

# SEQUENTIAL DIRECT SPEED PREDICTIVE CONTROL OF PMSM WITH TWO-STEP COMPENSATION

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## ABSTRACT

*Recent progress in model predictive control of permanent magnet synchronous machines (PMSMs) shows that sequential direct speed predictive control (S-DSPC) offers a promising alternative of eliminating weighting factors in the cost function. This paper presents a simulation-based validation of an S-DSPC strategy with computational delay compensation, where cost functions are evaluated sequentially to simplify weight tuning and reduce complexity. A linear Kalman filter-based load torque observer provides the torque estimation required for state prediction. To study the effects of delay, a computational delay is introduced, and a compensation algorithm is proposed. The method addresses real-time predictive control delays by advancing state predictions to the  $k+2$  sampling step, ensuring that the applied switching state reflects actual system conditions. The approach was tested in MATLAB/Simulink under three cases: delay without compensation, delay with compensation, and an ideal delay-free case. Results show that uncompensated delay causes distortion in  $dq$ -axis currents and increases the total harmonic distortion (THD) of phase currents. With the two-step compensation (TSC) method, THD was reduced by approximately 35% compared to the uncompensated case, achieving performance close to the ideal scenario. Speed tracking and transient responses remained largely unaffected, confirming that TSC effectively improves current quality in S-DSPC.*

**Keywords:** Model Predictive Control, Direct Speed Control, Sequential Predictive Control, PMSM, Computational Delay Compensation

## 1. INTRODUCTION

Permanent Magnet Synchronous Motor (PMSM) has become the preferred choice in modern electric drive systems due to their high efficiency, excellent torque density, and fast dynamic response. These motors are widely used in industrial automation, robotics, and electric vehicles, where high-performance control is essential. The implementation of advanced control strategies for PMSM is critical to fully exploit their capabilities, particularly in applications requiring accurate torque and speed control under transient conditions. Conventional control approaches, such as field-oriented control (FOC) with PI regulators, have served well in many applications. However, they have their limitations in multivariable control, handling nonlinearities, and implementing system constraints [1]. As the demands on drive performance increase, control methods offering greater flexibility and superior dynamics have become necessary.

Model Predictive Control (MPC) has emerged as a powerful alternative to traditional control techniques in power electronics and motor drives. Among its variants, Finite Control Set MPC (FCS-MPC) has been especially attractive for power converters and motor control due to its direct use of discrete switching states, eliminating the need for modulators [2]. However, classical implementations of FCS-MPC typically rely on a single cost function combining multiple control objectives weighted by tuning parameters. This introduces challenges related to the proper selection of weighting factors, which often lack a systematic tuning method and can compromise performance or robustness if not chosen appropriately [3, 4].

To address these limitations, Sequential Model Predictive Control (S-MPC) has been proposed [5–12]. Instead of evaluating a single cost function with multiple weighted

terms, S-MPC separates control objectives into individual cost functions and evaluates them sequentially. This hierarchical structure simplifies tuning and control structure. Sequential Direct Speed Predictive Control (S-DSPC) is an emerging variant that integrates speed control directly into the MPC framework, eliminating the conventional outer-loop PI controller and enabling a cascade-free architecture, however, so far, its validation has only been demonstrated through a single simulation study [13].

One critical aspect of predictive control in practical implementations is the effect of computational delay [14–16]. Since prediction and optimization must be completed within one sampling period, delays caused by processing time can degrade prediction accuracy, thereby reducing overall control performance. Two-step compensation (TSC) techniques have been proposed to mitigate this issue, where future system states are estimated further ahead to account for known processing delays [16]. This approach improves prediction accuracy, especially in fast-sampling, high-dynamic applications. Integrating two-step compensation into the S-DSPC framework offers a direction to maintain performance while reducing sensitivity to computation-induced delays, making it more suitable for real-time applications.

Although two-step compensation (TSC) has been successfully applied in various MPC frameworks, its use within sequential predictive control strategies has not yet been investigated. In this work, TSC is incorporated into the S-DSPC controller, and its impact on speed tracking accuracy, current quality, and harmonic distortion is analyzed. The method is validated through simulations and compared against both an uncompensated control and an ideal delay-free case. The results demonstrate that the advantages of TSC, previously confirmed in conventional FCS-MPC, can

be effectively extended to sequential predictive speed control, thus improving its robustness to computation-induced delays and advancing its potential for real-time implementation.

## 2. MATHEMATICAL MODEL

This section outlines the mathematical models used in the design of the predictive control algorithm. These include the discrete-time model of the surface-mounted permanent magnet synchronous motor (SM-PMSM) and the model of the two-level voltage source inverter (2L-VSI) required for the prediction of voltage vectors.

### 2.1. PMSM model and discretization

The dynamic model of a surface-mounted PMSM in the rotor reference frame ( $dq$ -axis) is given by:

$$\frac{di_d}{dt} = \frac{1}{L_s} (u_d - R_s i_d + \omega L_s i_q), \quad (1)$$

$$\frac{di_q}{dt} = \frac{1}{L_s} (u_q - R_s i_q - \omega L_s i_d - \omega \psi_{PM}), \quad (2)$$

$$\frac{d\omega}{dt} = \frac{1}{J} (T_e - T_L - B\omega), \quad (3)$$

where  $i_d$ ,  $i_q$  are stator currents in the  $dq$  frame,  $u_d$ ,  $u_q$  are stator voltages,  $R_s$  is the stator resistance,  $L_s$  is the stator inductance,  $\omega$  is angular speed,  $\psi_{PM}$  is the permanent magnet flux linkage,  $T_e$  is the electrical torque,  $T_L$  is the load torque,  $J$  is the moment of inertia, and  $B$  is the viscous friction coefficient.

The electromagnetic torque is calculated as:

$$T_e = \frac{3}{2} p \psi_{PM} i_q \quad (4)$$

where  $p$  is the number of pole pairs.

To implement the model in a discrete framework, the continuous-time equations are discretized. A Taylor Series Expansion (TSE) is used to obtain the following discrete-time state prediction model:

$$i_d^p(k+1) = a_1 i_d(k) + a_2 \omega(k) i_q(k) + a_3 u_{di}(k) \quad (5)$$

$$i_q^p(k+1) = a_1 i_q(k) + a_2 \omega(k) i_d(k) - a_4 \omega(k) + a_3 u_{qi}(k) \quad (6)$$

$$\omega^p(k+1) = a_5 \omega(k) + a_6 i_q(k) + a_7 \hat{T}_L(k) + a_8 \omega(k) i_d(k) + a_9 u_{qi}(k) \quad (7)$$

$$T_e^p(k+1) = \frac{3}{2} p \psi_{PM} i_q^p(k+1) \quad (8)$$

where  $\hat{T}_L$  is the estimated load torque. The variables  $u_{di}$  and  $u_{qi}$  represent the  $dq$  components of the candidate voltage vectors derived from the 2L-VSI switching states. Predicted values for the next sampling step are denoted by the superscript  $p$ . Constants  $a_1$  through  $a_9$  are the model coefficients obtained via discretization:

$$a_1 = 1 - \frac{T_s R_s}{L_s}, \quad (9)$$

$$a_2 = T_s p, \quad (10)$$

$$a_3 = \frac{T_s}{L_s}, \quad (11)$$

$$a_4 = \frac{T_s \psi_{PM} p}{L_s}, \quad (12)$$

$$a_5 = 1 - \frac{T_s B}{J} - \frac{a_{a1} \psi_{PM} p T_s^2}{2J} + \frac{a_{a2} B T_s^2}{2}, \quad (13)$$

$$a_6 = \frac{3 T_s p \psi_{PM}}{2J} - \frac{a_{a1} R_s T_s^2}{2J} - \frac{a_{a2} 3 p \psi_{PM} T_s^2}{4}, \quad (14)$$

$$a_7 = -\frac{T_s}{J} + \frac{a_{a2} T_s^2}{2}, \quad (15)$$

$$a_8 = -\frac{a_{a1} p L_s T_s^2}{2J}, \quad (16)$$

$$a_9 = \frac{a_{a1} T_s^2}{2J}, \quad (17)$$

where  $T_s$  is the sampling time.

### 2.2. Model of 2L-VSI for prediction

The 2L-VSI is responsible for generating the stator voltages  $u_d$  and  $u_q$  from a DC-link voltage  $V_{dc}$ . Each leg of the inverter consists of two complementary switches, and the inverter can generate 8 possible voltage vectors, of which 6 are active and 2 are zero vectors. The complex space vector representation of the stator voltage is given by:

$$v_s = \frac{2}{3} V_{dc} \left( S_a + S_b e^{j\frac{2\pi}{3}} + S_c e^{j\frac{4\pi}{3}} \right) \quad (18)$$

where  $S_a$ ,  $S_b$ , and  $S_c$  are the binary switching signals for each phase leg ( $S \in \{0, 1\}$ ), and  $V_{dc}$  is the DC-link voltage.

The inverter switching states directly determine the candidate control inputs  $u_{di}(k)$  and  $u_{qi}(k)$  used for prediction in the MPC algorithm. These are projected from the  $\alpha\beta$  plane to the  $dq$  rotating reference frame based on the measured rotor position.

### 3. SEQUENTIAL CONTROL

Sequential Direct Speed Predictive Control (S-DSPC) is a model predictive control strategy designed to eliminate the need for traditional weighting factors used in conventional cost functions. Instead of evaluating multiple control objectives simultaneously in a single cost function, the S-DSPC splits the optimization problem into multiple sequences. Each sequence addresses one control objective, and voltage vector candidates are progressively selected through the sequences. This approach inherently avoids the problem of tuning weighting factors.

The control objectives evaluated through the sequential stages of the cost function are:

- Speed reference tracking;
- Maximum torque-per-ampere optimization via  $i_d$  minimization;
- Electromagnetic torque reference tracking.

At each stage, the voltage vectors that yield the highest control error are discarded, while the best-performing candidates are retained and passed to the next stage, narrowing the selection and focusing the optimization process. The complete control scheme is illustrated in Fig. 1, which includes the controller, the load torque observer, and the model of controlled system composed of the PMSM and the 2L-VSI.

In each stage, overcurrent protection is enforced using a nonlinear penalization term  $i_{oc}^p$ :

$$f(i_d^p(k+1), i_q^p(k+1)) = \begin{cases} \infty, & \text{if } |i_s^p(k+1)| > i_{\max}, \\ 0, & \text{if } |i_s^p(k+1)| \leq i_{\max}. \end{cases} \quad (19)$$

where  $i_s^p$  is vector of current magnitude and is calculated as

$$i_s = \sqrt{i_d^{p2} + i_q^{p2}}. \quad (20)$$

The cost functions used in the S-DSPC algorithm are:

$$J_\omega = (\omega^*(k) - \omega^p(k+1))^2 + i_{oc}^p, \quad (21)$$

$$J_{i_d} = (i_d^p(k+1))^2 + i_{oc}^p, \quad (22)$$

$$J_{T_e} = |S| + i_{oc}^p. \quad (23)$$

where  $\omega^*$  is the reference speed. Initially, all seven voltage vectors of the 2L-VSI are considered. The first cost function,  $J_\omega$ , evaluates each vector based on speed tracking performance. The four best candidates with the lowest value of the  $J_\omega$  are passed to the second stage, where  $J_{i_d}$  is used to minimize the  $d$ -axis current, ensuring a maximum torque-per-ampere. In the final stage, the torque control is achieved using a sliding manifold, proposed in [17], instead of a traditional torque error term. The sliding surface  $S$  is proposed here as combination of weighted speed error  $e_\omega$  and torque error  $e_{T_e}$ :

$$S = c \cdot e_\omega - e_{T_e}, \quad (24)$$

where:

$$e_\omega = \omega^*(k) - \omega^p(k+1), \quad (25)$$

$$e_{T_e} = T_e^p(k+1) - \hat{T}_L(k), \quad (26)$$

where  $\hat{T}_L$  represents the load torque estimated by the Kalman filter.

The scalar  $c > 0$  determines the speed of convergence of the sliding surface. Higher values of  $c$  improve response time but may introduce current ripples and instability. The use of the sliding manifold enables faster correction of speed deviations by coupling the effect of both speed and torque errors within the control law. This structure allows the S-DSPC to offer improved performance in dynamic conditions without the need for weighting factor tuning while ensuring current constraints are respected.

Despite its simplified optimization structure, the S-DSPC algorithm still requires a considerable amount of computation. This is primarily due to the evaluation of the cost functions and prediction calculations. As a result, a non-negligible portion of the sampling interval is spent performing these computations. This introduces a delay between the moment the values are measured and sampled and the time the actuation is actually applied to the inverter. Such timing misalignment can lead to degraded control accuracy, especially under fast dynamic conditions. Therefore, it becomes necessary to implement a compensation mechanism that accounts for this delay, ensuring the applied actuation is precise.

### 4. COMPENSATION OF A CALCULATION DELAY

The two-step compensation (TSC), proposed in [16] and later adapted for direct speed predictive control in [18] was implemented in this paper.

If the control algorithm does not include compensation for computational delay, predictions are generated using measurements taken at time  $t_k$ , and the optimal switching state is determined for the subsequent time step  $t_{k+1}$ . However, since the switching state is applied only after prediction calculation and cost function evaluation, and considering the time required for computation, the selected switching state is effectively applied at time instant  $t_k + t_d$ , and remains active beyond  $t_{k+1}$ , until time instant  $t_{k+1} + t_d$ .

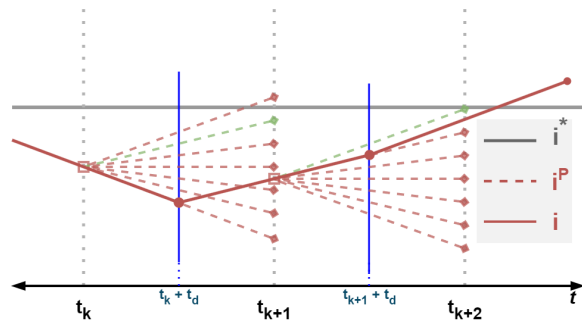


**Fig. 2** The illustrative example of predictive control operation for the system with calculation delay and no calculation delay compensation

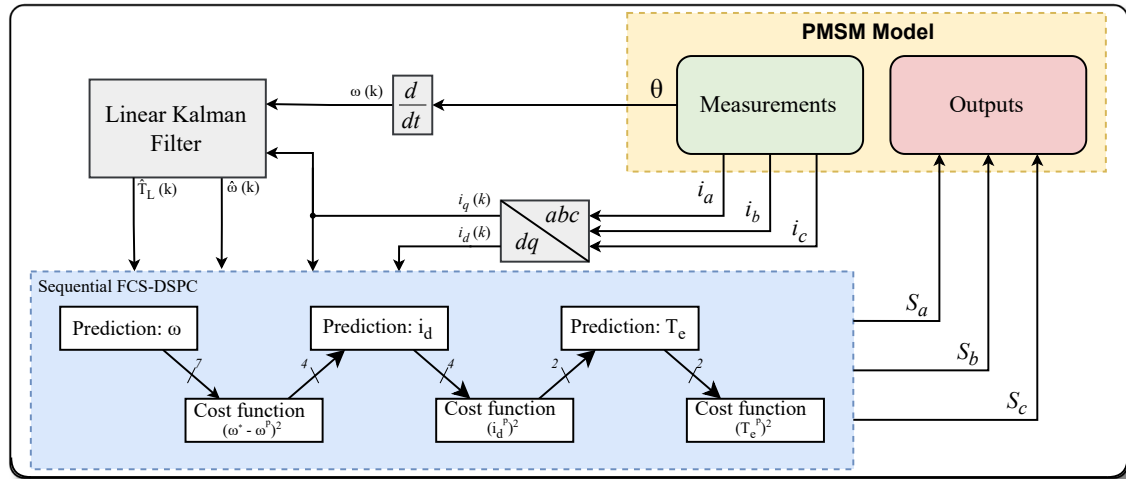


Fig. 1 The control diagram of a proposed sequential DSPC

Subsequent actuations are also delayed in the same manner. This results in inaccurate predictions, leading to the selection of a non-optimal switching state, as shown in Fig. 2.

To compensate for the computational delay, it is necessary to postpone the application of actuation to allow for both - accurate prediction calculations for that specific instant, and a sufficient time to perform the calculations needed. As a result, the predictions are no longer based on the most recently measured values. Instead, the estimations of measured values for  $t_{k+1}$  are calculated, based on just applied voltage vectors  $u_d, u_q$ :

$$\hat{i}_d(k+1) = a_1 i_d(k) + a_2 \omega(k) i_q(k) + a_3 u_d(k) \quad (27)$$

$$\hat{i}_q(k+1) = a_1 i_q(k) + a_2 \omega(k) i_d(k) - a_4 \omega(k) + a_3 u_q(k) \quad (28)$$

$$\hat{\omega}(k+1) = a_5 \omega(k) + a_6 i_q(k) + a_7 \hat{T}_L(k) + a_8 \omega(k) i_d(k) + a_9 u_q(k) \quad (29)$$

It means that predictions will be shifted by one step forward to  $t_{k+2}$ . Predicted values will be calculated as follows:

$$i_d^p(k+2) = a_1 \hat{i}_d(k+1) + a_2 \hat{\omega}(k+1) \hat{i}_q(k+1) + a_3 u_{di}(k+1), \quad (30)$$

$$i_q^p(k+2) = a_1 \hat{i}_q(k+1) + a_2 \hat{\omega}(k+1) \hat{i}_d(k+1) - a_4 \hat{\omega}(k+1) + a_3 u_{qi}(k+1), \quad (31)$$

$$\omega^p(k+2) = a_5 \hat{\omega}(k+1) + a_6 \hat{i}_q(k+1) + a_7 \hat{T}_L(k+1) + a_8 \hat{\omega}(k+1) \hat{i}_d(k+1) + a_9 u_{qi}(k+1), \quad (32)$$

$$T_e^p(k+2) = \frac{3}{2} p \psi_{pm} i_q^p(k+2). \quad (33)$$

where  $\hat{i}_d(k+1), \hat{i}_q(k+1)$  and  $\hat{\omega}(k+1)$  are estimated values in  $t_{k+1}$ , and  $u_{di}, u_{qi}$  are vectors of all possible actuations.

Instead of applying the actuation immediately after the calculation is finished, the actuation is delayed and applied in the beginning of the next step  $t_{k+1}$ . This will ensure that optimal actuation is applied at each sampling interval, followed by measurements for the computation of the next actuation. The current will no longer deviate from the reference and current ripples will be reduced [19], as shown in Fig. 3.

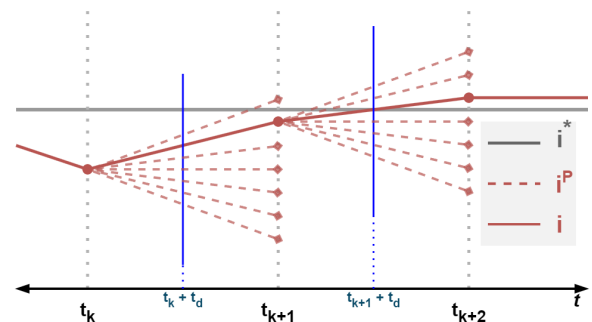


Fig. 3 The illustrative example of predictive control operation for the system with calculation delay and with calculation delay compensation

After suitable modification, the control algorithm will consist of the following steps:

1. measurement of phase currents and angular position,
2. application of selected switching states (selected in the previous step) to the inverter,

3. transformation of phase currents to  $dq$  coordinates, estimation of the load torque  $\hat{T}_L$ ,
4. estimation of the values for  $t_{k+1}$ , considering just applied switching state, via equations 29,
5. prediction of controlled variables ( $i_d^p, T_e^p, \omega^p$ ) for  $t_{k+2}$  via equations 30, 33, 32, for all possible inverter switching states,
6. evaluation of the sequential cost function,
7. selection of the optimal actuation.

Compared to DSPC without delay compensation, the application of actuation is moved to the beginning and estimation is added. The reference values in  $t_{k+2}$  can be calculated using extrapolation, however for a sampling time of  $T_s = 20\mu s$ , it is not necessary to calculate future references. Instead, approximation as  $T_L(k+2) \approx T_L(k)$ , and  $\omega^*(k+2) \approx \omega^*(k)$  can be applied.

All calculations pertaining to cost function minimization and the optimization algorithm will be calculated using the predicted values at  $t_{k+2}$ .

## 5. SIMULATION RESULTS

To validate the effectiveness of the proposed Sequential Direct Speed Predictive Control with Two-Step Compensation, a comprehensive simulations were conducted using MATLAB/Simulink. The simulation model was developed and includes a detailed inverter model using components from Simscape library, where MOSFET transistors were employed as switching elements to emulate the real switching behavior of the power converter. The parameters used in the model are summarized in Table 1.

**Table 1** Parameters of SM-PMSM machine and MPC algorithm

| Symbol               | Quantity         | Value   |
|----------------------|------------------|---------|
| $V_{DC}[V]$          | DC line voltage  | 560     |
| $P_n [W]$            | nominal power    | 1162    |
| $n_n [\text{rpm}]$   | nominal speed    | 3000    |
| $p [-]$              | pole pairs       | 5       |
| $k_t [\text{Nm/A}]$  | torque constant  | 1.7     |
| $J_M [\text{kgm}^2]$ | motor inertia    | 0.00015 |
| $R_s [\Omega]$       | phase resistance | 7.5     |
| $L_s [\text{mH}]$    | phase inductance | 22.7    |
| $T_s [\mu s]$        | sampling time    | 20      |

To reflect the reality of digital control systems, a computational delay of  $t_d = 10\mu s$  was deliberately introduced into the simulation loop to model the time consumed during measurement, prediction, and decision-making. Three simulation scenarios were carried out to evaluate and compare control performance:

- **Scenario 1** (Baseline): The control with delay and no compensation.
- **Scenario 2** (Proposed): The control with delay and two-step compensation.

- **Scenario 3** (Ideal): The control with no delay, simulating the ideal instant computation.

Each of the three approaches was tested under identical conditions, including a step change in reference speed and a subsequent application of a load torque. The simulation results are shown in three figures as a comparison in responses of angular speed and  $dq$ -axis currents.

Figure 4a shows the response under computational delay without compensation (Scenario 1). Figure 4b depicts the response with delay and Two-Step Compensation applied (Scenario 2), and Figure 4c provides the ideal case without any computational delay (Scenario 3). In Fig. 4a, noticeable distortions appear in the  $dq$  currents as a result of computational delay. With the application of TSC, the results become comparable to the ideal case without computational delay, as shown in Fig. 4b and Fig. 4c. The transient behavior and steady-state speed tracking are only marginally affected by the delay, indicating that the main degradation occurs in current control performance.

To quantify the influence of computational delay on current control quality, a spectral analysis was performed by calculating the Total Harmonic Distortion (THD) of the phase current  $i_a$  for each control scenario. The spectral analysis was conducted under steady-state operating conditions with the motor under load of  $T_L = 7Nm$ .

The uncompensated scenario yields the highest THD, reaching 23.27%, as shown in Fig. 5a. By applying of TSC, the THD is significantly reduced to 16.08%, as shown in Fig. 5b, indicating a notable improvement in current quality. This result closely approaches the ideal, delay-free case shown in Fig. 5c, where the THD reaches its lowest value of 14.12%.

The steady-state speed performance was evaluated using the root mean square error (RMSE), calculated between the measured speed and the reference speed. Once again, RMSE was calculated under steady-state operating conditions with the motor under load of  $T_L = 7Nm$ . Margins between different scenarios were very small; the uncompensated case resulted in  $RMSE_{\omega_{sc1}} = 1.558 \text{ rad/s}$ ; the two-step compensation case yielded  $RMSE_{\omega_{sc2}} = 1.691 \text{ rad/s}$ ; and case with no computational delay yields the worst results  $RMSE_{\omega_{sc3}} = 2.518 \text{ rad/s}$ . Overall, RMSE values remained small across all scenarios, consistent with typical results for predictive control without specific steady-state error mitigation.

## 6. CONCLUSION

This paper presented the implementation and simulation-based verification of two-step compensation applied to Sequential Direct Speed Predictive Control for PMSM drives. The purpose of TSC was to mitigate the adverse effects of computational delay by offsetting predictions to the  $k+2$  sampling step, thereby ensuring that the applied control action corresponds more accurately to the actual system state.

The proposed approach was evaluated in MATLAB/Simulink under three scenarios: uncompensated control with delay, compensated control with delay, and an

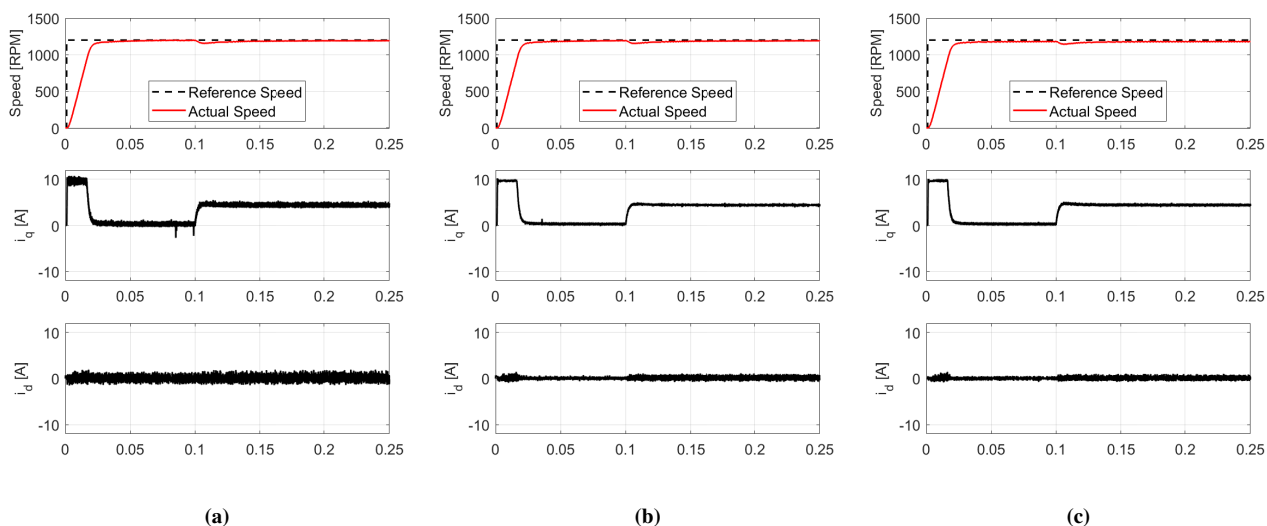


**Fig. 4** Simulation results for Sequential DSPC, speed tracking and dq currents: (a) Scenario 1, (b) Scenario 2, (c) Scenario 3

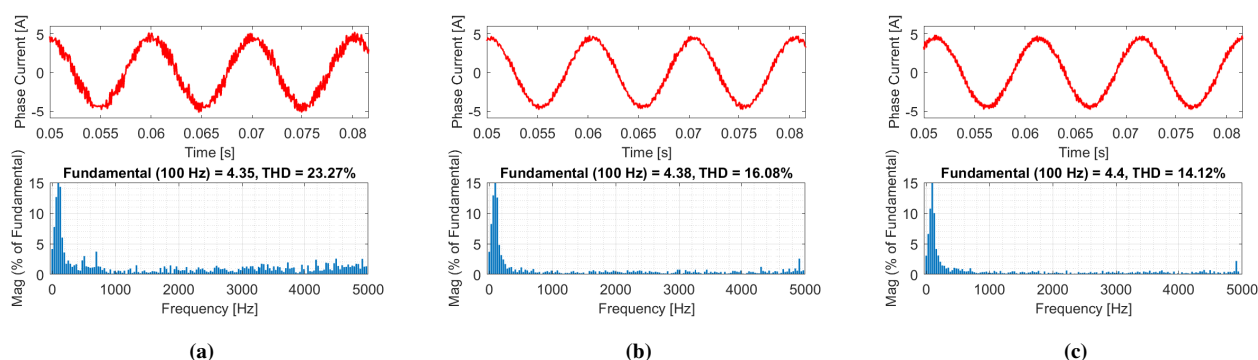


**Fig. 5** Simulation results for Sequential DSPC, phase current waveforms and spectral analysis: (a) Scenario 1, (b) Scenario 2, (c) Scenario 3

ideal case without delay. Results showed that computational delay, when left uncompensated, leads to significant distortion apparent in  $dq$  currents and a substantial increase in total harmonic distortion of the phase currents. The application of TSC reduced THD by approximately 35% compared to the uncompensated case, bringing performance close to the ideal delay-free scenario. Speed tracking and transient performance remained largely unaffected across the tested scenarios, with only marginal differences in steady-state RMSE values.

These findings demonstrate that TSC is an effective method for improving current quality in S-DSPC. The insights gained from this study provide the groundwork for future experimental validation and enhance the implementation of sequential predictive control methods.

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