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Improvised direct torque control of a permanent magnet synchronous motor

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ABSTRACT

Permanent magnet synchronous motor (PMSM) is widely used in different applications because of their different key operation features. But despite having important key features, PMSM suffers from torque ripple when simple control techniques like direct torque control (DTC) are employed. Several approaches have been raised by many researchers to lessen the ripple when DTC is used for controlling the PMSM drive. In this work, duty ratio-optimized DTC control, which has the same simplicity as conventional DTC (CDTC), and delay compensation for input signal prediction are proposed. In the proposed system, to determine the duty ratio, slope manipulation was made by considering the minimization of torque error and forcing the developed torque to be equal to the reference torque at the end of the span. An online slope determination approach was employed to compute the duty ratio. MATLAB 2021b is used for simulation purposes. The dynamics and steady-state performance of the proposed scheme were tested for both variable-load and variable-speed operations. In addition, the harmonic performance and ratio of harmonic power loss to total active power loss of the motor were evaluated. In general, the proposed scheme performs effectively in reducing steady-state ripple and harmonic.

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1. INTRODUCTION

Permanent magnet synchronous motor (PMSM) has gained universal acceptance for any application due to its performance. Even though [1] and [2] suggested improving PMSM performance through design modification. In this work, flux performance and weight optimization were forwarded. The characteristic improvement is tested by changing the shape of the magnet and rotor. As PMSM is suitable for continuous duty operation, fault-tolerant inverter topologies and fault detection approaches were recommended to have a reliable system [3]–[6]. For PMSM operating at high temperatures and high loads, the effect of ripple on the motor and supply component is significant. According to [7], adding model parameters to the control algorithm and signal processing is recommended to reduce the thermal effect. The parameters of the motor are changing nonlinearly with temperature and load current. The nonlinear control system is proposed to include the nonlinear nature of a control system for PMSM in [8]. The nonlinearity due to magnetic saturation in the operation and performance of PMSM is considered in [9].

A quick response in torque for direct torque-controlled PMSM is obtained by manipulating the angle quickly. Quick angle manipulation is achieved by omitting the null voltage level so that the angle can be varied. Direct torque control (DTC) has the nature of controlling torque and flux directly. The field weakening is incorporated into DTC for PMSM control [10]. A direct torque control approach based on a space vector (DTC-SVM) is suggested to lessen the flux and torque ripple [11]. An adaptive model and a better torque estimation equation are implemented in [12], where the harmonic flux is taken into consideration, gives better dynamics than the conventional one. The switching period manipulation and minimization of the torque ripple within one sampling period are performed by minimizing the derivative of the torque error square in the final value of duty ratio optimized direct torque control (DDTCF). The objective of the above method is to make average torque equal to reference torque. The objective of the duty ratio optimized based on root mean square (DDTC-RMS) is to minimize the average square of torque error [13].

Another method or approach is where the average torque error in one sampling period is forced to zero. Whereas in the deadbeat DTC method, the torque is forced to be equal to the reference torque at the end of one sample period. A duty ratio determination that does not depend on the parameter variation is proposed in [14]. PMSM may operate in a flux-lessening mode where the motor is running at a speed greater than the rated speed. DTC has advantages like insensitivity to parameter change compared to current control in the flux weakening area, according to the work stated in [15]. The trade-off ripple generation in nominal DTC can be minimized by using optimal duty ratio modulated DTC. Final value optimized DTC (DDTCF) on time, mean value optimized DTC on time, and root mean square value optimized DTC on time determination are among the duty ratio determination techniques widely applied. The slope of torque and flux for both active and null voltages determine the range of the duty ratio. Online slope determination is useful to estimate the optimal duty ratio determination, as the duration depends on the slope [16]. The maximum torque per ampere algorithm is suggested to enhance the performance of the DTC in PMSM. The efficiency of the motor is improved when MTPA is applied due to optimal current generation, according to the work stated in [17]. The optimum switching time for companies with predictive control (MP-DTC) minimizes the ripple. By compensating for the one-step delay in predicting the control signal and determining the optimum switching duration, the torque can be reduced. The optimum condition will be fulfilled when the function representing torque ripple and cost function derivation converges to zero, according to the work stated in [18].

According to [19], torque ripples and flux fluctuation can be reduced by using an extended infinite vector (EFV-DTC) from the three-six active state voltage by varying duty. The change in trend for both torque and flux at the discrete duty cycle is stored offline. The selection of vectors based on the trend is applied to reduce the ripples. Based on the trend stored offline for torque and flux information, the balanced three-phase voltage is applied to the motor. The issue of using a saturation controller (MPS-DTC) to obtain multiple voltages by stating the discrete level for a duty cycle is applied to obtain voltage based on the calculated duty value proposed in [20]. Multiple voltage outputs can be achieved by using the midpoint saturation controller. Applying the adaptive regulator to employ the capability to vary the duty ratio from 0 to 1 within one period will reduce the flux and torque error. Rather than using the fixed hysteresis control, using a saturation controller can reduce the ripple when a PMSM drive is considered. The advantage of a saturation controller is that it will improve the steady-state response compared to a nominal DTC. Ripple torque reduction using duty ratio determination, where the input to determine duty ratio is speed, change in flux, change in trust, and voltage selected for each period, the torque ripple can be reduced without the need for trust and flux gain tuning is explained in [21]. The duty ratio can be found by looking at the similarity between the acceptable level of torque ripple, the minimum switching duration, the maximum ripple torque, and the maximum switching period. The same principle is applied for flux by taking the difference between total switching periods and switching duration for torque ripple minimization. The remaining time will be used for null voltage.

According to [22], a comparison analysis is made among DTC, model predictive-based direct torque control (MPDTC) and field-oriented control (FOC), considering different parameters. FOC has a low torque ripple, current harmonics, and flux ripple, whereas DDTC has better performance than DTC and MPDTC. Comparatively, the algorithm complexity is less for DDTC than for MPDTC, whereas DTC has a simpler algorithm. Switching time and phase voltage calculations for deadbeat DTC are proposed to lessen torque and flux ripple [23]. In this algorithm, ripple and dynamics are treated independently using the torque error as input. For small torque errors, the flux and torque are forced to be equal to the required value. Otherwise, if the torque error is large, both the voltage and phase angle are set to the level that gives the best dynamic response. Maximum torque per ampere current generation without the inclusion of quadrature axis current is suggested in the DTC of PMSM to decrease the fluctuation of flux due to saturation [24]. Duty ratio determination using a rate of deviation of current is suggested to minimize torque and flux ripple for

DTC [25]. The sum of the square error minimization is used to find the active voltage over time. To improve the performance of the PMSM drive [26], optimized constant switching pulse width modulation (PWM)-based DTC is sent. The ripple level for both torque and flux are minimized by optimizing the on-time level of a selected voltage. According to this work, the vector selection depends on the sign of torque deviation, flux, and flux angle. The selected vector is used to determine the time. Duty ratio manipulation for PMSM torque response enhancement was studied in [27]. For nominal DTC, the deviation sign and sector are considered to select the voltage. The problem with this control scheme is the introduction of vibration and ripple in torque performance. Many authors recommend the PI controller for overcoming the issue of the ripple. A virtual torque reference manipulation for reduction of ripple for a DTC-controlled drive is forwarded in [28].

Constrained maximization of torque density for PMSM was performed using parameters such as motor dimension and winding factor [29]. Whereas in [30], multi-level torque regulators and binary flux regulators are used for torque ripple manipulation. Based on the deviation of torque, different vectors are selected. Performance enhancement of DTC-controlled PMSM was improved when carrier-based space vector pulse modulation was used for switching signal generation [31]. This scheme is better in terms of ripple compared to conventional direct torque control (CDTC), but it needs more computation. The torque performance improvement of PMSM was demonstrated in [32] by removing partial stator parts. A variety of variables were changed in the optimal search method, including split ratio, tooth size, air gap, and magnet size, in order to improve the motor's performance. A deep flux lessening was performed in [33] to broaden the operating speed range of PMSM. A PMSM's wide-range control is implemented by combining vector current control and flux vector control.

As it is mentioned in the review, CDTC is an easy control algorithm, but it produces considerable ripple due to the full-time switching on of a voltage. While DTC-SVM has a better ripple and steady-state response compared to CDTC, it has more computation due to coordinate transformation and dwelling time calculation. Whereas the duty ratio-optimized controls like DDTCF and DDTC-RMS have less ripple compared to CDTC, even if they add computation to CDTC. In addition, a control scheme like EFV-DTC needs the program stored offline for ripple reduction, but the system is not giving an optimal duty. Whereas control schemes like MPS-DTC and MP-DTC can vary the duty value from zero to one depending on the input variables, they do not give an optimal duty. PWM can reduce the torque error to zero, but time calculation is complex. This study proposes DTC with an optimized duty ratio and delay compensation (DDTC-DC) for ripple minimization in PMSM drives. The proposed scheme has simplicity as CDTC, duty ratio optimization for ripple reduction, and delay compensation to reduce the error due to prediction. To make slope determination simple, torque error square minimization is applied. In the method proposed for duty ratio, two objectives were achieved: minimizing error and forcing torque to be equal to reference torque at the end of the switching span. Whereas delay compensation is added for estimation of both current and voltage at the same time within one sampling span. In classical prediction, the voltage magnitude is used to predict the current, and the voltage is predicted from the current in the next step. In this scheme, both current and voltage are predicted during the sampling period.

PMSM was modeled on the d-q axis by using a simple equation depicted in (1) up to (6). In the equation, the variables v stand for voltage, *i* stands for current, P stands for pole, ωr stands for rotor speed, ωs stands for electrical speed, mf stands for magnet flux, TL stands for load torque, J stands for inertial constant, B stands for friction constant, whereas Ψ stands for flux for each axis.

$$\begin{cases} \psi_d = L_d i_d + m_f \\ \psi_q = L_q i_q \end{cases} \tag{1}$$

$$\begin{cases} V_q = R i_q + \frac{d\psi_q}{dt} + \omega_s \psi_d \\ V_d = R i_d + \frac{d\psi_d}{dt} - \omega_s \psi_q \end{cases} \tag{2}$$

$$\begin{cases} i_d = \frac{1}{L_d} \int \left(V_d - R i_d + \omega_s \psi_q\right) dt \\ i_q = \frac{1}{Lq} \int \left(V_q - R i_q - \omega_s \psi_d\right) dt \end{cases} \tag{3}$$

$$T_e = 1.5P\left(\psi_d i_q - \psi_q id\right) \tag{4}$$

$$\begin{cases} J \frac{d\omega_r}{dt} = T_e - T_L - B\omega_r \\ \omega_r = \frac{1}{J} \int (T_e - T_L - B\omega_r)\, dt \end{cases} \tag{5}$$

$$\begin{cases} \omega_s = 0.5P * \omega_r \\ \theta_r = \int \omega_s \mathrm{dt} \end{cases} \tag{6}$$

2. METHOD

Figure 1 depicts the steps taken in this project. Duty ratio optimization with torque error square minimization was used to improve torque response in terms of ripple performance. Furthermore, one-step delay compensation is used to improve torque and flux estimation based on measured parameters. During the same sampling period, the delay compensation predicts both current and voltage [18]. At the end of the switching span, the proposed scheme minimized error and forced torque to equal the reference torque.

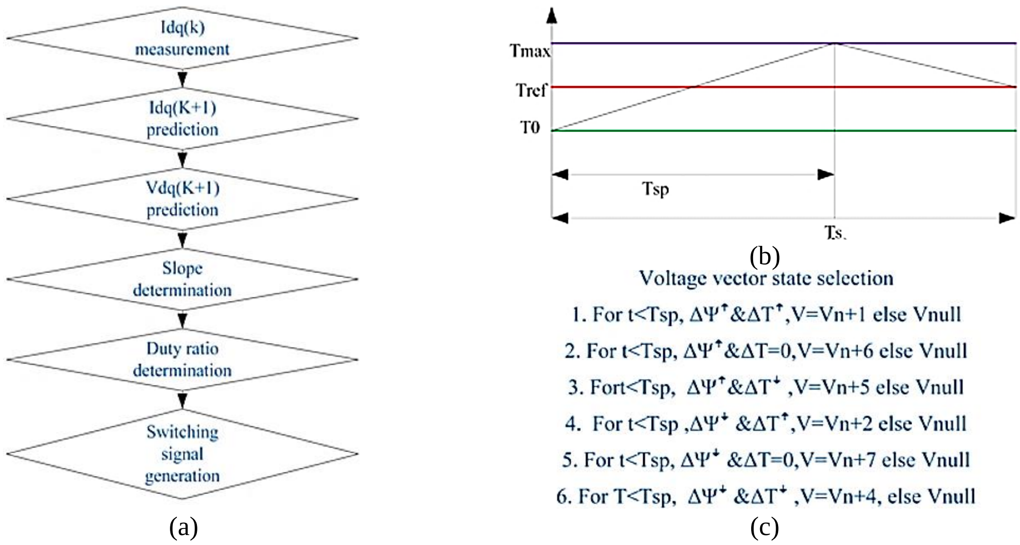

Figure 1. The sequence of steps followed in this work: (a) indicates the step to perform the work, (b) duty ratio optimization method used, and (c) way to select voltage vector based on control input signal

From the measured magnitude, the next step current is predicted using (7), when T is a small period less than the sampling time.

$$\begin{cases} id(k+1) = \left(1 - \frac{T*R}{Ld}\right) * id(k) + \frac{T*\omega s*Lq*iq(k)}{Ld} + \frac{T*vd(k)}{Ld} \\ iq(k+1) = \left(1 - \frac{T*R}{Ld}\right) * iq(k) - \frac{T*\omega s*Ld*id(k)}{Lq} - \frac{T*\omega s*mf}{Lq} + \frac{T*vq(k)}{Lq} \end{cases} \tag{7}$$

Assuming the $\frac{d\psi_q}{dt} = \frac{d\psi_d}{dt} = 0$, dq-axis voltage predicted using (8) within same the sampling period.

$$\begin{cases} V_q(k+1) = Ri_q(k+1) + \omega_s \psi_d(k+1) \\ V_d(k+1) = Ri_d(k+1) - \omega_s \psi_q(k+1) \end{cases} \tag{8}$$

The slope for the active and null voltage period is determined using (10) when S1 and S0 are the slope of torque during the active period and null voltage period respectively.

$$\begin{cases} \frac{d\psi_d}{dt} = V_d - \left(R * i_d - \omega_s * \psi_q\right) \\ \frac{di_q}{dt} = \frac{1}{L_q}\left(\left(V_q - R * i_q - \omega_s * \psi_d\right)\right. \end{cases} \tag{9}$$

The slope for null voltage is obtained by using zero magnitudes for voltage.

$$\begin{cases} S_1 = 1.5 * P\left(\frac{d\psi_d}{dt} * i_q + \frac{di_q}{dt} * \psi_d\right) \quad , for\ 0 < t < T_{sp} \\ S_0 = 1.5 * P\left(\frac{d\psi_d}{dt} * i_q + \frac{di_q}{dt} * \psi_d\right) \quad , for\ Tsp < t < T_s \end{cases} \tag{10}$$

When Ts and Tsp are switching period and optimal switching time. At any instant, the torque change is calculated by taking error.

$$T = \begin{cases} T_0 + S_1 * t, \;\; for, \; 0 < t < T_{sp} \\ T\,max + S_0(t - T_{sp}), \;\; for, \; T_{sp} < t < T_s \end{cases} \tag{11}$$

By minimizing the sum of error square, the expression for the switching time is obtained.

$$\frac{d}{dT_{sp}}\left(\sum_0^{T_s} e^2\right) = \frac{d}{dT_{sp}}\left(\int_0^{T_s}(Tref - T)^2 dt\right) = 0 \tag{12}$$

Solving the (12), the expression for switching period is obtained.

$$T_{sp} = \frac{Tref - T_0}{(S_1 - S_0)} + \frac{S_0 * T_s}{(S_1 - S_0)} \tag{13}$$

3. RESULTS AND DISCUSSION

The simulation is executed using MATLAB 2021b. Simulations are performed to assess the efficacy of the proposed scheme for operations involving variable speed and variable torque. Two scenarios were simulated: one involving variable speed and the other involving variable torque operation. In each scenario, one parameter was kept constant while the other was altered. The data utilized for simulation purposes were presented in Table 1.

The simulation took into account parameters such as torque ripple, speed ripple, and harmonic performance. The proposed scheme exhibits favorable speed, torque ripple, and flux performance, as depicted in Figures 2(a)-2(c). The steady-state fluctuation of flux, speed, and torque is determined by calculating the ratio of the maximum deviation from the reference value. The results shown in Figure 2 indicate that, during the time interval from 0 to 0.12 seconds, the reference values for flux, speed, and torque are 0.542 wb, 238.75 rpm, and 5 Nm, respectively. Following a brief period, the error in flux, velocity, and torque is 0.001, 0, and 0 respectively. So, from this information taking the ratio of maximum error to reference value, the normalized percentage (error/reference) *100 of ripple for flux, speed, and torque are 0.185%, 0%, and 0% respectively. In addition, the results in Figures 3(a)-3(c) indicate that the voltage harmonic, current harmonic and flux harmonic performance of the proposed scheme is very good. The ratio of active power loss due to total harmonic distortion (THD) to total active power loss ((current THD)^2/(1+current THD)^2) is 0.063%, which mean the scheme is effective from this perspective. In addition, in comparison to [31], the voltage harmonic and flux plot performance of the proposed scheme is superior. In addition to this, the scheme that was proposed has a superior steady-state torque performance compared to the one that was proposed in [30].

The response can be seen in Figure 4, which was created using 477.5 rpm and variable torque. The effectiveness of the plan is illustrated in Figure 4 (a) by the use of constant speeds. According to Figure 4(b), however, the system has a high ripple during a transient period when a sudden load change is created. This can be seen by looking at the graph. Once the transient period has passed, however, the torque performance of the system is outstanding. The current, the flux angle, and the sector number are depicted, respectively, in Figures 4(c)-4(e). On the other hand, as shown in Figure 4(f), the flux plot is virtually identical.

Table 1. Data used in simulation

Parameter	Magn	Parameter	Magn	Parameter	Magn	Parameter	Magn
Ld	21.3 mH	fs	1 khz	Vdc	200 V	Magnet flux	0.542 wb
Lq	24.2 mH	P	8	R	0.24 ohm	Imax	10 A

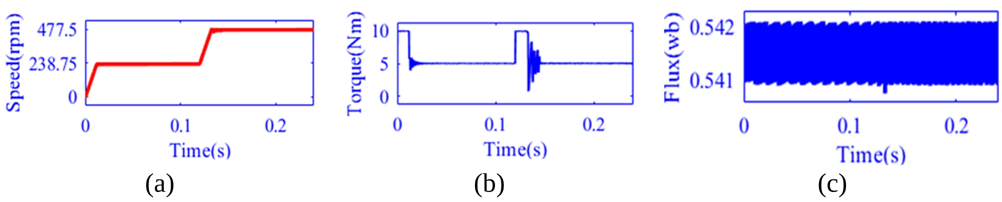

Figure 2. The response for variable speed and constant load of 5 Nm shows: (a) the speed, (b) the torque, and (c) the flux magnitude

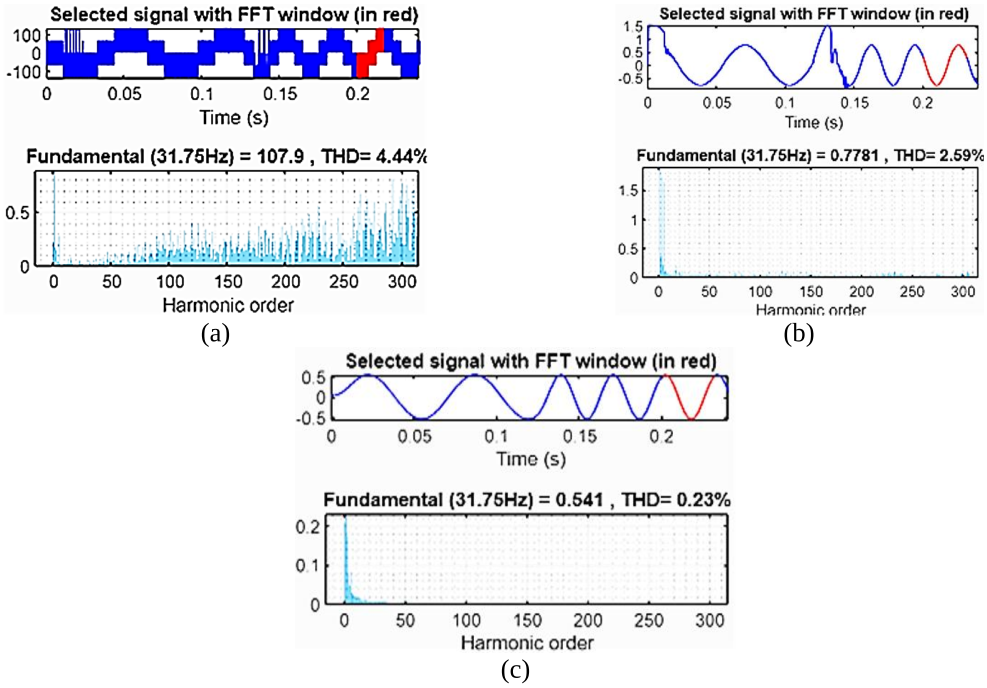

Figure 3. THD at 477.5 rpm and load of 5Nm when: (a) voltage THD, (b) current THD, and (c) flux THD

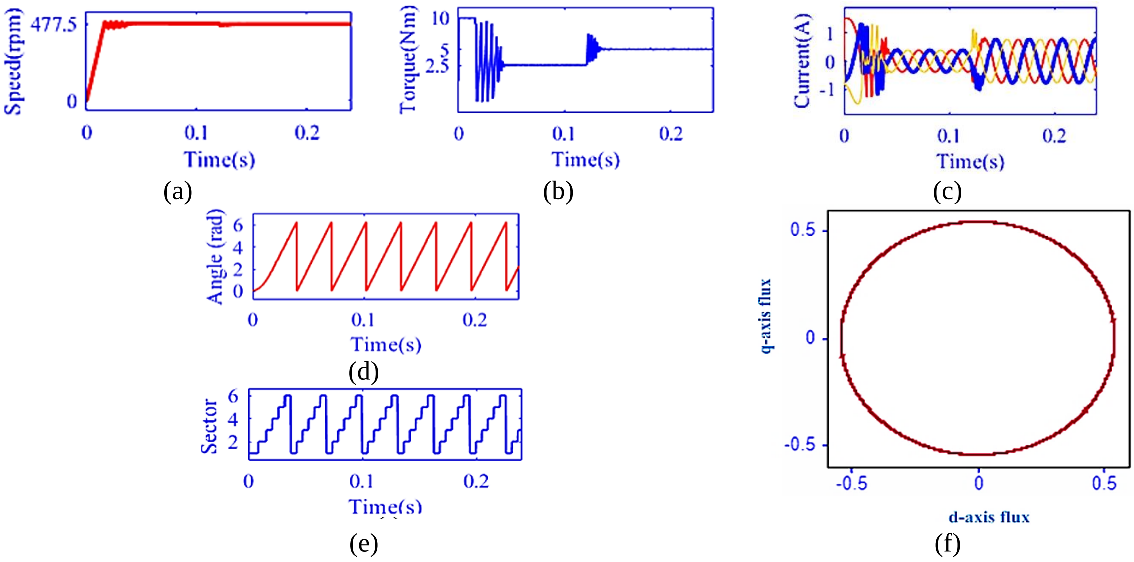

Figure 4. The response for 477.5 rpm and variable torque: (a) speed, (b) torque and (c) current, (d) flux angle, (e) sector number, and (f) shows the flux plot

4. CONCLUSION

This study introduces an improved direct torque control (DTC) method that is as straightforward as conventional DTC (CDTC) for controlling permanent magnet synchronous motor (PMSM) drives. The scheme employs optimal duty evaluation in order to minimize the steady state torque ripple. Moreover, delay compensation is employed to anticipate the amplitude of voltage and current in order to obtain refreshed data about the motor's condition. The proposed scheme was tested to evaluate its dynamics and steady-state performance under conditions of variable load and variable speed operation. Furthermore, an assessment was conducted on the motor's harmonic performance and the ratio between harmonic power loss and total active power loss. Overall, the proposed scheme effectively reduces steady state ripple and harmonic.

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