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Improving the Performance of Permanent Magnet Synchronous Motor by Using Direct Current Control Method Based On Predictive Controller with Continuous Control Set

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Abstract

In this paper, direct current control method is proposed to improve the performance of permanent magnet synchronous motor in steady and transient states. In this method, direct flow control based on predictive controller with continuous control set is provided. Thus, In steady state, an active voltage vector along with a zero-voltage vector is applied to the motor in each control cycle. The values of the phase, amplitude and duty factor of the active voltage vector are optimized in such a way that the stator current error is minimized. In the transient mode, to improve the dynamic response of the torque, a voltage vector with maximum amplitude is applied to the motor in the entire control cycle, and the angle of the voltage vector is calculated in such a way that the stator current error is reduced to zero at the end of the control cycle. Spatial vector modulation is used to generate the selected voltage vector. The performance of the method has been evaluated in MATLAB software; The obtained results show that the proposed method of harmonic distortion of the total stator current in the steady state reduces and improves the dynamic response of the motor in the transient state. In addition, the performance of the two presented methods has been compared with a number of recent control methods, and the results show that by using the proposed methods, the performance of the steady and transient state is improved.

1. Introduction

In the past, direct current motors, especially independent excitation direct current motors, were widely used in variable speed drives. But direct current machines had problems such as high price, high weight and volume, presence of commutator, presence of excitation losses, repair and maintenance. With the emergence of new permanent magnet materials with high energy density at the end of the 20th century, a great change was made in the structure of direct current machines. The use of these materials led to the elimination of the coil and the external energy source in the excitation of direct current motors. On the other hand, progress in the field of high-power semiconductor devices led to the expansion of the use of inverters, and inverters could replace mechanical commutators, and this was the beginning of the construction of permanent magnet synchronous motors and brushless direct current motors. For more than two decades now, permanent magnet synchronous machines have been used in variable speed drives and for normal applications in the power range of several watts to several kilowatts [1].

For the drive of AC motors, the vector control method is actually an evolution of the control methods created in 1970 by Blash and Hayes as a new control method. If in this method, the size and phase angle of the stator phase currents are controlled in order to create precise control over the motor. Vector control can be implemented in the reference frame corresponding to the coordinates of the stator, rotor or the space vector of the magnetizing flux and using the currents of the stator axes d and q defined in the corresponding coordinates. Generally, in drive systems, vector control is used to control the stator current from the current sensor in order to obtain the actual value of the motor current. Then the measured values are compared with their corresponding reference values. These DC currents are transferred to the reference frame of the three-axis stator to be used by the hysteresis method to generate switching pulses, or to be used by the current controller to generate the required reference voltage in controllers based on SVM[1] [2]. The current vector control method using hysteresis controllers for current control has disadvantages because the inverter's switching frequency is variable and its effective value depends on the motor rotation speed and load torque. Also, the current fluctuations are limited to the bandwidth of the hysteresis controllers. If this bandwidth is large, the harmonics of the stator current increase, and if the bandwidth is small, the switching frequency increases significantly [3-4]. Also, the vector control method based on proportional-integral controllers and SVM modulation in order to control the flow, have a slow dynamic response and high switching frequency, and in this category of controllers, generally, the process of transferring quantities from One reference frame is needed for another reference frame, which significantly increases the dependence of the accuracy of the control method on the motor parameters, and the amount of calculations necessary to implement the control method increases. In order to solve the above problems, predictive controllers can be used [5-6], which are widely used in industrial and commercial applications today. In this category of controllers, a precise mathematical model of the motor is obtained and based on this model, the behavior of the motor is predicted for one to several future cycles. In this category of controllers, an objective function is used to achieve different control goals. The working procedure in these controllers is such that in each sampling cycle, the behavior of the motor is predicted and based on the predicted value and the reference value, the objective function is evaluated and the voltage vector which has the lowest cost value is calculated as the optimum voltage vector.

There are many types of predictive controllers that differ in the set of available voltage vectors for motor control, the way to choose the voltage vector applied to the motor, and the goals of the control system. For example, in [7], the relationship between torque changes and the voltage vector applied to the motor is obtained, and then the amplitude of the voltage vector and the duration of its application to the motor are assumed to be constant, and the angle of the voltage vector is calculated in such a way that the motor torque at the end of the cycle Sampling is equal to reference torque. In another category of predictive control methods, the state space model of the motor is obtained, and then, using existing control techniques, the optimal voltage vector is selected to meet a specific control goal [8-10]. For example, in [8], a cost function is defined based on the motor state space model. Then the effect of each of the active voltage vectors in this cost function is investigated and the voltage vector that minimizes the cost function is selected as the optimal active voltage vector and is applied to the motor. In [9], after obtaining the system state space model, an active voltage vector and a zero-voltage vector are applied to the motor with the aim of reducing torque fluctuations. Due to the fact that performing the operations related to the selection of the active voltage vector and the calculation of the duty factor in a row leads to the passage of a lot of time, the efficiency of the method decreases at low speeds; Therefore, in this reference, in order to solve this problem, the mentioned operations are performed simultaneously. There is another category of predictive- control methods in which control operations are performed in such a way that the motor flux and torque reach their reference values exactly after one sampling cycle (at the end of each cycle). This control method is called deadbeat control method; This means that the error between the motor flux and torque and their reference values becomes zero exactly after one sampling cycle [11-13]. In predictive controllers, first, the mathematical model of the machine is obtained in the static reference frame, and based on that, the components of the stator current are estimated for the next sampling cycle. Then the RMS function of the stator current error is

[1] Space Vector Modulation

obtained and the parameters of the voltage vector applied to the motor are optimized in such a way that the minimum effective value of the error for the stator current components is obtained. By using these controllers, the stator current harmonics are significantly reduced. In the MPDCC[2] methods presented in recent years, modulation blocks are usually not used and only a limited number of voltage vectors have been available to apply to the motor. In some of these methods, only the duration of applying the selected voltage vector to the motor is optimized, which is much less effective compared to the method presented in this research, because in the proposed method in this research, not only the duration of applying the vector voltage to the motor is optimized, but two other parameters of the voltage vector, i.e. its amplitude and phase, are also optimized; Therefore, by using the proposed method in this project, the stator current harmonics are significantly reduced. The structure of the paper according to the explanations given in this part is such that the proposed direct flow control methods to improve the direct flow control have been evaluated in the second part and transient and dynamic stability of the motor are included in the proposed method. In the third part, the results of the simulations are shown in such a way that the efficiency of the proposed method is clearly shown. At the end, conclusions and suggestions for further work are given in the fourth part.

2. The Direct Control Method of the Proposed Predicted Current

The best performance of a control system is achieved when all the parameters of the voltage vector, i.e. the range, phase and duration of applying the voltage vector to the motor are optimized by the control system. Therefore, in order to effectively reduce stator current harmonics, torque fluctuations and stator flux fluctuations, in this paper, a continuous control set - predictive model current controller (CCS-MPDCC[3]) is presented, by which all parameters of the voltage vector are optimized. In this part, first, the features of predictive controllers based on system modeling for flow control will be explained, and then the direct flow control method presented in this paper will be explained in detail.

[2] Model predictive Direct Current Control

[3] Continious Control Set-Model predictive Direct Current Control

The very important feature of the MPC[4] controller, which has turned it into a very powerful tool in control, is that nonlinear systems with multiple outputs and multiple inputs can be easily modeled and controlled by this control system.

A) Control System Model

Usually, MPC controllers are modeled in discrete space with fixed sampling time T_s. In this way, the inputs of the system are necessarily changed in the moments that are integer coefficients of T_s; In other words, at moments $t = kT_s$ where $k \in \{0,1,2,\ldots\}$ is and it indicates the number of samples. Because power electronic applications generally have nonlinear dynamics, it is more common to model the controlled system in the form of equation 1 in the nonlinear state space, where x(k) represents the value of the state variable in the kth sample and u (k) represents the input value of the system in the kth sample:

$$x(k+1) = f\big(x(k), u(k)\big), \quad k \in \{0,1,2,\ldots\} \quad (1)$$

As mentioned, in this part, MPC controllers with continuous output are examined, in which the output of the control system is given to the modulator unit, and then the status of the power switches is determined by the modulator. Therefore, the constraint related to system inputs can be defined according to equation (2).

$$u(k) \in \mathbb{U} \subseteq \mathbb{R}^p, \quad k \in \{0,1,2,\ldots\} \quad (2)$$

where p is the number of system keys and the set U is determined according to the type of inputs. The system input u(k) can be a voltage vector, or a duty factor, or the state of a key. For example, if u(k) is the state of the keys, the set U is equal to $\mathbb{U} = [0, 1]^p$ [14]. In addition to the constraints in the inputs can be considered by MPC, the constraints in the controlled states can also be considered. For example:

$$x(k) \in \mathbb{X} \subseteq \mathbb{R}^n, \quad k \in \{0,1,2,\ldots\} \quad (3)$$

where n is the number of state variables. For example, the constraint related to the state can be the voltage of a capacitor in a converter, or the voltage of the neutral point in a three-level inverter, or the inductor current in a resistive-inductive load.

b) Cost Function

In the MPC method, in each sampling cycle for a specific state x(k) (obtained by estimation or measurement) and for several dimension N samples, the pre-defined cost function related to

[4] Model predictive Control

the control objectives is minimized. The cost function introduced in (4) is a general form of the cost function that has been widely used in recent years' papers.

$$V\left(x(k),\vec{u}'(k)\right) \triangleq F\left(x'(k+N)\right) + \sum_{l=k}^{k+N-1} L(x'(l),u'(l)) \qquad (4)$$

In relation (4), L(.,.) and F(.) are weighting functions that are used to determine the appropriateness of the system's behavior for a specific input; For example, they specify the amount of error between the reference voltage value and the predicted value. The predicted values related to the system state are formed according to equation (5):

$$x'(l+1) = f\left(x'(l),u'(l)\right), \quad l \in \{k, k+1, k+2, \dots, k+N-1\} \qquad (5)$$

in which

$$u'(l) \in \mathbb{U}, l \in \{k, k+1, k+2, \dots, k+N-1\} \quad (6)$$

They represent the experimental inputs of the control system. The recursive relationship stated in (5) is initialized with the current value of the system states. It means:

$$x'(k) \longleftarrow x(k) \qquad (7)$$

Therefore, equation (5) is the predictive expression of the state of the control system, which is obtained by applying the inputs stated in (8) in $\{k, k+1, k+2, \dots, k+N-1\}$ samples.

$$\vec{u}'(k) = \{u'(k), u'(k+1), \dots, u'(k+N-1)\} \quad (8)$$

Predicted state variables and system inputs are both bound according to equation (2), so we have:

$$u'(l) \in \mathbb{U}, \; x'(l) \in \mathbb{U} \quad \forall \; l \in \{k, k+1, k+2, \dots, k+N-1\} \qquad (9)$$

In addition, it is usually necessary that $x'(k+N)$ satisfy a certain condition constraint; For example

$$x'(k+N) \in \mathbb{X} \qquad (10)$$

It is necessary to pay attention to this point that the selection of the constraint related to the state $x'(k+N)$ is usually done according to the stability problem. According to the above explanations, the constrained optimization introduced in relation (4) determines the order of the system inputs to realize the optimal control in the kth sample and for the state x(k).

$$\vec{u}'(k) \triangleq \{u(k;k), u(k+1;k), \dots, u(k+N-1;k)\} \qquad (11)$$

c) How to Solve the Optimization Problem and Select the Voltage Vector with the Passing of Sampling Cycles

Despite the fact that $\vec{u}'(k)$ has the optimal voltage vector for all future cycles, only the first voltage vector is selected by the control system and applied to the motor. That is, the input of the control system is adjusted according to equation (12):

$$u(k) \longleftarrow u(k;k) \qquad (12)$$

In the next sampling cycle, i.e. the k+1th sample, the system states x(k+1) are measured (or estimated), then all the above actions are repeated again for the new cycle and the optimal voltage vector $\vec{u}'(k+1)$ is obtained. If, this set includes the optimal voltage for all future cycles, but only its initial voltage vector is selected to be applied to the motor, i.e. $u(k+1) \longleftarrow u(k+1;k+1)$. This process is repeated for all subsequent cycles. To clarify the meaning of the mentioned content, Figure(1) shows how to perform operations during the sampling cycles and select the optimal voltage vector for the case where the predictive controller has N equal to 3. Therefore, the MPC method can be called an open-loop optimal method.

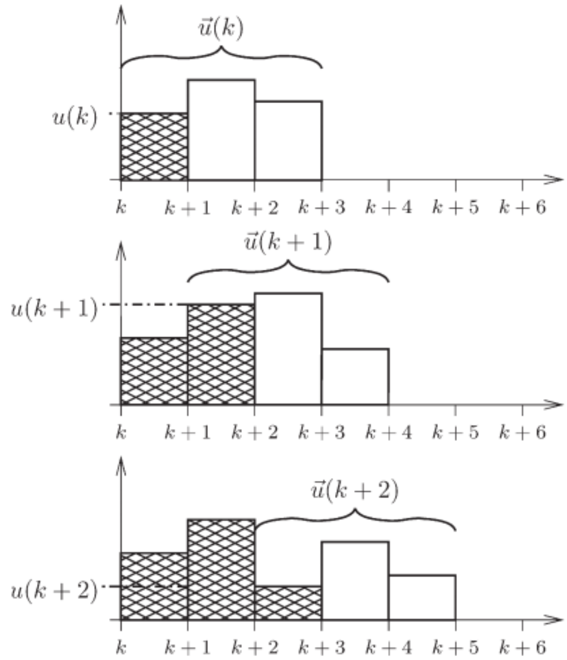


Figure (1): How to perform operations for the case where N is equal to 3.

d) Parameters Related to Design

As seen in the previous section, the MPC controller has the ability to control a nonlinear multivariable system. In order to implement the predictive controller, in addition to choosing the appropriate value for the duration of a sampling cycle, i.e. T_s, it is necessary to choose the appropriate objective function to achieve the control goals. In other words, suitable functions for weighting functions, ie, L(.,.) and F(.) should be selected. Also, the number of cycles that need to be predicted in each cycle (horizon), i.e. N, should be selected based on control objectives. If possible, the constraints related to the inputs and states of the system, i.e. X and X_f, can also be designed.

3. The Controller of the Continuous Control Set, the Direct Control of the Flow of the Proposed Prediction Model

In the proposed CCS-MPDCC method, the stator current components are the controlled variables and spatial vector modulation has been used to produce the selected optimal voltage vector. Therefore, due to the use of SVM, the amplitude and phase of the voltage vector can be adjusted to any desired value based on the objectives of the controller. The main purpose of this method is to minimize stator current ripples in steady state and obtain a fast- dynamic response for motor torque in transient state. The process of obtaining the optimal voltage vector parameters is shown in detail in the following sections:

3-1) Improved Steady State Performance

a) Permanent Magnet Synchronous Motor Model

In this proposed method, in order to prevent the transfer of rotating coordinates and reduce the complexity of calculations, the static reference frame is used to formulate the motor equations, the motor equations can be considered from [13].

b) Changes in Stator Current Components

Since the proposed method is implemented using a digital processor, it is necessary to obtain the discrete time representation of equations (16) and (17). If by discretizing them, we have:

$$\Delta i_{sd} = \frac{T_s}{L_d}(u_{sd} - Ri_{sd} + \omega_r\psi_f \sin\theta_r) \quad (13)$$

$$\Delta i_{sq} = \frac{T_s}{L_q}(u_{sq} - Ri_{sq} - \omega_r\psi_f \cos\theta_r) \quad (14)$$

According to the above equations, the values of i_{sd}, i_{sq}, ω_r and θ_r can be calculated in each control cycle, by proper control of the voltage vector applied to the motor, i.e. u_{sd} and u_{sq} in equations (18) and (19), controlling the stator current components towards Their reference values become possible. If the following parameters are defined:

- The length of the control cycle is T_s.
- An arbitrary non-zero voltage vector ($\overrightarrow{\boldsymbol{u_s}}^* = [u_{sd}^* \quad u_{sq}^*]^T$) with duration T_k^* ($T_k^* \le T_s$) is applied to the motor.
- A zero voltage vector (ZVV) that is applied to the motor in the remainder of the control cycle.

Considering these definitions and based on the variables of equations (13) and (14), the stator current components due to the application of a ZVV and the reference voltage vector ($\overrightarrow{\boldsymbol{u_s}}^*$) are formulated as equations (15) to (18):

$$\Delta i_{sd0} = \frac{(T_s - T_k^*)}{L_d}(-Ri_{sd} + \omega_r\psi_f \sin\theta_r) \triangleq S_{d0}(T_s - T_k^*) \quad (15)$$

$$\Delta i_{sq0} = \frac{(T_s - T_k^*)}{L_q}(-Ri_{sq} - \omega_r\psi_f \cos\theta_r) \triangleq S_{q0}(T_s - T_k^*) \quad (16)$$

$$\Delta \boldsymbol{i_{sd1}} = \frac{T_k^*}{L_d}\left(u_{sd}^* - Ri_{sd} + \omega_r\psi_f \sin\theta_r\right) \triangleq \frac{T_k^*}{L_d}u_{sd}^* + S_{d0}T_k^* \quad (17)$$

$$\Delta i_{sq1} = \frac{T_k^*}{L_q}(u_{sq}^* - Ri_{sq} - \omega_r\psi_f \cos\theta_r) \triangleq \frac{T_k^*}{L_q}u_{sq}^* + S_{q0}T_k^* \quad (18)$$

if

$$S_{d0} = \frac{1}{L_d}(-Ri_{sd} + \omega_r\psi_f \sin\theta_r) \quad (19)$$

$$S_{q0} = \frac{1}{L_q}(-Ri_{sq} - \omega_r\psi_f \cos\theta_r) \quad (20)$$

In equations (15) to (18), $\Delta i_{sd0}$and Δi_{sd1} are the changes of stator current components d, q respectively, due to the application of a ZVV and $\overrightarrow{\boldsymbol{u_s}}^*$ for the motor. If T_s is included in about 100 microseconds [15-16], assuming that all variables are constant in a control cycle; Therefore, the slopes of S_{d0} and $S_{q0}$are the same in a control cycle. As a result, the value of the stator current components at the end of the Kth control cycle (or the beginning of the control cycle (k+1) are calculated as follows:

$$i_{sd}(k+1) = i_{sd}(k) + \frac{T_k^*}{L_d}u_{sd}^* + S_{d0}T_s \quad (21)$$

$$i_{sq}(k+1) = i_{sq}(k) + \frac{T_k^*}{L_q}u_{sq}^* + S_{q0}T_s \quad (22)$$

which, $i_{sd}(k)$ are the d axis stator current at the beginning of the kth control cycle.

c) Minimizing Stator Current Ripples

In general, in order to evaluate the performance of a signal that is different from the reference signal, the square root is a common measurement [17]. The RMS value of the stator current error on a control cycle is defined as follows:

$$\left|\vec{i}_{s-error(RMS)}\right|^2 = \frac{1}{T_s}\int_0^{T_s}\left\{(i_{sd}^* - i_{sd}(k+1))^2 + (i_{sq}^* - i_{sq}(k+1))^2\right\}dt \quad (23)$$

i_{sd}^* and $i_{sq}^*$are the reference values of stator current components. Using equations (26) and (27) and simplifications of equation (28), the following equation is obtained.

$$\left|\vec{i}_{s-error(RMS)}\right|^2 = \frac{1}{T_s}\int_0^{T_s}\left\{\left(i_{sd-error} - \frac{T_k^*}{L_d}u_{sd}^* - S_{d0}T_s\right)^2 + \left(i_{sq-error} - \frac{T_k^*}{L_q}u_{sq}^* - S_{q0}T_s\right)^2\right\}dt \quad (24)$$

If

$$i_{sd-error} = i_{sd}^* - i_{sd}(k) \quad (25)$$

$$i_{sq-error} = i_{sq}^* - i_{sq}(k) \quad (26)$$

The function $\left|\vec{\boldsymbol{i}}_{s-error(RMS)}\right|^2$ in equation (24) is a cost function, whose variables are T_k^*, u_{sd}^* and u_{sq}^*. In order to obtain the minimum of stator current ripples, the cost function optimization problem must be solved. The form of this problem is similar to the quadratic optimization problem (QP) in references [18]. As a result, this optimization problem is highlighted and will have an optimal solution in the practical area [19]. By minimizing the optimization problem, the equations of the components of the optimal voltage vector and the optimal duration are given as the following equations.

$$u_{sd}^* = \frac{L_d(i_{sd-error} - S_{d0}T_s)}{kT_s} \quad (27)$$

$$u_{sq}^* = \frac{L_q(i_{sq-error} - S_{q0}T_s)}{kT_s} \quad (28)$$

$$T_k^* = \frac{i_{sq-error} - S_{q0}T_s}{2S_{q1} - S_{q0}} + \frac{i_{sd-error} - S_{d0}T_s}{2S_{d1} - S_{d0}} \quad (29)$$

After calculating u_{sd}^*, u_{sq}^* and T_k^*, these values are applied to the SVM block. The SVM block generates two adjacent active voltage vectors (AVV) based on the values of u_{sd}^* and u_{sq}^*, and then they are applied to the motor in the time period calculated according to the values of u_{sd}^*, u_{sq}^* and T_k^*, are used. In summary, based on the above, if the d-axis and q-axis components, the applied voltage vector of the motor, are adjusted according to equations (27) and (28), and this applied voltage vector for the motor is calculated in a period of time according to equation (29), the ripples The minimum stator current is obtained in steady state.

d) Reducing the Switching Frequency of the Inverter

According to the explanations given, in steady state, two adjacent AVVs (which are selected based on the components of the optimal voltage vector) with a zero-voltage vector (ZVV) to the motor respectively for time intervals T_k^* and $(T_s - T_k^*)$ is applied. According to reference [17], ZVV should be applied symmetrically at the beginning and end of the control cycle to obtain the minimum RMS ripple. Since two-level VSI[5] is used to implement the proposed method, ZVV can be u_0 or u_7. To reduce the switching frequency, ZVV should be selected based on the adjacent voltage vectors in such a way that the minimum switching transfer is obtained. It means that if SVM uses u_0 or u_7 as ZVV to combine with the selected voltage vector, then u_0 or u_7 must be selected by the control system. By applying this method, only the state of one switch is changed at each moment of switching. Therefore, unnecessary switching transfers are prevented and switching losses are reduced.

e) Improving Motor Efficiency Using the Principle of Maximum Torque in Terms of Amperes

One of the ways to improve motor efficiency is to use the principle of maximum torque in terms of amperes in the range below the rated speed. In this method, by optimally adjusting the magnetic flux of the stator, the losses are significantly reduced and, as a result, the efficiency is increased. In this research, using this principle, the current components are calculated in different working conditions and stored in the memory of the digital processor in the form of an observation table. During the implementation of the control algorithm, according to the working conditions of the motor, the stator current components are fetched from this table.

3-2) Improving Transient Mode Performance

Improving the dynamic response of the motor is the main goal of the controller in transient mode. Therefore, the parameters of the voltage vector (phase, amplitude and duration) should be set in a different state of the proposed method from the previous parts of the steady state. In the transient state, the parameters of the voltage vector are adjusted so that the actual value of the stator current components reach their reference values at the end of the control cycle. It means that the deadbeat control method, which has a fast-dynamic response, should be applied to control the stator current components in the transient state. As a result, the following set of equations should be considered to find the optimal voltage vector parameters:

[5] Voltage Source Inverter

$$\begin{cases} i_{sd}(k+1) = i_{sd}^{*} \\ i_{sq}(k+1) = i_{sq}^{*} \end{cases}$$

$$\Rightarrow \quad \begin{cases} i_{sd}(k) + \frac{T_k^{*}}{L_d} u_{sd}^{*} + S_{d0}T_s = i_{sd}^{*} \\ i_{sq}(k) + \frac{T_k^{*}}{L_q} u_{sq}^{*} + S_{q0}T_s = i_{sq}^{*} \end{cases} \tag{30}$$

In order to obtain a fast-dynamic response in the transient state, a voltage vector with the largest amplitude is applied to the motor in the entire control cycle. It means that, in the transient state, T_k^{*} and $|\overrightarrow{\boldsymbol{u_s}^{*}}|$ are set equal to T_s and V_{max}, respectively, where V_{max} is the maximum voltage range that can be obtained in the linear region of SVM. Therefore, by replacing T_k^{*} and $|\overrightarrow{\boldsymbol{u_s}^{*}}|$ In equation (30) and simplifying, the optimal voltage vector phase equation is obtained based on equation (31):

$$\alpha_s^{*} = tan^{-1}\left(\frac{L_q(i_{sq-error} - S_{q0}T_s)}{L_d(i_{sd-error} - S_{d0}T_s)}\right) \tag{31}$$

where α_s is the phase of the voltage vector applied to the motor relative to the axis d of the stationary reference frame. In summary, based on the above information, if the amplitude of the stator voltage vector V_{max} is adjusted and the phase of the voltage vector is calculated based on equation 36 and this voltage vector is applied in all motor control cycles, it effectively improves the dynamic response of the motor in the transient state. It should be noted that in the implementation of the deadbeat control method, the current error is measured at the beginning of each control cycle and must be zero at the end of each control cycle, so no excess current occurs in the transient state.

3-3) Identifying Steady State and Transient State

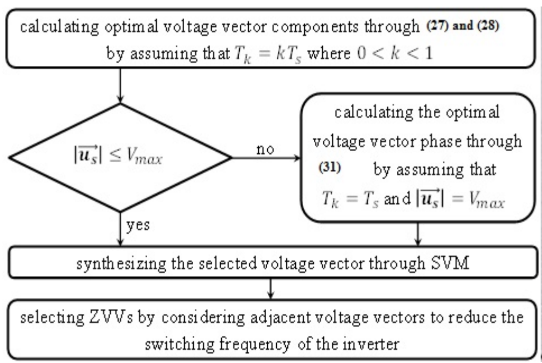
After calculating the components of the optimal voltage vector from equations (32) and (33), the amplitude of the voltage vector is calculated from equation (32). If the harmonics of the stator current in the over modulation region of SVM are higher than the harmonics in the linear region. Over modulation area is not used in the proposed method. Therefore, the diagnosis of steady state and transient state is done on the basis that if $\frac{T_k^*}{T_s}$ is greater than one and $|\overrightarrow{\boldsymbol{u_s}^{*}}|$ is greater than V_{max}, it is not possible to combine the optimal voltage vector in a control cycle used in the linear region of SVM. In these conditions, the range of the voltage vector is limited to V_{max} and T_k^* is limited to T_s. Therefore, the stable state can be identified by having the conditions of equations (33) and (34) and otherwise it is a transient state:

$$|\overrightarrow{\boldsymbol{u_s}^{*}}| = \sqrt{(u_{sd}^{*})^2 + (u_{sq}^{*})^2} \tag{32}$$

$$\frac{T_k^*}{T_s} \le 1 \tag{33}$$

$$|\overrightarrow{\boldsymbol{u_s}^{*}}| < V_{max} \tag{34}$$

Based on the explanations provided in this section, the calculation steps of the proposed CCS-MPCC method in each control cycle are summarized in Figure (2). In this research, in order to effectively reduce stator current harmonics, which leads to reduction of harmonic losses, reduction of torque fluctuations and reduction of stator flux fluctuations, direct current control method based on predictive controller with continuous control set (CCS- MPDCC) is used. In this method, in order to achieve the optimal voltage vector with the desired amplitude and phase, SVM spatial vector modulation is used, and all parameters of the voltage vector are optimized with the aim of minimizing stator current harmonics. In the presented controller, first, the mathematical model of the machine is obtained in the static reference frame, and based on that, the stator current components are estimated for the next sampling cycle. Then the RMS function of the stator current error is obtained and the parameters of the voltage vector applied to the motor are optimized in such a way that the minimum RMS value of the error for the stator current components is obtained. By using this controller, the harmonics of the stator current are significantly reduced because, firstly, the RMS function of the error, which is the best indicator for evaluating the tracking quality of the reference signal by another signal, has been selected as the target function. And secondly, all parameters of the voltage vector are optimized simultaneously. Thirdly, the SVM modulation method is used in order to reach the selected optimal voltage vector. In the MPDCC methods presented in recent years, modulation blocks were not used and only a limited number of voltage vectors were available to be applied to the motor. In some of these methods, only the duration of applying the selected voltage vector to the motor is optimized, which is much less effective compared to the method presented in this research, because in the proposed method in this project, not only the duration of applying the voltage vector to the



motor is optimized, but two other parameters of the voltage vector, i.e. its amplitude and phase, are also optimized; Therefore, by using the proposed method in this research, the stator current harmonics are significantly reduced.

Figure (2): Calculation steps of the proposed CCS-MPCC method

4) Results of Simulations Related to the Presented Method

In order to evaluate the efficiency of the methods presented in this research, simulation was used in MATLAB software. If during simulation in the MATLAB/Simulink software environment, it is possible to view all motor quantities online. In such a way that all the information to be studied in each sampling cycle (for example, once every 100 microseconds) is calculated by the control system and then various processing operations are performed on the information by MATLAB software; For example, the harmonic spectrum of the stator phase currents is obtained and the graph of instantaneous changes of all quantities is drawn and the effective switching frequency is also calculated. The effectiveness of the proposed CCS-MPCC method is shown in this section using MATLAB/Simulink software. The implementation of the proposed method has been done carefully and then it has been compared with the conventional hysteresis implementation based on the MPCC method and the method proposed in reference [20]. In order to obtain minimum stator current ripples in the hysteresis method based on the MPCC method, the bandwidth of the two hysteresis controllers is set to 0.07 [21]. Motor and control system parameters in all simulations and practical results are shown in Table (1). As can be seen, the sampling time of all methods is set to 100 microseconds according to the sampling time of the methods implemented in references [22-26]. To simplify the continuation of this research, the hysteresis-based DCC[6] method, the proposed MPCC method in reference [20], and the proposed CCS-MPCC method are given with DCC, Duty-MPCC, and CCS-MPCC, respectively.

Table (1): control system and motor parameters

Parameters	Value
Number of pole pairs	2
Permanent-magnet flux	0.901 (Wb)
Stator resistance	7.9 (Ω)
d -axis stator inductance	0.070 (H)
q -axis stator inductance	0.117 (H)
Rated speed	1500 (rpm)
Rated voltage	400 (V)
Rated torque	1.4 (Nm)
Rated current	0.7 (A)
Rated power	200 (W)
DC link voltage	250 (V)
Sampling time ($\boldsymbol{T_s}$)	100 (μs)
Bandwidth of the hysteresis current controller in DCC method	0.07

a) Harmonic spectrum of stator current

In order to show the performance of the proposed steady state method, the harmonic spectrum of one phase of the stator current at 100% of the nominal speed is drawn in Figure (3). that the rated load is applied to the motor. In this simulation, the THD[7] of the stator current has been calculated up to 6 kHz. Based on these figures, it is clear that in all speed ranges, the lowest THD of the stator current is obtained by applying the proposed CCS-MPCC method, because in this method, the parameters of the voltage vector are optimized with the aim of minimizing the stator current ripples. have been made Based on Figure 3 to 5, the numerical comparison of THDs at rated speed shows that a

[6] Direct Current Control

[7] Total Harmonic Distortion

73.26 percent THD reduction is achieved by applying the proposed CCS-MPCC method compared to the DCC method. While the reduction of THD, by applying Duty-MPCC methods, is 66.12%. The simulated results in the figure confirm that THD is effectively reduced by applying the proposed method.

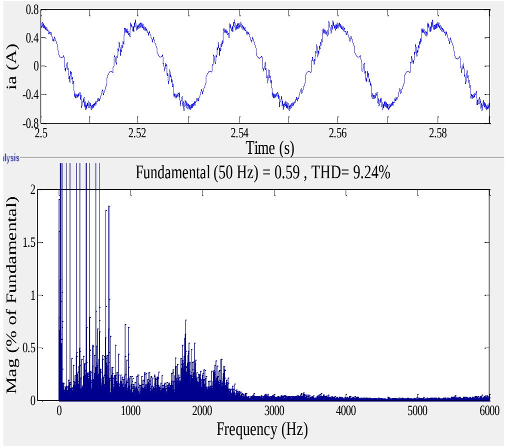


Figure (3): Harmonic spectrum at 1500 rpm DCC method

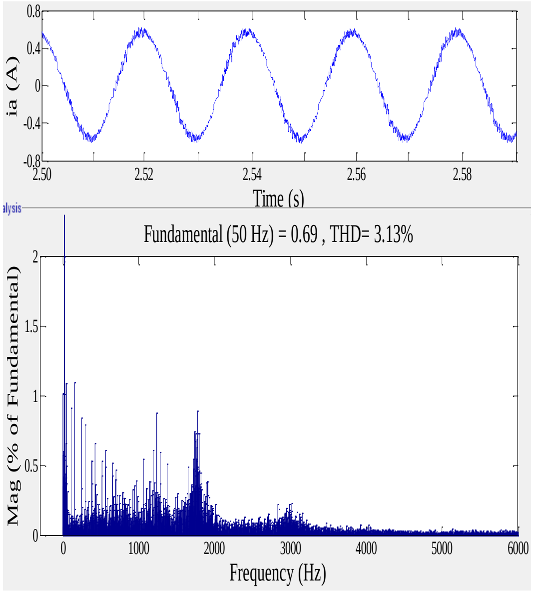


Figure (4): Harmonic spectrum at 1500 rpm Duty-MPCC method

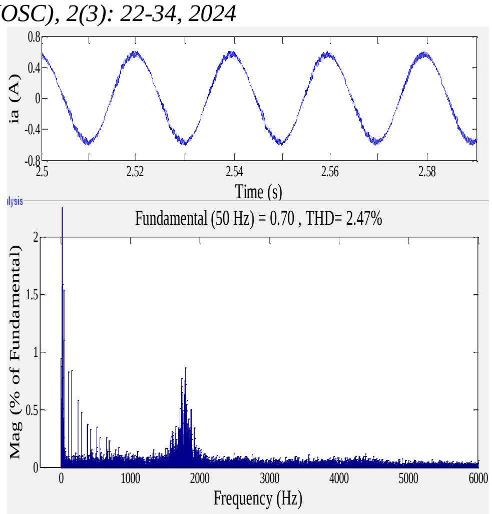


Figure (5): Harmonic spectrum at 1500 rpm Proposed CCS-MPCC method

b) Effect of Average Switching Frequency

The average switching frequency is one of the important issues in comparing the performance of the stable modes of the methods. It is clearly seen that a higher (lower) average switching frequency leads to a lower (higher) current ripple and as a result, it will have a lower (higher) THD. Therefore, in order to have a specific comparison, the average switching frequency of all methods should be considered the same. It should be noted that the average switching frequency of the inverter is calculated based on equation 35, if N is the number of switching transitions of the inverter during a constant period, for example, in the period of 200 milliseconds in this experiment; and K is the number of inverter switches, which is equal to 6 in two-level VSI [27-28].

$$f_{ave} = N/K/\Delta t \tag{35}$$

To investigate the effect of average switching frequency on the implementation of the DCC method, a similar simulation as before has been carried out under the same conditions but with a sampling time of 40 microseconds (that is, a sampling frequency of 25 kHz). In DCC, when the sampling frequency increases to 25 kHz, the switching frequency increases to about 7.5 kHz. By increasing the switching frequency, THD reduction results, and choosing an optimal voltage vector with optimal parameters can further reduce THD. Apart from this, in order to implement the DCC method at a sampling frequency of 25 kHz, more powerful digital processors and faster analog-to-digital converters are needed, which significantly increases the implementation costs. In Table (2), the THD value in all methods is summarized.

Table (2): Comparison of THD values at a speed of 1500 rpm

Method	THD	f_{ave} (kHz)
DCC (at 10-kHz)	9.24 %	3.1 %
duty-MPCC	3.13 %	7.5 %
proposed CCS-MPCC	2.47 %	7.5 %
DCC (at 25-kHz)	3.70 %	7.5 %

c) Startup response

In order to test the dynamic response of the torque in all methods, the motor starting response is checked from the stop state to the rated speed in no-load conditions. As in all methods, PI controllers with specific integral and proportional gains have been used to regulate the motor speed. The gains of the PI controller are adjusted so that the motor speed is controlled without any overshoot. In such a way that the starting response of these methods is almost the same and there is no steady state error in the speed and torque of the motor. In all methods, after starting the motor, the speed reaches its nominal value after 0.33 seconds without any overshoot. For greater clarity of the dynamic torque response comparison, the torque response is enlarged in Figure 6 to 8. If, the torque responses are almost the same in all methods, but there is a very small amount of difference in the time of torque increase.

According to Figures (6) to(8), the dynamic response of the torque in the proposed CCS-MPCC method is faster than the other two methods, because a voltage vector with the optimal amplitude and phase is applied to the motor in the entire control cycle. While in the DCC method, there is no prediction and optimization to obtain a fast torque response, and the torque increase time in the DCC method is 7.9 milliseconds, in the Duty-MPCC method, 8.6 milliseconds and in the proposed CCS-MPCC method is 6.2 milliseconds.

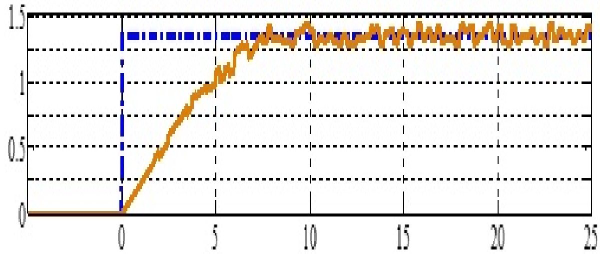


Figure (6): Magnified torque response in start-up test DCC method

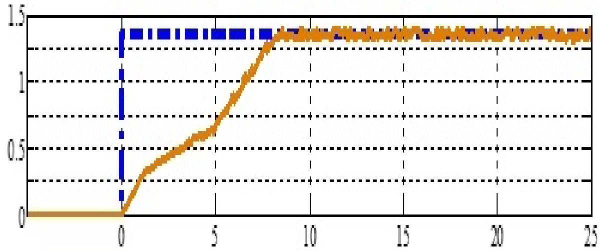


Figure (7): Magnified torque response in start-up test Duty-MPCC method

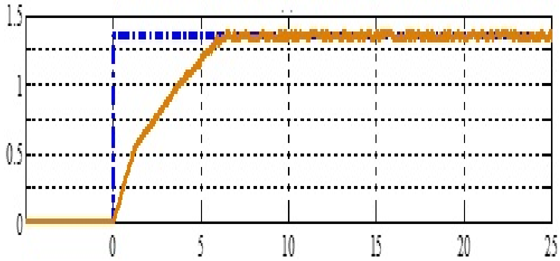


Figure (8): Magnified torque response in start-up test Proposed CCS-MPCC method

It results that the dynamic response of the DCC method is improved by applying the proposed CCS-MPCC method. If the proposed CCS-MPCC method in this research minimizes the stator current error by using SVM space vector modulation. Also, the voltage vector parameters are calculated in each control cycle to find the optimal voltage vector.

5) "Comparative Analysis of the Proposed CCS-MPCC Method with Recent Similar Methods"

This section demonstrates the advantages of the proposed CCS-MPCC method over several recent methods. These advantages are theoretical and will be validated in subsequent sections through simulations and experimental results.

a) Comparison with the Method Presented in Reference [28]

In reference [28], an optimal voltage vector is selected by the control system for simultaneous control of torque and stator flux. This voltage vector is then applied to the motor using space vector modulation. In this method, the RMS torque ripple is considered as the cost function, while deadbeat control of the stator flux magnitude is considered as a constraint. The Lagrange multiplier method is used to solve the optimization problem and obtain the voltage vector parameters. By comparing the analysis of the proposed method in this reference with the proposed CCS-MPCC method, the following results are obtained:

1) The computational complexity of the proposed CCS-MPCC method is lower than the method presented in this reference.

This is because in reference [28], a closed-loop estimator or observer is required to estimate torque and stator flux in each control cycle, whereas in the proposed CCS-MPCC method, no estimation is required.

2) The voltage vector selection process in this reference is more complex than the process used in the proposed CCS-MPCC method. This is because in reference [28], a constrained optimization problem must be solved to obtain the optimal voltage vector, while in the proposed CCS-MPCC method, an unconstrained optimization problem must be solved.

3) The stator current THD in the proposed CCS-MPCC method is lower than the method presented in this reference.

This is because in the proposed CCS-MPCC method, the stator current components are directly controlled, while in reference [28], torque and stator flux are directly controlled. In other words, the stator current is controlled indirectly. In other words, the stator flux ripple and torque ripple in this reference are less than the proposed CCS-MPCC method.

b) Comparison with the Model Predictive Current Control Method Presented in Reference [20]

In the method proposed in reference [20], an active voltage vector and a zero voltage vector are applied to the motor in each control cycle. In this method, two ways are shown to select the best active voltage vector in each control cycle. In the first way, the cost of each available voltage vector is calculated, and the voltage vector with the lowest cost is selected as the best voltage vector. After selecting the best voltage vector, the deadbeat control method is used to calculate the duration of the selected active voltage vector. In the second way, to avoid checking all available vectors and selecting the optimal vector, a theoretical optimal voltage vector is calculated for using the deadbeat control method, and then the closest active voltage vector to the optimal voltage vector is selected as the best voltage vector. Finally, the duration of the selected voltage vector is calculated with the aim of minimizing the error between the selected voltage vector and the theoretical optimal voltage vector. As can be seen, in both methods shown in this reference, only one active voltage vector is used for the motor; therefore, the stator current error cannot be minimized.

To overcome these shortcomings, the proposed CCS-MPCC method in this study minimizes the stator current error using space vector modulation (SVM). In the first method shown in this reference, the cost of all active voltage vectors in each control cycle is calculated for the best voltage vector. While in the proposed method, the voltage vector parameters are calculated in each control cycle to find the optimal voltage vector. Also, in this reference, the methods used to control the motor in steady-state are used without any changes for controlling the motor in transient state as well. Whereas, in the proposed CCS-MPCC method in this study, the predictive control model is adapted to minimize the stator current error in steady-state and the deadbeat control method is used to obtain a fast dynamic response in transient state.

6) Conclusion

In the proposed CCS-MPCC method, the components of the voltage vector and the duration of the application of the motor voltage vector are optimized so that the stator current ripples are minimized in the steady state and in the transient state, the largest voltage vector is applied to the motor in the entire control cycle. In this case, in order to control the stator current components in the deadbeat state, the phase of the voltage vector is adjusted so that the error of the stator current components is reduced to zero at the end of the control cycle. The performances of both steady state and transient state of the proposed method have been shown using simulations and practical results, as the following results have been obtained:

The torque ripple, stator flux ripple, and stator current THD of the proposed method are significantly lower than conventional DCC methods, and the dynamic response of the motor in the proposed method is faster than DCC methods.

In summary, the proposed method effectively improves the steady state and transient performances. Therefore, the proposed MPCC method can be considered as a useful algorithm in high-performance PMSM drives that require precise motor control.

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