92*, Vol. 1, pp. 435-442, Toledo 1992
[36] S. Salama, S. Lennon, "Overshoot and limit cycle tree current control method for PWM inverters", in *Conf. Record EPE'91*, Vol. 3, pp. 3.247-3.251, Firenze 1991
[37] P. Vas, A. F. Stronach, M. Rashed, M. Zordan, B. C. Chew, "DSP implementation of torque pulsation reduction techniques in sensorless DTC induction and p. m. synchronous motor drives", *Intelligent Motion*, june 1999 proceedings, pp. 107-111
[38] J.-K. Kang, S.-K. Sul, "New Direct Torque Control of Induction Motor for Minimum Torque Ripple and Constant Switching Frequency", *IEEE Transactions on Industry Applications*, Vol. 35, No. 5, pp. 1076-1082, Sept./Oct. 1999
[39] K.-K. La, M.-H. Shin, D.-S. Hyun, "Direct Torque Control of Induction Motor with Reduction of Torque Ripple", in *Conf. Record IECON 2000*, pp. 1087-1092, Nagoya 2000
[40] T. Noguchi, M. Yamamoto, S. Kondo, I. Takahashi, "Enlarging Switching Frequency in Direct Torque-Controlled Inverter by Means of Dithering", *IEEE Transactions on Industry Applications*, Vol. 35, No. 6, pp. 1358-1366, November/December 1999
[41] J. Maes, J. Melkebeek, "Discrete Time Direct Torque Control of Induction Motors using Back-EMF measurement", in *Conf. Record IEEE IAS Ann. Meeting 1998*, Vol. 1, pp. 407-414, St. Louis 1998
[42] C. Lascu, I. Boldea, F. Blaabjerg, "A Modified Direct Torque Control (DTC) for Induction Motor Sensorless Drive", in *Conf. Record IEEE IAS Ann. Meeting 1998*, Vol. 1, pp. 415-422, St. Louis 1998
[43] D. Casadei, G. Serra, A. Tani, "Implementation of a Direct Torque Control Algorithm for Induction Motors Based on Discrete Space Vector Modulation", *IEEE Transactions on Power Electronics*, Vol. 15, No. 4, pp. 769-777, July 2000
[44] C. El Moucary, E. Mendes, T. Raithel, R. Ortega, "A New Strategy for Direct Torque and Flux Control of Induction Motor Drives", in *Conf. Record ICEM International Conference on Electrical Machines 2000*, Vol. 2, pp. 923-927, Espoo 2000
[45] M. E. Nillesen, J. L. Duarte, M. Pasquariello, A. Del Pizzo, "Direct Torque Control with the Application of a Predictive Pulse Width Control", in *Conf. Record IEEE IAS Ann. Meeting 2000*, Vol. 3, pp. 1375-1379, Rome 2000
[46] H. R. Mayer, G. Pfaff, "Direct control of induction motor currents – design and expemimental results", in *Conf. Record EPE'85*, Vol. 3, pp. 3.7-3.12, Brussels 1985
[47] H. du Toit Mouton, J. H. R. Enslin, "An Optimal On-Line-Tuning Current Regulator for High-Power IGBT Converters", *IEEE Transactions on Industry Applications*, Vol. 35, No. 5, pp. 1132-1140, Sept./Oct. 1999
[48] D. G. Holmes, D. A. Martin, "Implementation of a Direct Digital Predictive Current Controller for Single and Three Phase Voltage Source Inverters", in *Conf. Record IEEE IAS Ann. Meeting 1996*, Vol. 2, pp. 906-913, San Diego 1996
[49] R. E. Betz, B. J. Cook, S. J. Henriksen, "A Digital Current Controller for Three Phase Voltage Source Inverters", in *Conf. Record IEEE IAS Annual Meeting 1997*, Vol. 1, pp. 722-729, New Orleans 1997
[50] I.-H. Oh, Y.-S. Jung, M.-J. Youn, "A Source Voltage-Clamped Resonant Link Inverter for a PMSM Using a Predictive Current Control Technique", *IEEE Transactions on Power Electronics*, Vol. 14, No. 6, pp. 1122-1132, November 1999
[51] C. Attaianese, V. Nardi, A. Perfetto, G. Tomasso, "Vectorial Torque Control: A Novel Approach to Torque and Flux Control of Induction Motor Drives", *IEEE Transactions on Industry Applications*, Vol. 35, No. 6, pp. 1399-1405, November/December 1999
[52] C. Rech, H. Pinheiro, H. A. Gründling, H. L. Hey, J. R. Pinheiro, "Analysis and Design of a Repetitive Predictive-PID Controller for PWM Inverters", in *Conf. Record PESC 2001*, Vol. 2, pp. 986-991, Vancouver 2001