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Comparative Study of Maximum Torque Control by PI ANN of Induction Motor

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Abstract

A novel maximum torque per Ampere (MTPA) controller for the induction motor (IM) drives is presented. It is shown to be highly suited to applications that do not demand an extremely fast dynamic response, for example, electric vehicle drives. The proposed MTPA field oriented controller guarantees asymptotic torque (speed) tracking of smooth reference trajectories and maximizes the torque per Ampere ratio when the developed torque is constant or slow varying. An output ANN based feedback linearizing concept is employed for the design of torque and flux subsystems to compensate for the torque-dependent flux variations required to satisfy the MTPA condition. As a first step, a linear approximation of the IM magnetic system is considered. Then, based on a standard saturated IM model, the nonlinear MTPA relationship for the rotor flux are derived as a function of the desired torque, and a modified torque-flux controller for the saturated machine is developed. The static and dynamic flux reference calculation methods to achieve simultaneously an asymptotic field orientation, a torque-flux decoupling, and an MTPA optimization in a steady state, is proposed. The proposed ANN based MTPA control algorithm also demonstrates a decoupling of the torque (speed) and flux dynamics to ensure asymptotic torque tracking. In addition, a higher torque per Ampere ratio is achieved together with an improved efficiency of electromechanical energy conversion.

INTRODUCTION

During recent decades there has been a growing trend within many applications to replace the induction machine (IM) with a permanent magnet synchronous machine (PMSM) due to its higher efficiency, torque, and power density. However, the cost of a PMSM is significantly higher than that of the IM due to the use of rare-earth magnetic materials which have a very limited origin and their cost is continuously increasing. The tendency to reduce the use of expensive rare-earth magnets in industrial and electrical traction drives has driven a renewed interest for research into advanced design and control concepts for IM. Field-oriented vector control (FOC), advanced FOC, and direct torque control (DTC) of IMs have been established as a defacto industrial standard for high and medium dynamic performance applications. Vector controlled and DTC IM drives typically operate with constant flux magnitude even at low values of produced torque which results in a good dynamic performance. However, conversely, the machine efficiency and power factor can be low, especially for small torque values.

The IM torque is a product of the flux amplitude and the torque component of the stator current, providing a degree of freedom for reduction of the power conversion losses or for attaining other performance criteria. The optimization techniques typically reported in publications adjust the flux level as a function of the electromagnetic torque using various optimization procedures. The flux regulation restricts the drive's dynamic performance; hence, this approach can be employed in applications not requiring an extremely fast response, for example, in electric vehicle drives where the drive only operates at a rated torque for a limited proportion of time. A number of control strategies to optimize different performance objectives are known including minimization of active and total losses, power factor maximization, maximum torque per Ampere (MTPA) control, maximum torque per voltage control, and maximum power transfer. The established optimization methods are designed for a steady-state operation (i.e., the drive is operating in constant torque). Dynamic behavior optimization during torque transient is only considered in very few papers.

MTPA control minimizes the stator current for a given machine torque. Maximizing the machine torque by having limited source voltage and inverter current capability improves the electromechanical system performance. This is particularly beneficial for traction systems. Under the MTPA control strategy, the torque controller adjusts the flux reference to increase the efficiency at low loads. As a result of this optimization, the torque per Ampere ratio is maximized and, in addition, the achievable values of motor efficiency are close to those obtained using the minimum active losses optimization criterion. The basic MTPA control objective is achieved by controlling stator current torque and flux components, expressed in terms of rotor flux reference frame, to be equal. This leads to an IM operation with a constant slip frequency which is equal to the reciprocal of the rotor time constant. The MTPA relations are derived from the condition of the IM when producing constant electromagnetic torque. A few theoretical results based on vector and scalar control concepts are: modified field-orientated control nonholonomy approach, and voltage frequency control . However, simultaneous control of machine torque and flux results in poor torque dynamics; moreover, these dynamics cannot be specified due to the complexity and nonlinearity of the controlled plant (IM).

For all the optimization techniques above, an important issue for the variable flux operation is the machine saturation effect. This effect results in varying machine inductances; hence, the assumption of linear magnetic circuits, common for standard optimization routines, is no longer valid. In addition, algorithms for the flux estimation will no longer provide accurate information required for torque and flux controls. For MTPA control, these issues have been studied in, a modification of is presented using an IM model which accounts for the effects of magnetizing and leakage saturation. The desired stator current amplitude and slip frequency are approximated as nonlinear functions of the torque reference. Field oriented control with a standard MTPA approach for speed regulation of electric vehicles is proposed in Torque and flux components of the stator current references are computed at the base of the MTPA curve as functions of speed controller output, proportional to the motor torque reference. MTPA algorithm based on direct-flux vector control (DFVC) provides fast stator flux regulation using direct axis voltage control within a stator flux oriented reference frame. Fast torque regulation is achieved by controlling the torque component of the stator current vector (quadrature), while the flux current component (direct) is not controlled. An additional control action is needed to limit the stator current amplitude. The flux reference required in order to achieve the MTPA condition in is given by a nonlinear static function of the desired torque. The nonlinear saturation effect is taken into account in using the stored computed or measured data.

TORQUE CONTROLLER DESIGN FOR A LINEAR MAGNETIZING CURVE (MTPAL)

This section deals with the design of torque–flux controllers that simultaneously guarantee an asymptotic tracking of the permissible torque references, the rotor flux orientation, and flux–torque decoupling. Flux tracking allows us:

1. to design the flux reference trajectories as a static or dynamic function of the desired torque in order to achieve the MTPA condition in steady state and improve stator current transients;
2. to avoid singularity (when flux is zero) selecting the flux reference and controller initialization.

At the initial stage, two controllers assuming linear magnetic circuits were designed: an MTPA controller with indirect field orientation and an MTPA controller with direct field orientation employing a rotor flux observer. For both these cases, current-fed control is assumed. Following these, a full-order direct field-oriented MTPA control is proposed, including proof of its asymptotic stability.

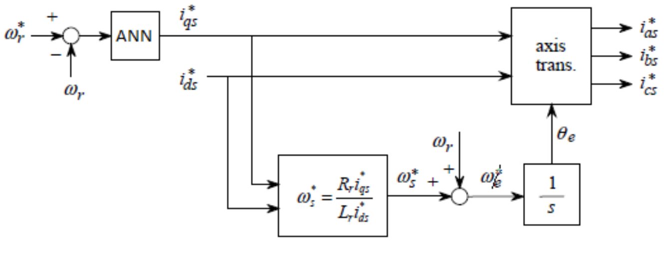

Figure 1. Block diagram of ANN based indirect vector control

A. Indirect Field Orientation for the Current-Fed IM

Indirect field orientation allows the vector control design to achieve a high IM drive performance. In a standard configuration with the independent torque and flux references, it is simpler in comparison to direct orientation methods from the point of view of practical implementation. At present, published studies address the asymptotic torque regulation problem for constant torque references. However, a complex nonlinear torque–flux dynamic is generated by an MTPA optimization making this approach unsuitable for technological applications where accurate torque tracking control is required, for example, in order to enhance passenger comfort during vehicle motion. Tracking of the smooth references is a more general solution of the torque control problem and can be considered as an extension of the fast torque regulation typically achieved with a fast flux and the torque current subsystems having high gain flux and current controllers. Torque tracking is a necessary requirement in order to successfully track the desired speed trajectories in a speed control mode.

This paper addresses the problem of asymptotic torque tracking control with the MTPA optimization for the saturated IMs. In, this problem was investigated assuming linear magnetic circuits for the MTPA optimization and controller design. This study, in order to improve the torque–flux tracking performance, takes into account the effect of saturation within the controller design.

The key contribution of this paper is a novel torque–flux tracking controller design that simultaneously provides asymptotic torque tracking of the smooth reference trajectories in the whole range of the machine torques and tracking of the torque-dependent flux references in order to achieve the MTPA optimization in steady state. Torque–flux decoupling allows the flux reference trajectories to be formulated as a static or dynamic function of the torque reference; hence, avoiding a singularity at torque zero-crossing and improving stator current transients. Flux tracking allows us to set the initial machine excitation level close to zero; hence, preserving singularity free operation. The proposed approach is based on an output-feedback linearizing control and applied to both indirect and direct (observer based) field orientations. The theoretical findings of this study and the effectiveness of the proposed approach are confirmed by a thorough experimental validation. This paper is an expanded and further developed version of the earlier conference paper.

DESIGNING & TRAINING OF ANN

An ANN is essentially a cluster of suitably interconnected non-linear elements of very simple form that possess the ability of learning and adaptation. These networks are characterized by their topology, the way in which they communicate with their environment, the manner in which they are trained and their ability to process information. Their ease of use, inherent reliability and fault tolerance has made ANNs a viable medium for control. An alternative to ANN controllers in many cases, neural controllers share the need to replace hard controllers with intelligent controllers in order to increase control quality. A feed forward neural network works as compensation signal generator. This network is designed with three layers. The input layer with seven neurons, the hidden layer with 21 and the output layer with 3 neurons. Activation functions chosen are tan sigmoidal and pure linear in the hidden and output layers respectively.

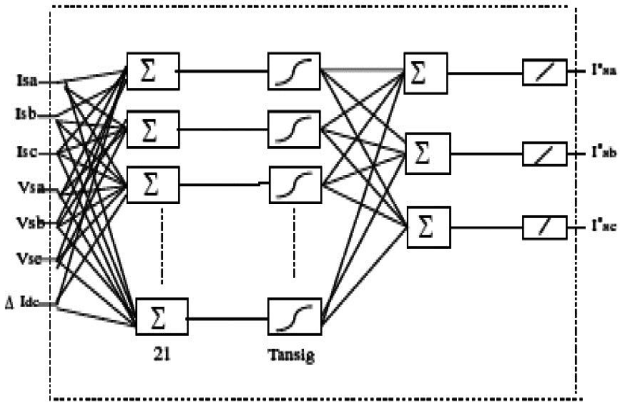

Figure 2. Network Topology of ANN

The training algorithm used is Levenberg Marquardt back propagation (LMBP). The Matlab programming of ANN training is as given below:

```
net=newff(minmax(P),[7,21,3],
{‘tansig’, ‘tansig’, ‘purelin’}, ‘trainlm’);
net.trainParam.show = 50;
net.trainParam.lr = .05;
net.trainParam.mc = 0.95;
net.trainParam.lr_inc = 1.9;
net.trainParam.lr_dec = 0.15;
net.trainParam.epochs = 1000;
net.trainParam.goal = 1e-6;
[net,tr]=train(net,P,T);
a=sim(net,P);
gensim(net,-1);
```

The compensator output depends on input and its evolution. The chosen configuration has seven inputs three each for reference load voltage and source current respectively, and one for output of error (PI) controller. The neural network trained for outputting fundamental reference currents. The signals thus obtained are compared in a hystersis band current controller to give switching signals. The block diagram of ANN compensator is as shown in Figure 2.

RESULTS & DISCUSSIONS

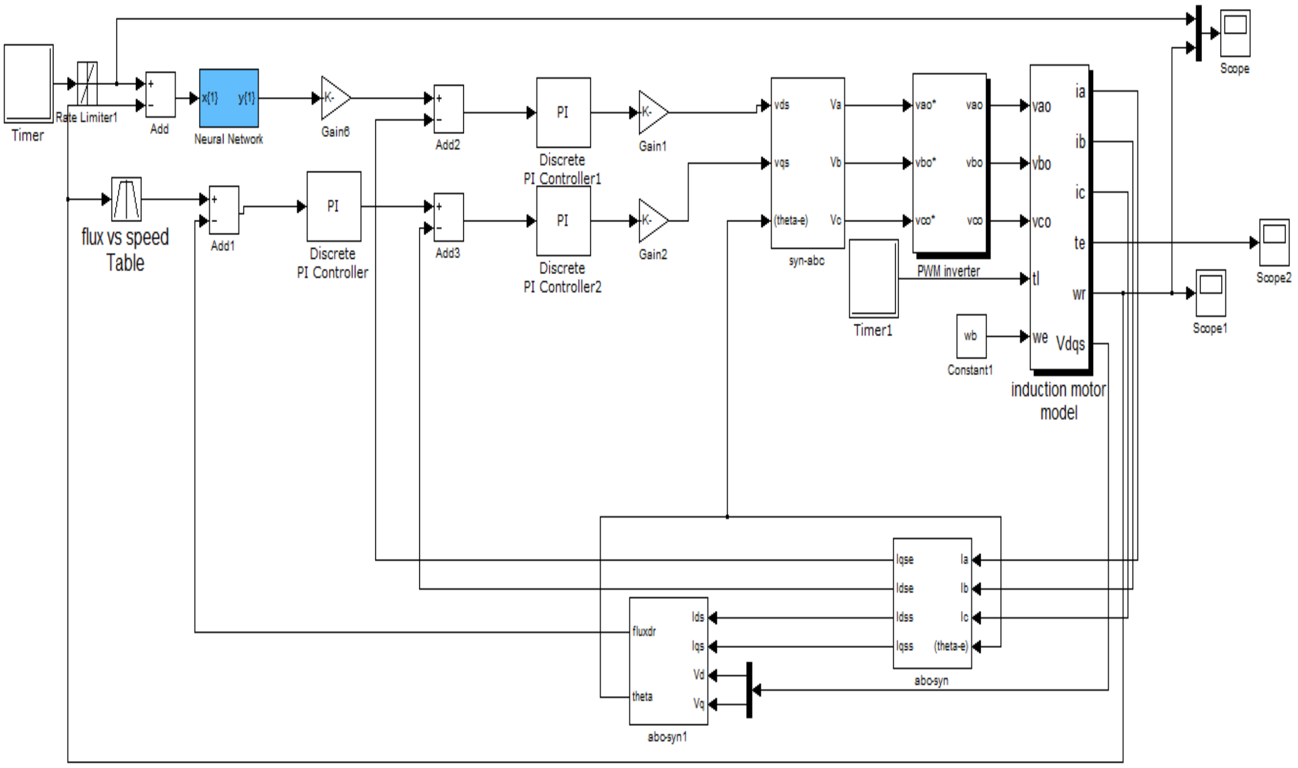

Figure 3. ANN Maximum Torque control based IM design

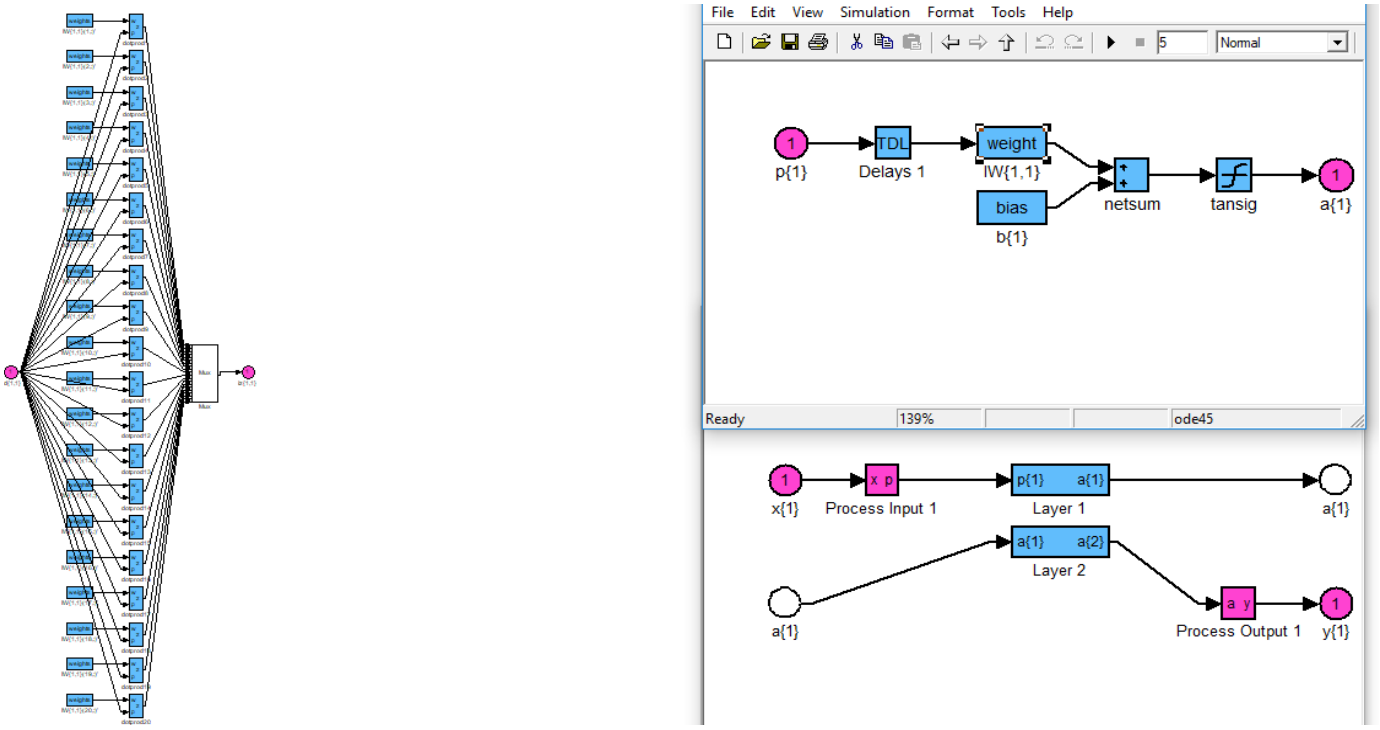

Figure 4. ANN control circuit

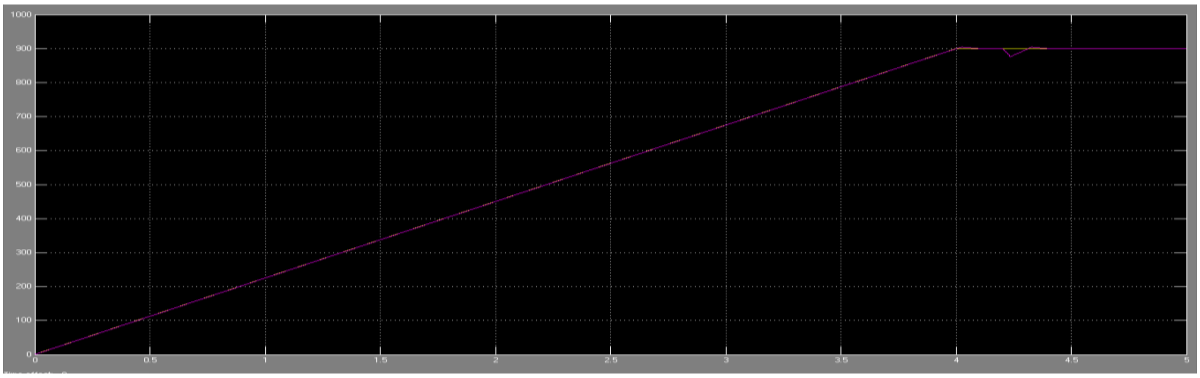

Figure 5(a) PI controller based Reference speed & actual speed

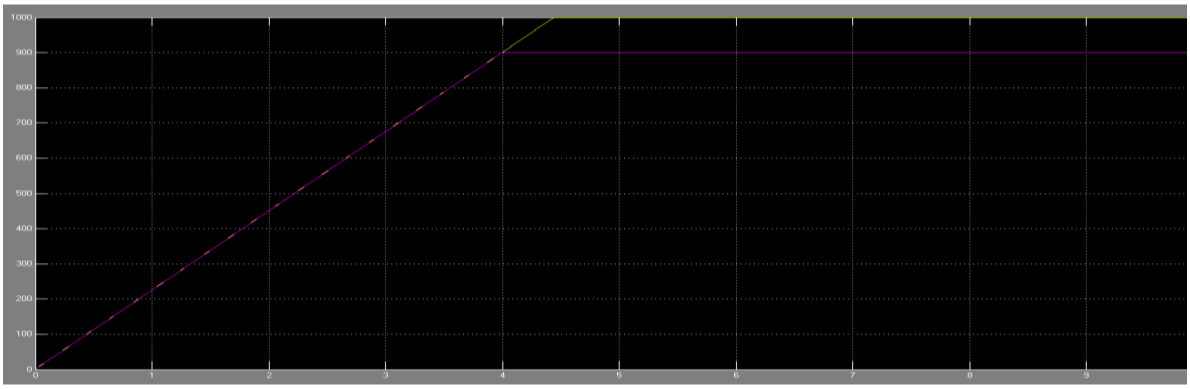

Figure 5(b) ANN controller based Reference speed & actual speed

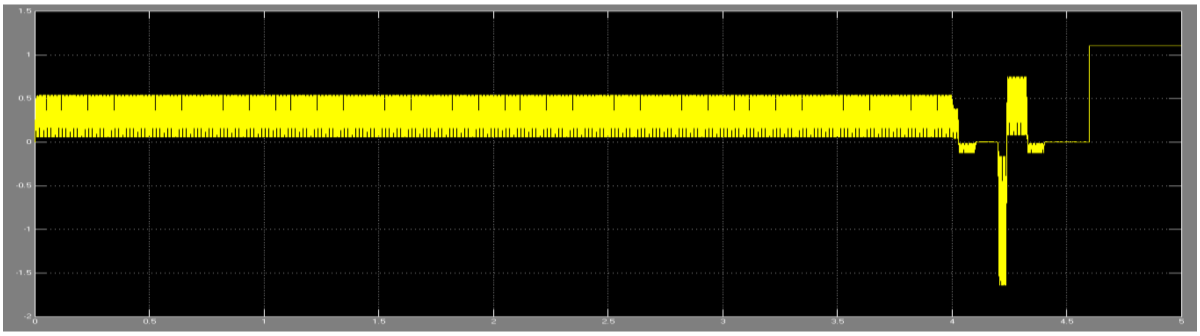

Figure 6(a) PI controller based torque

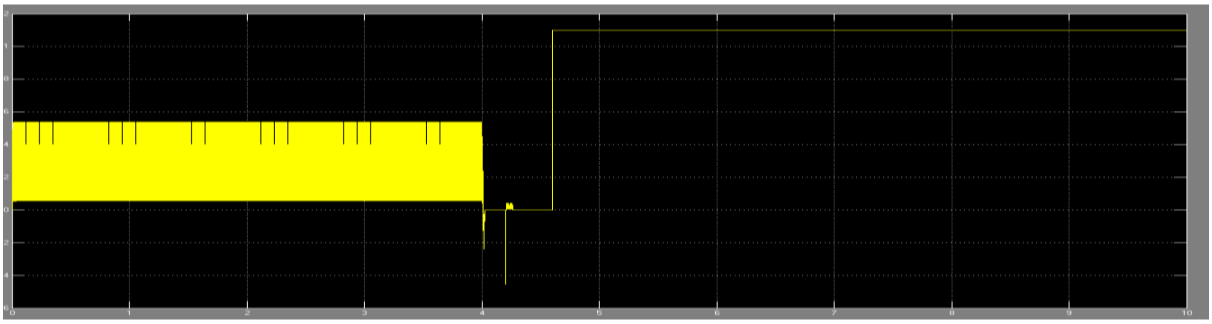

Figure 6(b) ANN controller based torque

Fig. 5 & 6 shows response characteristics about changing of command speed and load torque that command speed is 900[rpm] at 0.1[sec] and load torque is 5[*N.m*] at from 0.6[sec] to 0.8[sec]. Fig. 5(a) is command and estimation speed of PI, ANN controller, fig. 6 (a) is generation torque. Fig. 6 (b) shows expansion of fig. 6 (a) to analyze clearly. Fig. 5 (a) is part of speed rising, fig. 5 (b) is part of changing load torque. Proposed ANN controller in this paper has lower overshoot, faster stabilizing time than PI controller. Fig. 6 shows response characteristics of maximum torque control about forward and reverse operation. The MTC means maximum torque control, NMTC means non maximum torque control. Because of the generator torque of proposed maximum torque control in this paper is high more than tradition method, speed of the proposed method rises fast more than traditional method. Fig. 5 shows response characteristics about verity changing of command speed. Also, the proposed maximum torque control in this paper shows excellent response characteristics more than traditional method.

CONCLUSION

In this paper, a novel ANN MTPA field-oriented control algorithm for IM drives based on the output-feedback linearizing technique has been designed and experimentally verified. The nonlinear controller guarantees asymptotic torque (speed) tracking of smooth reference trajectories and maximizes the torque per Ampere ratio when the machine is operating with constant or slow varying torque. The two torque–flux controllers based on indirect and direct field orientation employing a reduced-order flux observer are designed. The ANN controllers and MTPA criterion take into consideration the effect of magnetic saturation in order to provide an improvement of the ANN tracking accuracy during the whole range of machine torques. Since the maximization of torque per Ampere ratio is similar to the criterion of active losses minimization, the machine efficiency at light loads is improved. The external speed tracking controller for the torque control system is designed and presented as well. The methodology of the flux reference calculation as static or dynamic function of the required torque is given, which allows us to achieve MTPA optimization in steady state, guarantees singularity free operation with small initial excitation for zero torque and can be used as a mean to improve current transients.

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