REVIEW PAPER

A REVIEW OF THE CONTROL TECHNIQUES FOR BRUSHLESS DIRECT CURRENT MOTORS

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Abstract This paper surveys the literature of the brushless DC motor speed control techniques. The paper should prove useful to both researchers as well as practising engineers as a signpost to the current state of the art. Based on the review some further studies are suggested.

Key Words Brushless DC Motors, Control Techniques

چکیده نوشته حاضر مقالات مربوط به روش های کنترل سرعت موتور DC بدون جاوربک را مورد بررسی دقیق قرار می دهد. این نوشته می تواند بعنوان رهنمائی برای پژوهشگران و نیز مهندسین عملی در زمینه وضعیت موجود روش های کنترل مزبور بکار رود. براساس مرور انجام شده، بعضی مطالعات آتی پیشنهاد شده اند

INTRODUCTION

To limit the length of this review we have confined ourselves almost entirely to the work done in the last ten years or so, no aspersion to the preceding 30 years, during which much of the conventional control techniques was worked out and many valuable data obtained. Nevertheless, it is also interesting to reflect that the majority of the adjustable speed drive systems in existence today have been designed since power electronic and microprocessor components have become available.

The number of electrical motors and adherent circuits which are used as control devices has increased considerably in the last few years. Modern control techniques are widely used in order to obtain a robust smooth control of the electrical motor drive. The method chosen depends on the applications and specifications of the performance to be met.

The main aim of this paper is to review the work done in the area of the speed control of brushless direct current motor (BDCM). The review should prove useful to both researchers and practising engineers as a signpost to the current state of the art. Although not every paper published on the subject is cited, it is believed that those that are mentioned would give a fair indication of the progress made thus far. It should be mentioned, however, that reviewing the results of several years' work reported by a hundred scientists and engineers is bound to some omissions, but it is hope that none is serious. It should also be mentioned that some of the advantages and disadvantages of the control methods, applied to the BDCM, are generally applicable to other electrical machines as well.

Many control techniques have been applied on different drives. In section 1, hysteresis current controller is incorporated with an inverter supply PWM inverter. It is discussed why this technique has been empolyed, how it might be operated with a square-wave inverter, and what a software oriented method is. In section 2, the current PWM control technique is discussed. It is desirable to control BDCM in such a manner that an optimum performance is obtained. In section 3 different ojbective functions such as torque, efficiency or position are discussed. In section 4, an attempt is made to present a comprehensive picture concerning more recent control techniques. These techniques include state observer control, adaptive control and sliding mode control. In section 5, the progress made in the vector control technique in the last decade is reviewed.

1. HYSTERESIS CURRENT CONTROL TECHNIQUE

In recent years Permanent Magnet Direct Current Motors (PMDCM) are rapidly replaced by Permanent Magnet Synchronous Motors (PMSM) in the precise applications such as machine tools and robots. Advantages of PMSM over PMDCM are: **1)** the absence of brushes and commutators, **2)** lower inertia, **3)** a better heat transfer and **4)** a smaller volume. To achieve a fast response on four-quadrants along with a smooth control, the PMSM is often supplied through the inverter. Many methods are recommended for the control of an inverter supplied PMSM, which give the required performance in servo-drive. One of the most general methods is the use of a voltage source PWM inverter with hysteresis current controller.

The aim of the method is to minimize the error between the reference three phase line current and feedback three phase motor current in a hysteresis band using the transistors of the inverter. The reference currents are produced in such a manner that the resultant vector of the stator current becomes perpendicular to the rotor flux vector. This is a necessary condition to maximize the torque per ampere of the motor [1-6]. PMSM supplied by a square-wave inverter has a better performance compared with the other available methods without requiring complicated strategies; the direct torque control is obtained simply by controlling the amplitude of the currents in the armature and their difference with the emf. In this way the dynamic performance required for modern applications such as robotics and machine tools, is obtaiend [7]. Figure 1 shows the principle of the control system and Figure 2 illustrates the simulation and experimental results for a typical PMSM. A brushless DC motor drive has been simulated and analyzed using hysteresis, ramp comparison and predictive current control schemes and the results are compared the advantages and disadvantages of each technique and the range of applications are discussed [8].

Microprocessor-based controller may achieve complete software control which can improve the performance of the motor [9]. Sometimes such a software oriented method is not a convenient procedure for the control. The reason is that the speed

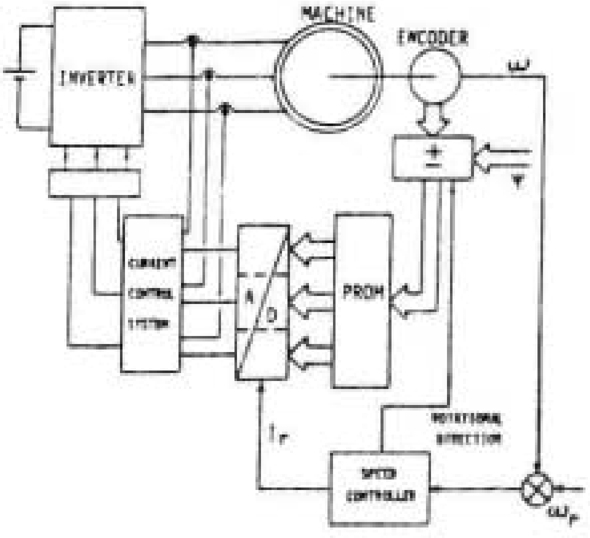


Figure 1. Principal of hysteresis current control

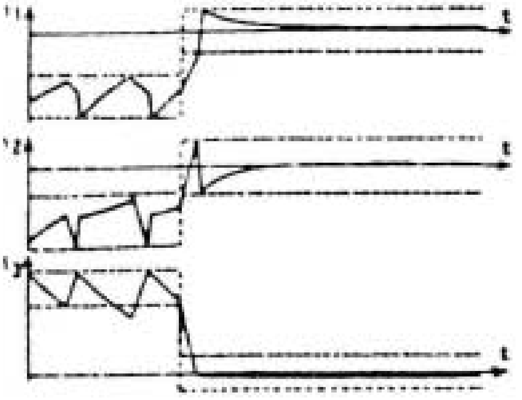


Figure 2. The three-phase currents of the hysteresis current control.

of the signal processed by the software is lower compared with that of the hardware. Therefore, a combined method using both software and hardware has been designed to control the drive, to obtain a flexible and reliable control method, and achieve a better performance for the system [10].

In spite of oldness, the hysteresis current controller is still applicable to BDCM. In many industrial installations, the presence of the shaft sensor substantially reduces the over ruggedness of the drive. In addition, the drive system may be more expensive and less reliable [11]. Therefore, suitable approach to the position sensor elimination of the motor is required. This was probably the main reason for introducing hysteresis current controller without a sensor. A simple control system is presented for a PM motor drive with sinusoidal phase current supply in [11], which provides a wide range of speed range without a shaft sensor. Stator voltage and current signals are used to construct a flux-linkage position signal through which the phase angle of the stator current can be controlled to maintain near unity power factor over a wide range of speed and torque.

In a number of cases, sensor elimination schemes for the back *emf* of the motor are integrated in order to estimate the rotor position.

An indirect approach to position sensing can be used in an interior permanent magnet (IPM) synchronous motor. The phase inductance of this motor varies as a function of the rotor position and the ratio L_q/L_d is greater than 2.5. The larger permeance on q-axis in the IPM motor is another major advantage for variable speed drives. For example a higher permeance on the q-axis reduces the inverter switching frequency, thus reducing the inverter losses[12]. The phase inductance of an IPM motor can be calculated from the current and the voltage, and then used for estimation of the rotor position with the help of a look-up table. In this design, a current regulator using constant frequency switching is used with the hysteresis current controller to circumvent the problem of random switching [13]. Two approaches have been presented in order to eliminate the sensor. The basis of the proposed sensorless control algorithm is to use the differences between the detected actual state variables and the estimated state variables, the latter are calculated from an equivalent motor model in the controller. Therefore, the approach is different depending on the type of the motor model, the voltage model, and the current model [14].

2.CURRENT PULSE WIDTH MODULATION (PWM) CONTROL

In a PWM controller, rotor position of BDCM is generally measured by a digital shaft encoder. Under the assumption that the pulse period is much smaller than the time-constants of the system, the control system can be modelled by a linear discrete time transfer function with the pulse width playing the role of the control signal. This model enables the application of classical control engineering to the design of pulse width modulated systems for the control of BDCM [15].

The precise current control is a key technology to realize high-performance drives such as BDCM. Consequently, the procedure to obtain precise current control has received much attention [16].

Among the existing current controls, the current hysteresis-controlled PWM and the sub-harmonic PWM control have been widely used. In the hysteresis-controlled PWM, the sinusoidal current is maintained within the hysteresis band, but the voltage waveform is not necessarily desirable and the switching frequency is changed according to the operating condition of the motor. On the other hand, while the sub-harmonic PWM has no problem associated with the voltage waveform and the switching frequency, they suffer from the steady-state phase lag in the high-frequency operation. Although some researchers have given solution to minimize this phase lagging, there still exists a problem of acoustic noises generated by the motor. That is why a new current control for BDCM using digital signal processors is employed. In this system, DSP performs not only the current control but also a necessary control processing such as rotor position sensing, speed calculation and a calcualtion of the torque command through the speed control loop [16]. Figure 3 presents the adaptive current control system and the control system configuration.

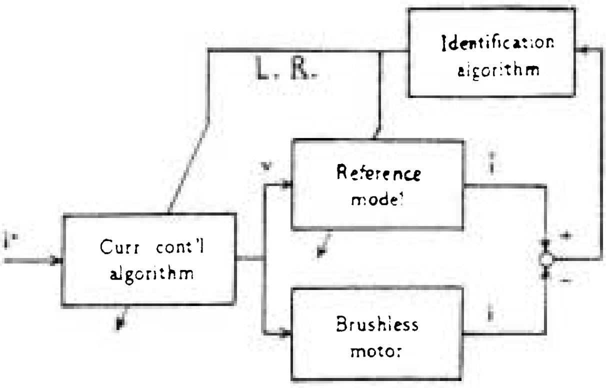


Figure 3. Adaptive current control system.

The above mentioned current control technique has been also used for sensorless machines. This interesting method employs the on/off states of the inverter switching devices for the rotor position estimation [16].

Another method has been suggested that directly uses the instantaneous voltage equation of the BDCM with a sinusoidal flux distribution. Without position sensor, the controller has no information about rotor position, and therefore, the controller determines the applied voltage according to the hypothetical rotor position. While the applied voltage through the inverter can be measured, directly, the ideal applied voltage can be measured under the ideal condition which happens when hypothetical rotor postion is coincides with the actual one. In such a condition, the ideal applied voltage can be calculated by using the instantaneous voltage equation of the motor and the detected current. The findings indicate that the difference between the actual and the ideal voltages is proportional to the angular difference between hypothetical and actual rotor positions. Therefore, self-synchronization is possible by reducing the angular difference to zero. Furthermore, in this control algorithm, the actual applied voltage can be obtained from inside the controller with a knowledge of the PWM pattern, the dead time information, and the DC voltage value; in such a case, then, there is no need for measurement [17]. The outputs of the system are shown in Figure 4. Figure 4a shows a comparison between the estimated and actual rotor positions under sensorless regime. The agreement between the two curves is visible. Figure 4b illustrates the step response to the reference input from 250 to 750 rpm. Figure 4c presents the speed reversing characteristics when the reference input is between-2000 to 2000 *rpm*. It is clear that in both cases, even for a transient condition, the actual and estimated speeds are very close.

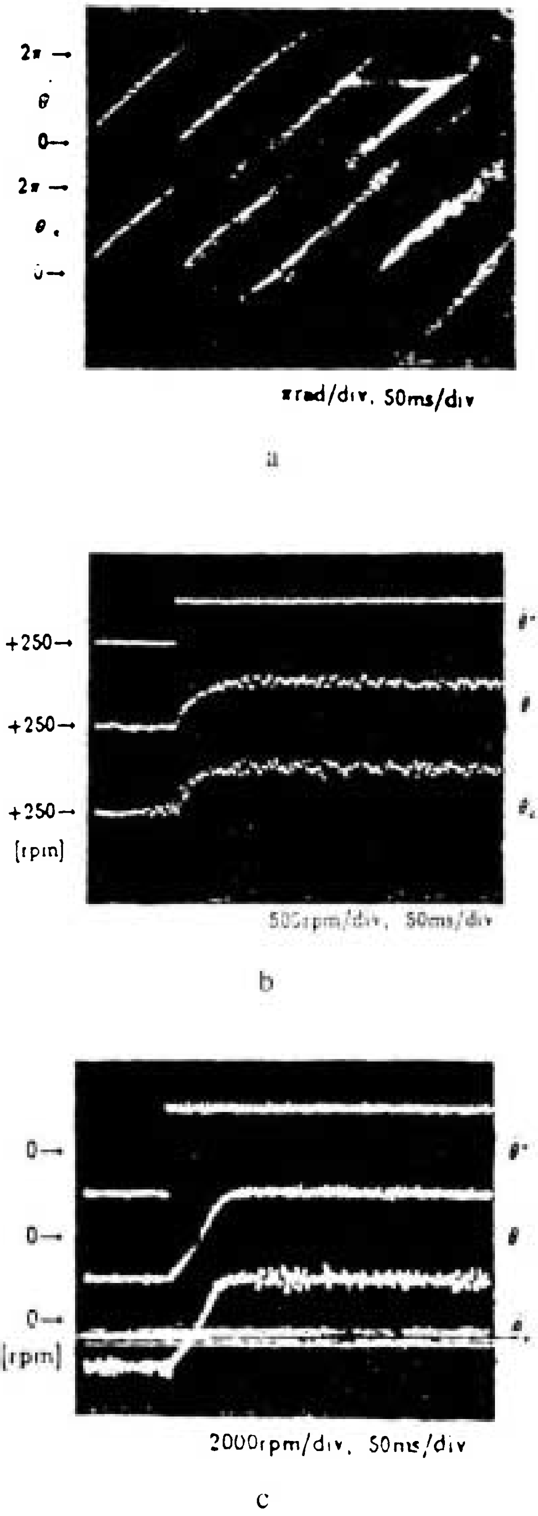
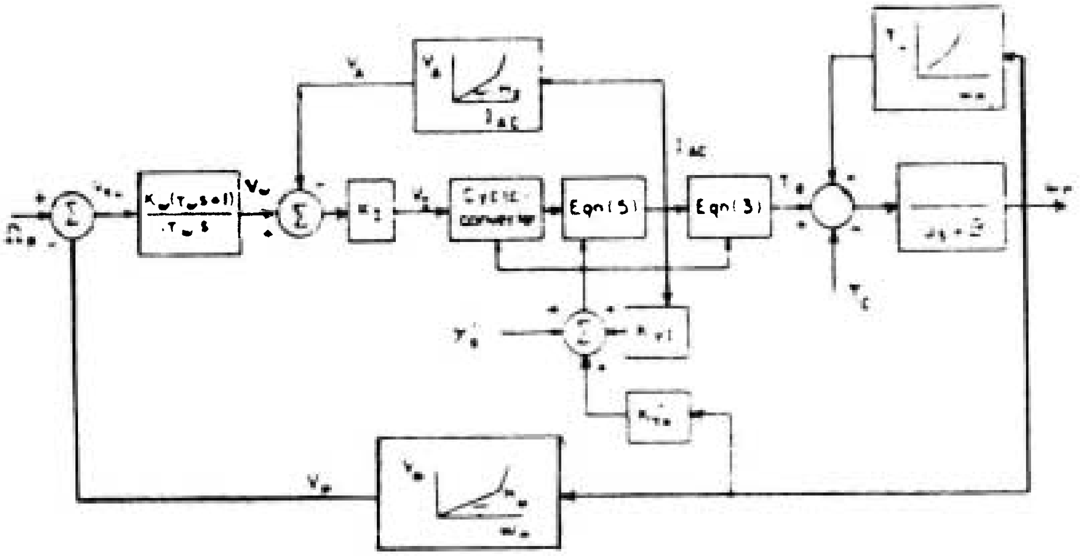


Figure 4. **a**) The actual and estimated rotor position, **b**) step response of speed, and **c**) reversing characteristics.

3. OPTIMIZATION OF CONTROL PERFORMANCE OF BDCM

3.1. Torque Optimization

Torque ripples in BDCM are mainly due to fluctuations of the field distribution and the armature MMF which depends upon the motor structure and the feed current waveform. At high speeds, torque ripples are usually filtered out by the system inertia, but at low speeds, torque ripples produce noticeable effects that may not be tolerable in applications such as positioning robotics. For this reason the elimination of the torque ripple has been paid due attention and suitable approaches have been suggested [18]. This is why several methods have been recommended for eliminating the torque ripples. These methods are mainly based on the optimum design of the motor using a new control algorithm. Here the control techniques and design methods are taken into account [19]. One of the most popular approaches is to use programmed excitation waveforms for the phase currents to cancel the pulsating torque components. A simplified control block diagram which applies to many of these related techniques is shown in Figure 5. As shown in this figure, for a base line three phase machine, the individual phase current command waveforms are programmed as the predetermined function of torque command and angular position to generate the desired average torque while cancelling the pulsating torque components. One of the earliest of these techniques [20] that was proposed for trapezoidal PMDC drives calls for adjusting the crest width of the square of trapezoidal-wave current excitation waveforms in order to minimize the pulsating torque. Subsequently, the majority of proposed algorithms have been based on shaping the individual phase current waveforms by injecting selected harmonic components to perform the desired pulsating torque cancellation. For example, one of the earliest schemes for three phase PMDC machines



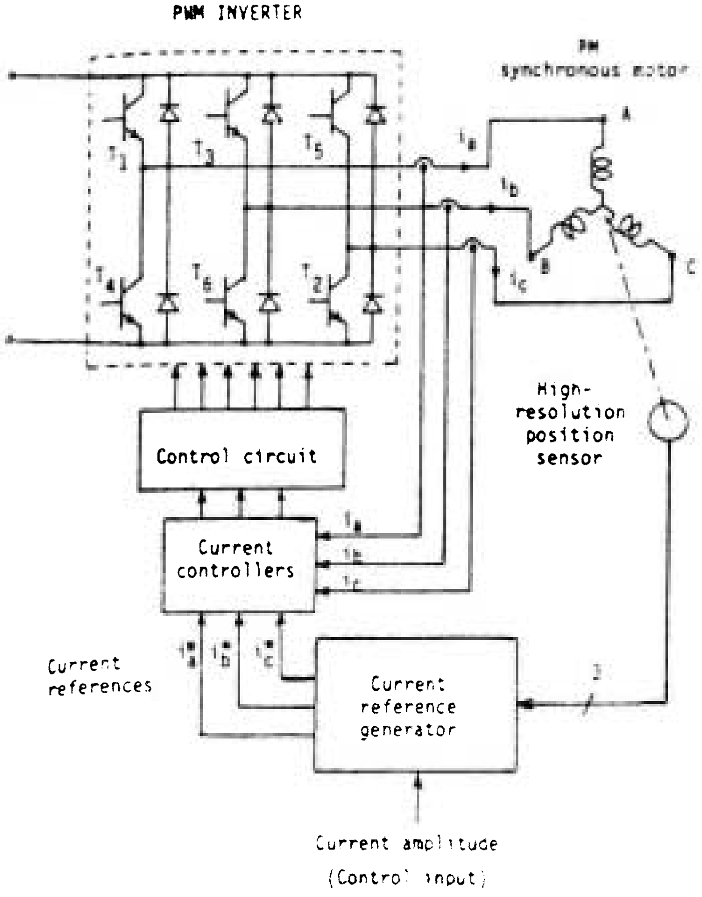


Figure 5. Three-phase feeding of BDCM for eliminating torque ripples.

[21] was designed to minimze the sixth and twelfth harmonics of torque since these are typically the dominant components in the pulsating torque waveform.

One of the appealing features of the resulting optimized current waveform for torque ripples elimination in surface magnet PM machines is that all of the harmonic current components scale in direct proportion to the fundamental due to linearity of the machine's basic torque equation [22].

Whereas only four of the pulsating torque harmonics are cancelled using closed-form solutions as proposed by Piriou and Razek [23], iterative calculations are employed by others [24] to determine the necessary current harmonics to cancel several additional pulsating torque components.

Furthermore, some attempts have been made to generalize the harmonic injection approach by employing numerical optimization techniques in order to calculate current wave shapes for eliminating all ripples and cogging torque components up to an arbitrary high harmonic order [22,25,26].

Another important approach comes from recognizing the fact that the instantaneous torque contributed by each machine phase is proportional to the product of the back-emf and phase current. As a result, the optimized current can be derived as being proportional to the reciprocal of the back-emf under the appropriate condition. The application of this technique to sinusoidal PMDC machine at dq synchronously rotating reference frame is proposed in [27] and in stationary reference frame in [28] using back-emf waveforms which have been calculated by means of finite element analysis.

An approach to minimizing torque ripples in BDCM is an optimum combination of counter emf and feed current waveforms, taking into account motor structure and stator feeding method [29]. This method is very flexible, but close control of the current in each phase is required. A block diagram of three phase feeding scheme for BDCM is depicted in Figure 5 [29]. The conventional current controllers are aimed to force the stator phase currents to be as close to the reference supplied as possible for a constant torque command. These controllers are normally a combination of analogue and digital devices.

In recent years many researches have concentrated on the direct control of inverters, in which the switching singals for inverter are generated directly by microprossors. A great advantage of direct digital control is that it has made possible new control algorithms that are not easy to implement using conventional analogue current controllers. It is also very easy to modify or upgrade the control programs [30]. The combination of the three phase inverter and PM motor is regarded as a torque producing unit controlled by a three-bit digital command from the torque controller. The instantaneous torque feedback signal can be estimated from the knowledge of the instantaneous currents and rotor position. Thus, by designing an appropriate control algorithm, it is possible to eliminate torque pulsation by direct control of the inverters. This leads to the optimum performance of BDCM and improvement of the motor's capabilities.

A current harmonic injection technique is used [31] by adopting a real-time harmonic flux estimator in order to calculate the sixth and twelfth harmonic pulsating torque components rather than depending on stored coefficients. An alternative approach [32,33] uses a Gopinath observer to estimate the machine's torque in combination with a Fourier decomposition to determine the compensating current comnand to cancel the pulsating torque.

3.2 Efficiency Optimasation

A PM motor can be operated with optimal efficiency for a given speed and torque, by adjusting the amplitude of the voltage. This condition departs somewhat from the condition of maximum torque per ampere in machines where there is an appreciable core loss. The departure will be significant at high speeds. PM synchronous motors have traditionally been employed in self-controlled drives, in which the inverter frequency is dictated by the rotor speed. Such motors operate normally at a fixed torque angle between the stator *mmf* and rotor position (voltage is proportional to the speed). This feature, while advantageous for torque control, makes the BDCM ill-suited to an efficiency-optimizing control, where the voltage must be adjusted to minimize the losses. An efficiency-optimizing control is more easily achieved with frequency-programmed drive where there is an independent control of the voltage and frequency [34]. A frequency-controlled PM synchronous motor drive is used that employs an adaptive control to find the maximum efficiency operating point at any speed and load [34].

The stability problems associated with frequency-controlled synchronous motor drives have been extensively reported in the literature. A PM motor has no damper winding and it cannot be treated similar to a synchronous motor. However, a mid frequency instability similar to that observed in hybrid PM stepping motors may be expected.

Krause [35] used tachometer feedback to modulate the phase of the voltage applied to a reluctance synchronous motor in proportion to the inverter frequency. A quasi-steady-state analysis of the PM synchronous motor is developed that shows how perturbation in the DC link current can be used as a feedback signal. The analysis also yiedls a simple approximation useful in selecting the feedback gain for the stabilizer loop. The two principal control functions of this drive, the efficiency optimization and stabilization, are implemented with just one easily measured signal, the DC link current. No AC current sensors or speed sensors are required [34].

3.3. Optimal Control of Position

In the area of electrical drives, microprocessor technology is advanced to the point that modern theoretical optimal control methods can be put into practice [36]. In contrast to the previously considered time-optimal control, the optimal control with quadratic performance index is proposed. The general optimal control solution applies only in the case of linear, time-invariant and undisturbed systems. Electrical drives are, in principle, non-linear systems, because of current, voltage and speed boundaries. In addition, their parameters such as resistance, inductance and inertia can vary. Also in real drive systems, the differences such as load torque on the motor shaft, must be taken into account. For these reasons, the idea of using the model-following control in the optimally controlled drive is proposed.

A linear time-invariant system which is disturbance free, will be used as a model. The difference between the state vectors of the model and those of the real system is used in order to generate an additional control signal. This signal is corrected by the appropriate choice of the feedback factors and the control of the real system so that the difference either moves close to zero or is drastically reduced. Using such a method can reduce and eliminate the disturbance. This method is used in positioning drive system with PMSM. Of course, the practical limits in the method are accounted for [36]. Figure 6 represents the block diagram used for computer simulation of the drive system. Figure 7 shows the simulation and practical results based on the above-mentioned method.

However, the machine equations for PMBDC are strongly non-linear and a systematic method has not yet been presented for the optimal control of the machine. One of the previously mentioned methods is the linearization of the non-linear system around the operating point which satisfies only for small variations.

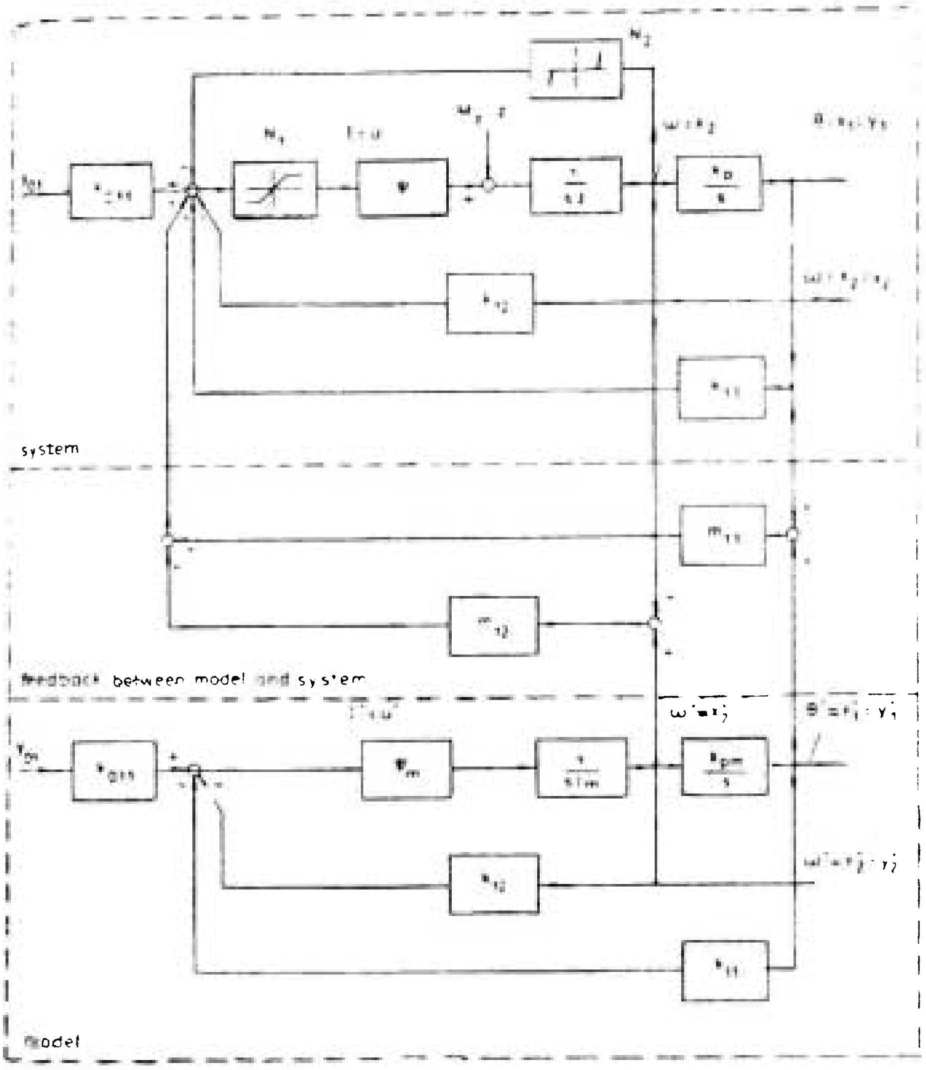


Figure 6. Block diagram of the optimal model-following drive system with PMSM.

Another method for system linearization has been suggested. The nonlinear system is transformed to such an equivalent linear system to which a linear control system can be applied. In this field Brockett [37] in 1978 showed that by the help of nonlinear transformation and state feedback, a non-linear single-input system can be replaced by controllable a linear system. Then Jakubczky and Respondek [38] extended the previous works and found the necessary and sufficient conditions for such non-linear transformations in which a non-linear multi-inputs system is transformed into equivalent controllable linear system. Su [39] presented a more general condition compared with the Brockett's transformation [37] and finally Hunt, Su, Meyer and Hunt [40] generalized Su's work to multi-inputs non-linear system. This full linearization method transforms a non-linear model to a controllable linear model [41]. This method can be now used to obtain the linear system model, and by the help of the existing algorithms for optimal control, the position is controlled in minimum time. The control law satisfies

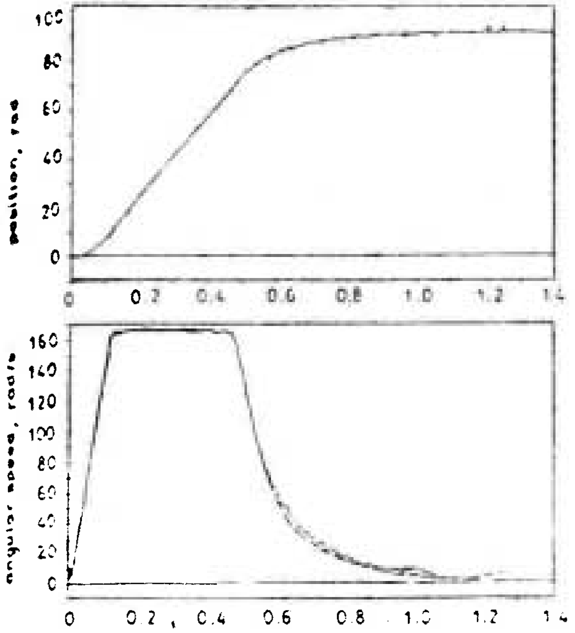


Figure 7. Simulation and experimental step response of the drive system: **a)** position, **b)** speed.

both transient and steady-state modes of operation [42]. This linearization feedback method is also used to control the system with the magnetic saturation and reluctance change. For this purpose, BDCM is taken to be a multi-variable non-linear coupled system and its control is possible using the existing route control algorithms for multi-variable systems [43].

4. OTHER CONTROL TECHNIQUES

4.1. State Observer

An electrical motor may be employed as its motional sensor. The motion influences the motor voltage and current which, in turn, give information about the motion. For this purpose digital signal processing method is required. The use of this method can extend the electronic control of the machine. As a first step, the state observer can be used to estimate the electrical and mechanical states of PMSM.

Estimation of the motor motion using the electrical parameters is not a new subject as there are many recommended methods. One group includes the diagnosis methods of the waveform which are applicable to both PM and VR motors. However, all the required pieces of information about the waveform may not be provided and the estimation is not very accurate. In fact, there will be a motional voltage when the rotor moves, and this voltage contains information about the rotor position. One of the methods to derive all required pieces of information from the waveforms is the dynamic modelling of the motor. This dynamic model is run with systems having inputs similar to those of the real motor and minimizing the error between output of the model and that of the real system. The state observer develops such an idea. In a state observer, the output is defined as a combined states, and this output is compared with the equivalent measured output from the real motor.

The idea of the state observer has been used on different motors. One of the first works was introduced by Ucda [44] in which a non-linear estimator was fixed on an infinite-bus connected to a non-salient synchronous generator. Okongwa suggested a very simpler structure [45] in which a linear observer based on a linearization model of a synchronous generator has been studied. Lumsalaine [46] suggested an observer for VR motors where the space variations of the phase inductances affect the phase fluxes. This observer has been built to model the motor dynamic space variations and to estimate accurately the rotor position at a constant speed. Yamashita [47] designed an observer for a synchronous generator which was linear due to a constant gain but he used the non-linear model. A complicated structure has been designed by Gharbon and Cory [48] in which the theory of the optimal estimation is applied to the osberver, and the random as well as measured noises constructed by signals such as the position, velocity and current, which contain information on disturdances and parameter variations. Consequently the entire control system is compeletly closed and has a desirable performance. This method operates based on the voltage space vectors of the six pulse inverter, each pulse corresponding to a structure of the variable structure system (VSS). The combination of the space vectors is determined according to VSS logic so as to minimize energy loss, switching frequency, etc. [54]. This method has been also experimentally applied and tested successfully [55].

In Reference 56 a similar method has been described for a square-wave driven BDCM which controls the motor speed using SM. In further steps, designing and manufacturing of a VSS controller have been followed on an experimental sample. In this method the controller is designed in continuous time domain and it is then transformed to a discrete time domain by a constant sampling time. Of course the sampling speed cannot be very high. Features of a quasi-sliding system has been then described and the slip line has been extended to the slip region. The size of this region depends upon the sampling speed and switching gain [57,58].

The experimental results of this system for a no load motor is presented in Figure 9, which confirms the previously obtained simulation results.

The changes carried out on the SM control method is not continuous which imposes stress on the controlled device. That is why the designers are not interested in application of the SM control. The SM observer is a method for a stable estimate of the state variables of the controlled object. When a SM observer is used, no stress is applied on the system. An SM observer has also other advantages such as robustness against disturbance. In Reference 59 a new position-and-velocity sensorless control of BDCM using adaptive SM observer is presented. The new observer is robust to disturbances including the measurement noises.

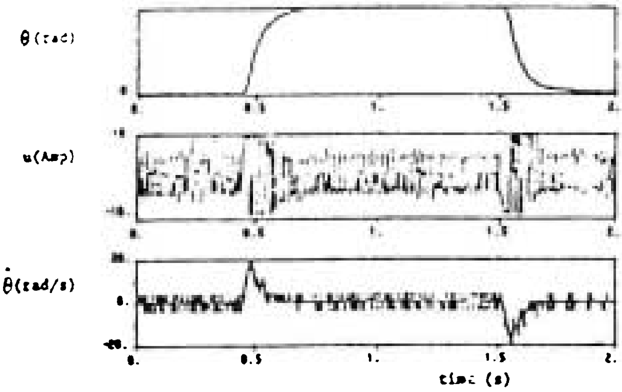


Figure 9. The experimental results for the built control system.

5. VECTOR CONTROL

In the last decade one of the primary limiting features of PMSM has been the lack of excitation control. As a result, the internal *emf* of the motor rises in proportion to the motor speed. Such a behavior is desirable in the so-called constant torque range, because it is consistent with the constant voltage/frequency control method. When the voltage limit of the inverter voltage is reached, the motor enters the field weakening or constant power model of operation. The internal voltage must now be adjusted to be compatible with the applied converter voltage. However, because of the fixed field of PM motors, the internal *emf* of the machine continues to increase as speed increases. Consequently the motor power factor leads and the inverter current increases. If a current source inverter is used, the voltage stresses on the inverter elements continue to rise. These problems have lead to investigations of the idea of field oriented control for PM motors [60].

One of the first methods recommended for a field-weakening control of PM motors was utilizing the demagnetization due to the armature reaction. This scheme enlarges the operating speed range of the PM motors. The quick response of the current controller is desirable in the precise servo system. Generally transistors of PWM inverters are switched by signals through hysteresis comparators, comparing the current references with the feedback currents. However the current control scheme faces two following problems:

1) The potential variation of the three-phase due to the zero sequence component; and

2)The switching frequency variation corresponding to the load condition [61].

An interior PM (IPM) is used where a variable speed is required [62]. One of the advantages of this machine is its constant power feature, which may be acheived in a wide range of the speeds by field-weakening scheme. Since the field-weakening of a PMSM is not directly possible, the airgap field-weakening is used, which is similar to that of the armature reaction of a DC machine. Saturation of a current regulator in IPM is employed for field-weakening. To do this, an algorithm has been given which is sensitive to the saturation of the current regulator. As a result, a good performance is obtained for IPM in a wide range of speeds [63].

In the available techniques, the motor must operate on the trajectory in which the torque/current ratio is optimal. However, the current regulators and voltage source limits are problems in generating torque in the high speeds [62,64].

In order to suppress these limitations, two methods are suggested. First, the current regulator is designed for frequencies below the threshold of saturation. Such a design has no general use because of its complicated configurations [64]. The second method is the feed-forward control which eliminates the dependency of the back-*emf* and inductive voltage drop upon the frequency, in such a manner that the steady-state current error for the all speeds (considering the saturation limits of the current regulator) diminishes. However it is possible to improve the torque generation by injecting an additional current in the direction of the rotor flux axis [64]. Figure 10 illustrates the block diagram of this control scheme.

A number of techniques have been recommended to overcome the limitations of the current inverters, in which attempts have been made to extend the speed range of the machine [65, 66].

The effective current vector control method and the drive system, in which the current phase angle is actively controlled, are examined for high torque operation. Several characteristics such as torque, power factor, efficiency, power capability and so on were studied in detail by the computer simulations and experimental procedures. Performance characteristics are affected by the motor parameters which depend on the rotor configurations and permanent magnet geometry. Since the effective airgap of an interior PM motor is smaller than that of a surface PM motor, reluctance torque can be produced. Effects of the motor parameters and rotor configurations are also examined considering the inverter capacity. The tendency toward magnetic saturation and demagnetization PM due to the armature reaction are also studied [67].

Control problems of IPM drives are pointed out in [68]. The adoption of flux-oriented reference frame is suggested for robustness control. A flux observer that minimizes the sensivity to errors on the measurements and on the magnetic model is proposed. Suitable loci in the dq state plane are related to the drive performance in different working conditions and the permissible operating area is defined. The suggested control strategy, implemented in a prototype drive, is verified by findings of experiments [68].

An sensorless algorithm is proposed in [69], which is based on the idea of calculating the rotor

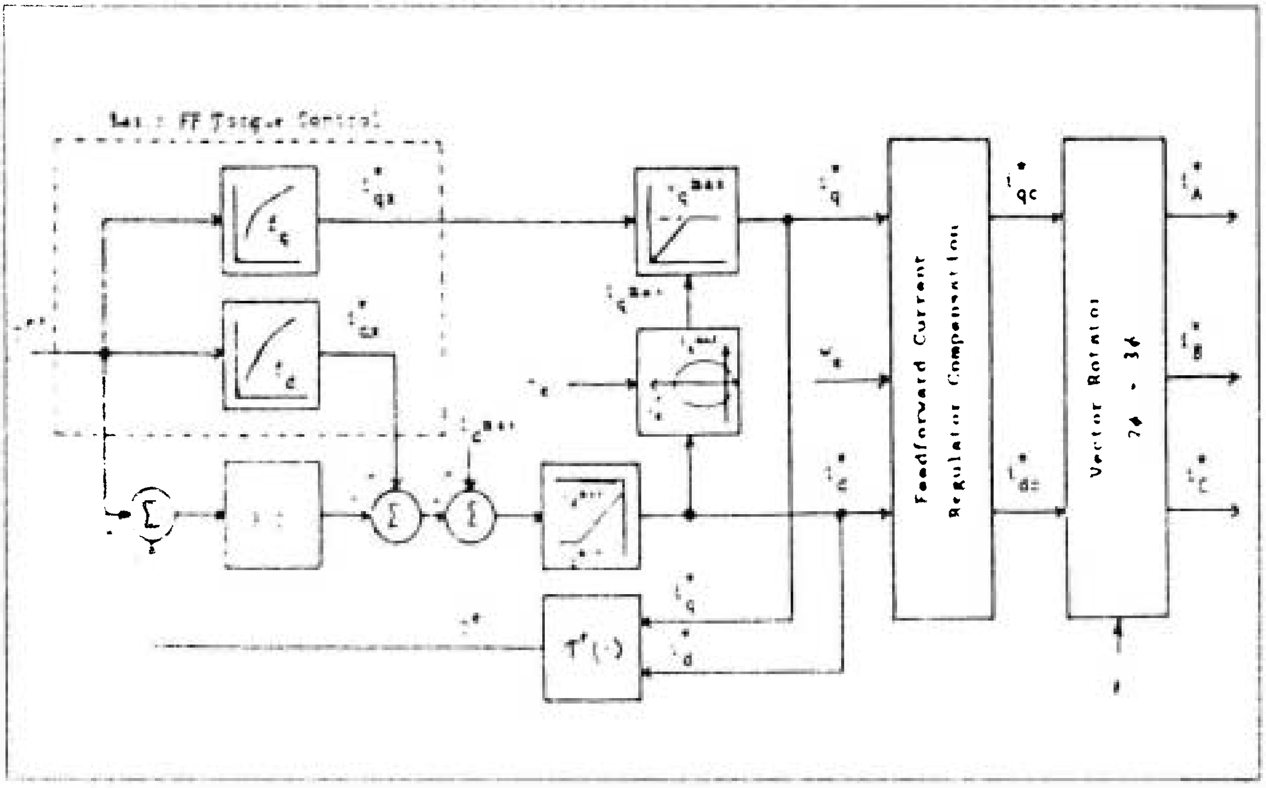


Figure 10. Block diagram for torque drive controller using a new field-weakening algorithm.

postion through an estiamted load angle and the instantanous stator flux position obtained by stator voltages. A speed feedback signal is obtaiend by means of a state observer [69]. In the supplementary works on the vector control, the following trend is followed [67].

1) A closed-loop torque control system is implemented with precision estimation of feed-back torque taking into account the machine saturation, nonlinearity, and temperature sensitivity of the NeFeB magnet. A high gain torque loop linearizes the plant characteristics and permits high bandwidth speed and position control systems.

2) Total stator flux is programmed as a function of the torque to improve efficiency at the light load. The flux is controlled in closed-loop fashion with estimation of feedback flux.

3) Control in the constant-torque region is based on vector control where the direct axis is oriented to stator flux (instead of magnet flux). This orientation gives faster response [70-73], because active and reactive currents of the machine are determined to control the torque and stator flux, respectively.

4) The control in the flux-weakening constant-power region is based on the orientation of the torque angle of the six-step square-wave voltage. Vector control in this region is intentionally suppressed for efficiency improvemet of the inverter-machine system.

5) The transition control between the PWM and square-wave modes is smooth for all conditions of operation.

CONCLUSIONS AND SUGGESTIONS FOR FURTHER STUDIES

This paper has presented a comprehensive review of the state of the art in the field of control strategies for PMSM or BDCM. It is hoped that the description on the different control techniques will give the reader a better understanding of the BDCM control and make the choice of a technique for his application easier. The number of techniques already available is large, but the quest for better techniques continues.

In order to clarify the subject, digital control problem and impressive growth of the modern control have been described and applications of BDCM and its control techniques have been discussed. Drive technology progress in recent years is indebted to the advanced power electronic and microelectronic devices which facilitate the application of the complicated control techniques. The microelectronic devices are fairly fast and very precise and quite flexible. Various microelectronic and associated power electronic circuits may be used in different applications and forms. Although many control techniques have been covered in the literature, much is yet to be done in the area of BDCM control. The following are some of the topics for further study:

- To design the high power density machines using new magnetic materials;

-To improve and make cheaper power electronic converters;

-To develop a completely digital control by microelectronic circuits using the ordinary and available chips and employing software for high level controllers;

-To use self-regulated and adaptive functions for variable load drives;

-To employ the optimal control strategy for higher level objective functions.

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