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Fault-Tolerant Generalized Predictive Control for DC Motor Systems

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- GPC.
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Abstract – This paper investigates a fault-tolerant Generalized Predictive Control (GPC) strategy for a DC motor system subjected to sensor failures, actuator degradation, and external disturbances. The study highlights the design and implementation of a discrete-time GPC scheme with a focus on maintaining performance under fault scenarios. Simulation results demonstrate the robustness of the proposed approach in tracking reference speed and mitigating the effects of faults and disturbances.

I. INTRODUCTION

DC motors are integral components of various industrial and robotic systems due to their reliability, versatility, and ease of control. Their applications span from automated manufacturing to precision robotics, where maintaining consistent performance is crucial [1, 2]. However, challenges arise due to faults in sensors, actuators, and external disturbances, which can significantly degrade system efficiency and stability. To address these issues, various advanced control strategies have been explored, each offering unique advantages depending on the system's requirements and operational environment.

Among the widely used control approaches, Proportional-Integral-Derivative (PID) control remains a cornerstone for its simplicity and effectiveness in many scenarios. However, its performance can degrade under significant uncertainties, disturbances, or system faults [3, 4]. To overcome these limitations, Sliding Mode Control (SMC) is often employed for its robustness against parameter variations and external disturbances, though it may suffer from chattering issues [5, 6]. Similarly, Model Predictive Control (MPC) provides a more sophisticated alternative by

solving an optimization problem at each time step to predict and manage system dynamics over a defined horizon, making it suitable for systems with constraints and complex dynamics [7].

GPC, a subset of MPC, is particularly appealing for DC motor control due to its ability to anticipate future system behavior and optimize control actions accordingly. GPC integrates system dynamics into its optimization framework, allowing for precise trajectory tracking while considering system constraints. Its inherent predictive nature makes it well-suited for handling faults and disturbances, as it can adapt control actions preemptively to mitigate their effects.

This study focuses on designing and simulating a fault-tolerant control framework for a DC motor using GPC. The proposed approach is tested under two critical fault scenarios: sensor failures, where incorrect feedback can lead to erroneous control actions, and actuator degradation, which reduces the motor's torque efficiency. Additionally, the motor is subjected to external time-varying disturbances, simulating real-world operational conditions. The primary objective is to achieve accurate speed tracking while ensuring robust performance against these adversities, demonstrating the effectiveness and resilience of GPC in fault-tolerant applications.

II. DC MOTOR MODEL AND FAULT SCENARIOS

The DC motor's dynamics are described by a continuous-time state-space model. The state vector $x = [\omega, i]^T$ represents the motor speed (rad/s) and armature current (A), while u denotes the control input voltage (V).

The dynamics are governed by the equations:

$$\dot{x} = A_c x + B_c u + E_c \omega, \quad y = Cx \quad (1)$$

where A_c , B_c and Cx are system matrices derived from motor's physical parameters. These matrices incorporate the motor's resistance (R), inductance (L), torque constant (K_t), back EMF constant (K_e), inertia (J), and friction coefficient (B). The disturbance ω represents external torques acting on the motor.

For digital implementation, the system is discretized with a sampling time $T_s = 0.5$ seconds. The discrete-time state-space model is given as:

$$\begin{aligned} x[k+1] &= A_d x[k] + B_d u[k] + E_d \omega[k] \\ y[k] &= Cx[k] \end{aligned} \quad (2)$$

where A_d , B_d and Cx are the discrete-time matrices.

To evaluate fault tolerance, two fault scenarios are introduced:

- **Sensor Failure:** The motor's speed measurement is replaced with a constant erroneous value for a specified duration.
- **Actuator Degradation:** The actuator's torque efficiency is reduced by a degradation factor ($\eta < 1$), simulating wear or damage.

Additionally, the system is subjected to time-varying sinusoidal disturbances modeled as:

$$\omega[k] = 0,1 \sin(0,1k) \quad (3)$$

III. GENERALIZED PREDICTIVE CONTROL DESIGN

The GPC controller optimizes control inputs by minimizing a quadratic cost function defined as:

$$J = \sum_{i=1}^{Np} (r[k+i] - y[k+i])^2 + \lambda \sum_{j=1}^{Nc} (u[k+j])^2 \quad (4)$$

where Np is the prediction horizon, Nc is the control horizon, and λ is a regularization factor that penalizes large control inputs. The first term ensures

tracking accuracy, while the second term promotes control effort efficiency.

The predictive control law is derived using predictive matrices H and Φ , which encode the system dynamics over the prediction horizon. The optimization problem is solved to obtain the optimal sequence of control inputs, of which only the first input is applied at each step.

The predictive matrices H and Φ are constructed iteratively as:

$$\Phi[i] = CA^i, \quad H[i,j] = \begin{cases} CA^{i-j}B, & j \leq i \\ 0, & j > i \end{cases} \quad (5)$$

The control sequence is computed as:

$$u_{opt} = -(H^T H + \lambda I)^{-1} H^T (r - \Phi x[k]) \quad (6)$$

where r is the desired trajectory.

IV. RESULTS

The DC motor parameters used in the simulation are $R = 1 \Omega$, $L = 0,5 \text{ H}$, $k_t = K_e = 0,01$, $J = 0,01 \text{ kg} \cdot \text{m}^2$ and $B = 0,1 \text{ Nms}$. The sampling time is set to $T_s = 0.5$ seconds. The GPC parameters include a prediction horizon of $Np = 50$, a control horizon of $Nc = 25$, and a regularization factor $\lambda = 10^{-5}$.

The simulation consists of 100-time steps. During steps 50 to 60, a sensor fault is introduced, where the output measurement is locked at a constant value. Between steps 70 and 90, actuator degradation reduces the torque efficiency by 50%. Throughout the simulation, the motor is subjected to a time-varying sinusoidal disturbance.

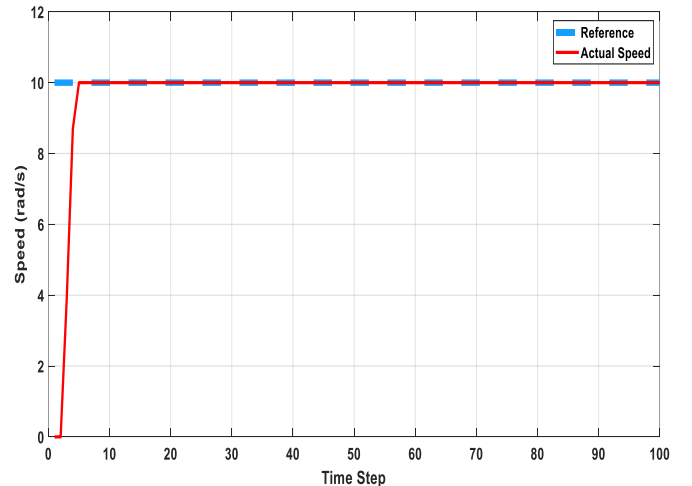


Fig.1 DC motor speed tracking under fault scenarios and subjected to disturbances.

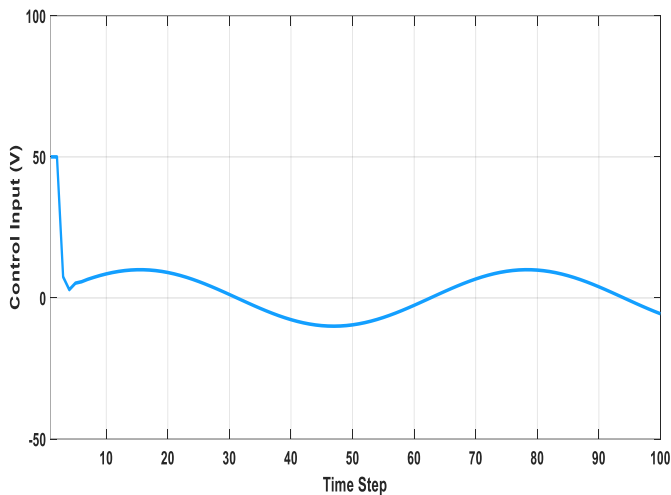


Fig.2 Control input under fault scenarios and subjected to disturbances.

V. DISCUSSION

- The GPC controller demonstrated robust performance across all fault scenarios. During the sensor fault period, the controller relied on model-based predictions to maintain stable operation. The reference speed of 10 rad/s was accurately tracked, even with erroneous sensor readings.
- In the actuator degradation scenario, the controller compensated for the reduced torque efficiency by adjusting the control inputs. Despite the degraded actuator performance, the motor speed remained close to the desired trajectory. The sinusoidal disturbance introduced additional challenges but was effectively mitigated by the predictive control strategy.
- The control input profile remained bounded throughout the simulation, with no significant overshoots or oscillations. This indicates the controller's ability to balance tracking accuracy and control effort under dynamic conditions.

VI. CONCLUSION

This study presented a Generalized Predictive Control framework for a fault-tolerant DC motor. The proposed approach demonstrated robust speed tracking and effective fault mitigation under sensor failures, actuator degradation, and external

disturbances. The simulation results validate the effectiveness of the GPC strategy in maintaining system stability and performance. Future work will focus on experimental validation and extending the approach to multi-motor systems with more complex fault scenarios.

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