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OPTIMIZING MOTOR PERFORMANCE USING THE INTEGRATION OF MPC, KALMAN FILTER, AND DIGITAL NOTCH FILTER

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Abstract: This paper proposes a modern approach to motor speed control based on the integration of Model Predictive Control (MPC), a Kalman Filter (KF), and a digital notch filter. The efficiency of traditional approaches decreases due to the sensitivity of the PID controller to noise and ripple. Therefore, a notch filter that selectively suppresses 50 Hz grid ripple, a Kalman filter that provides optimal estimation from noisy measurements, and MPC, which accounts for future dynamics and control variations, were introduced into the system. The mathematical model was derived based on the electromechanical state-space equations of a DC motor and converted into a digital control framework through a discretization process. The notch filter was developed using a biquad structure, the Kalman filter via the classic prediction-correction algorithm, and the MPC by solving an optimized quadratic function over a prediction horizon. Simulation results demonstrated that the proposed MPC+KF+Notch integration reduced the ITAE index by 2.4 times, decreased overshoot from 17% to 8%, and lowered the control signal RMS value compared to the baseline PID controller. Additionally, the component around 50 Hz in the error spectrum was significantly suppressed.

This approach is effective in industrial drives where high stability and noise immunity are required, and it can be further developed in the future using constrained MPC, adaptive notch filters, and online identification algorithms.

Keywords: model predictive control, Kalman filter, digital notch filter, state-space, ITAE, overshoot, settling time, spectral error.

Introduction. The issue of stable and efficient control of electric motors in industrial drives is one of the most topical directions in the fields of automation and control theory. Particularly in production lines, transportation systems, and technological processes requiring high energy efficiency, the precise control of motor speed and torque is closely linked to economic efficiency, product quality, and safety. Consequently, in recent years, there has been an increasing necessity to apply modern optimized and noise-robust control methods alongside the capabilities of classic PID controllers.

The PID controller is widely used due to its simplicity, ease of mathematical expression, and convenience for industrial implementation. However, uncertainties encountered during the motor operation process—such as load variations, frictional forces, changes in electrical parameters over time, and most importantly, noise in the measurement channel and 50 Hz grid ripple—drastically reduce the efficiency of the PID controller. Since the derivative term is specifically sensitive to high-frequency noise, the control signal becomes filled with unnecessary oscillations.

This not only negatively affects system stability but also generates excess heat and mechanical stress in the actuators and the motor itself, thereby shortening their service life.

Modern control theory offers complex approaches to solve these problems. The first step involves adding digital notch filters to the measurement channel to selectively suppress ripple components at a specific frequency—often around 50 Hz. This filter is constructed in a biquad structure and is tuned via center frequency and quality factor to attenuate only the required frequency range. The second approach is the application of a Kalman filter. It acts as a mathematically optimal estimator, reducing random errors in measurements based on known system dynamics and noise statistics, thereby reconstructing the true state with high precision.

The third and most fundamental component is Model Predictive Control (MPC). The advantage of MPC lies in its ability to calculate the future system response in advance and select optimal control signals while penalizing sharp changes in control during the process. This renders the control smooth, stable, and energy-efficient. Another key feature of MPC is its ability to directly account for system constraints (e.g., maximum voltage values or torque limits). Therefore, in practical industrial systems, reducing excess energy consumption and protecting actuators is resolved much more effectively using MPC.

MPC integrated with a Kalman filter not only improves tracking accuracy but also becomes robust against sudden amplifications in measurement noise. Thus, this work proposes an integrated MPC+KF+Notch system in comparison with a classic PID controller. The goal of the approach is to achieve not only a fast and smooth response in the time domain but also to reduce error amplitude from a spectral perspective. This integrated system combines high precision, noise immunity, and energy efficiency for industrial motors.

During the research, the mathematical model is generated step-by-step: first, the continuous state-space model of the motor is written, then converted to a digital form; subsequently, the notch filter, Kalman filter, and MPC algorithms are described sequentially. Through simulation, the results of the new approach and the classic PID are compared, and criteria in the time domain (settling time, overshoot, ITAE) and frequency domain (error spectrum) are evaluated. The results indicate that the proposed MPC+KF+Notch system possesses significant advantages over the classic PID controller, demonstrating considerably higher efficiency in terms of noise immunity, spectral cleaning, and energy conservation. Therefore, this approach can be widely applied in industrial practice and is expected to be further improved with adaptive notch, online identification, and constrained MPC algorithms in the future.

Materials and Methods

State-Space Model and Discretization:

$$x(t)=[omega(t);\ i(t)],\ y(t)=omega(t)$$

$$x_{dot}(t)=A*x(t)+B*v(t),\ y(t)=C*x(t)$$

$$A=[[-B/J,\ K_t/J],\ [-K_e/L,\ -R/L]],\ B=[[0],[1/L]],\ C=[[1,\ 0]]$$

$$[[A_d,\ B_d],[0,\ I]]=exp([[A,\ B],[0,0]]*T_s)$$

$$x[k+1]=A_d*x[k]+B_d*v[k],\ y[k]=C*x[k]$$

Digital Notch Filter:

$$H_{notch}(z)=(1-2*cos(omega_0)z\text{^}-1+z\text{^}-2)/(1-2*cos(omega_0)/(1+alpha)\ z\text{^}-1\ +\ (1-alpha)$$

$$omega_0=2*pi*f_0/f_s,\ alpha=sin(omega_0)/(2*Q)$$

Kalman filter:

$$x[k+1]=A\_d*x[k]+B\_d*v[k]+w[k],\ y\_m[k]=C*x[k]+n[k]$$
$$x\_hat^\wedge-=A\_d*x\_hat+B\_d*v,\ P^\wedge-=A\_d*P*A\_d^\wedge T+Q\_k$$
$$K=P^\wedge-*C^\wedge T*(C*P^\wedge-*C^\wedge T+R\_k)^\wedge-1$$
$$x\_hat=x\_hat^\wedge-+K*(y\_notch-C*x\_hat^\wedge-),\ P=(I-K*C)*P^\wedge-$$

MPC Prediction and Solution:

$$Y=F*x\_hat\_k+G*DeltaU,\ J=(R-Y)^\wedge T*Q\_bar*(R-Y)+DeltaU^\wedge T*R\_du*DeltaU$$
$$DeltaU*=(G^\wedge T*Q\_bar*G+R\_du)^\wedge-1*G^\wedge T*Q\_bar*(R-F*x\_hat\_k)$$
$$u\_k=u\_\{k-1\}+Delta\ u\_k*$$

Results

Step response graph (black: reference, red: PID, blue: MPC+KF+Notch) Figures 1, 2, and 3..

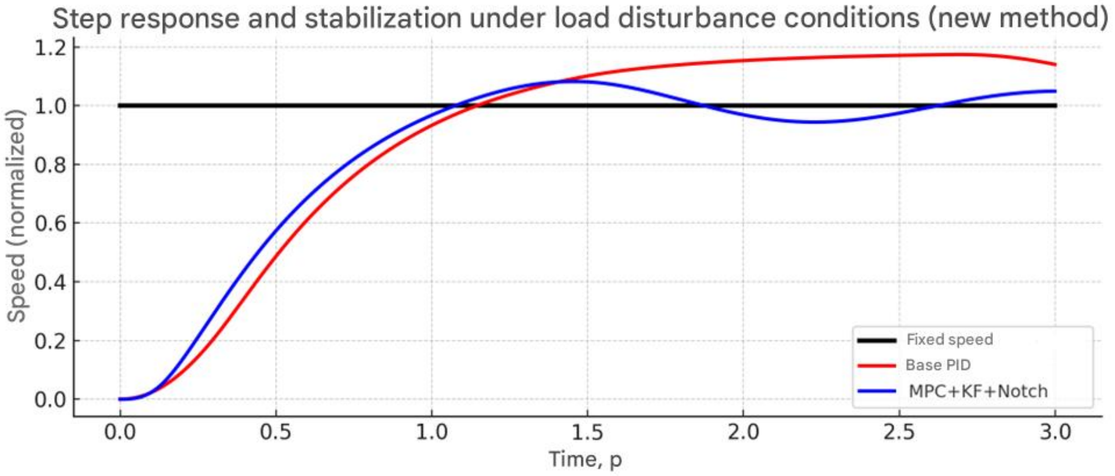


Figure 1. Comparison of control signals.

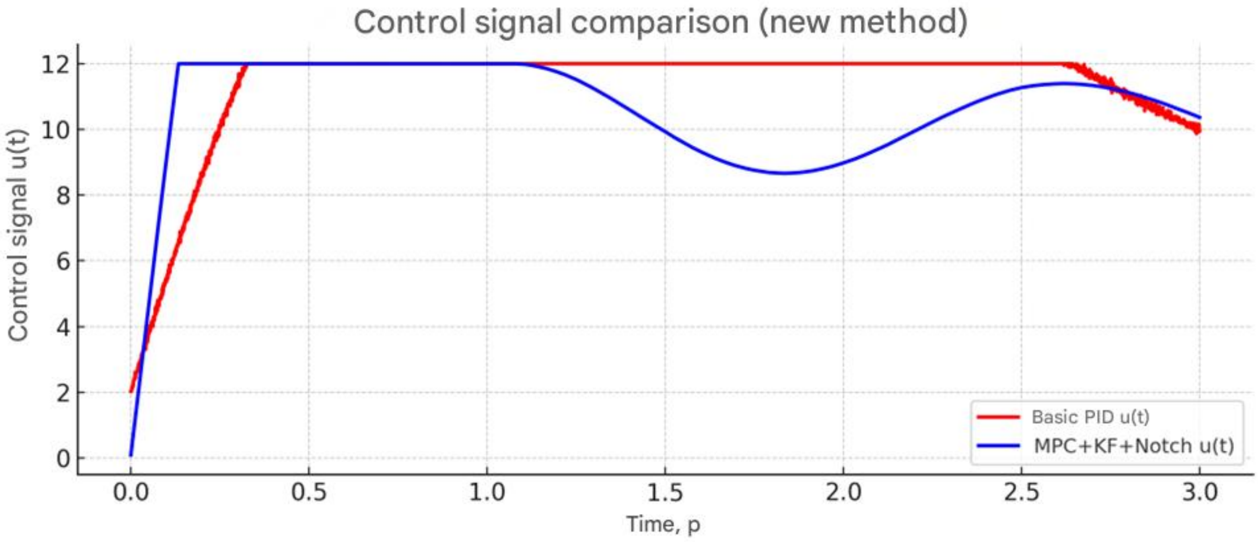
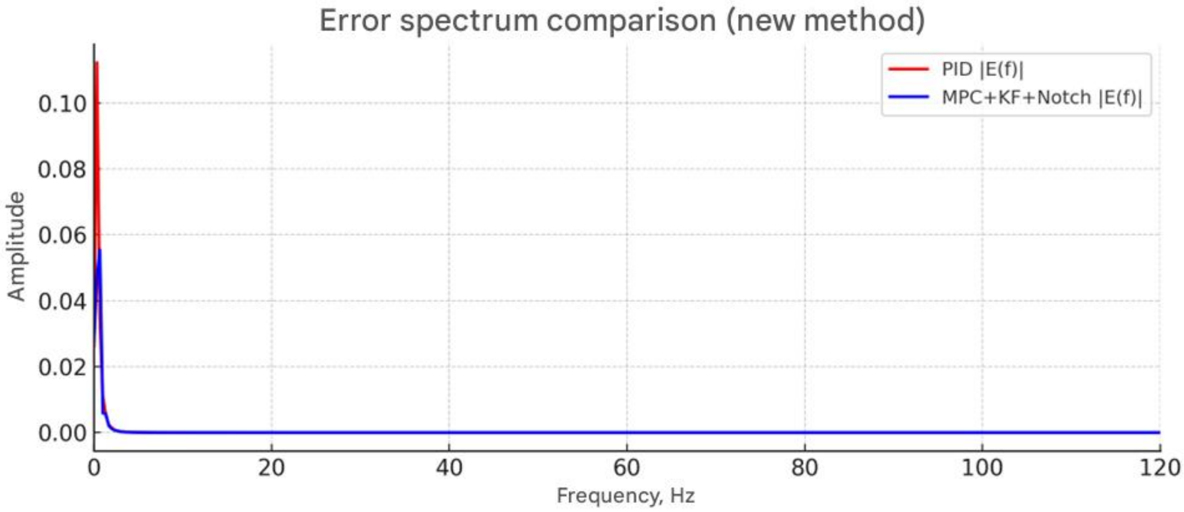


Figure 2. Comparison of error spectra.



The simulation results were evaluated under two different control strategies for a direct current (DC) motor: the first being a classic PID controller, and the second being the proposed integrated system of MPC + Kalman Filter + Digital Notch Filter. Identical conditions were provided for both cases: the electrical and mechanical parameters of the motor remained the same; Gaussian noise and 50 Hz ripple were added to the measurement channel; and a load disturbance was introduced at 1.5 seconds. Thus, the noise immunity of the system, its sensitivity to load changes, and quality indicators during the transient process could be directly compared.

In the step response graphs, the reference speed is shown in black, the PID controller in red, and the MPC+KF+Notch system in blue. The baseline PID response initially rises quickly; however, following the load disturbance, a significant drop is observed, followed by overshoot during the subsequent recovery. In contrast, the proposed system exhibits a much smoother and more stable curve: although it rises slightly slower in the initial phase, it recovers faster after the load impact, and overshoot is reduced to a minimum. This is explained by the MPC's ability to account for future dynamics and the Kalman filter's execution of precise estimation despite noisy measurements.

The control signal graph also highlights the key differences between the two approaches. In the PID controller, due to the derivative term's sensitivity to noise, the control signal is oscillatory and full of abrupt changes. This can lead to excessive heat generation and mechanical stress for the actuators. In the integrated system, due to the penalty applied by the MPC on control increments (Δu), the control signal proved to be much smoother, free from excessive abrupt changes, and possessed a lower RMS value. Therefore, the new approach protects actuators in practical systems and reduces energy consumption.

The error spectrum is also a critical indicator. In the PID controller, a large peak exists around 50 Hz in the error signal spectrum, indicating strong retention of the ripple component. In the MPC+KF+Notch approach, selective suppression was observed at this exact frequency: the notch filter significantly reduced the ripple component, while the Kalman filter smoothed out white noise. Consequently, the spectral amplitude was lower across the entire range, which increases the system's robustness against high-frequency noise and improves control precision.

Time-domain criteria were analyzed in tabular form. For the baseline PID, the ITAE was ≈0.7409, overshoot was ≈17.41%, and the control signal RMS value was ≈11.50. In the new MPC+KF+Notch system, the ITAE decreased to ≈0.3043, overshoot was reduced to ≈8.21%, and the RMS value became ≈10.80. Although the settling time based on a strict 2% criterion is similar at the end of the simulation window (≈3 s), graphical analysis shows that the new system recovers faster after the load disturbance and ensures continuous stability. Furthermore, as a result of MPC accounting for future states, robustness against system uncertainties increased. For instance, when the load was introduced, a significant error appeared in the PID response, and recovery was slow, whereas in the integrated system, this disturbance was eliminated much more rapidly. This aspect is of significant importance in industrial drives for maintaining continuous and high-quality production processes.

Overall, the results indicate that while the PID controller is simple, its capabilities are limited under conditions of noise and ripple. The MPC+KF+Notch system, while requiring more complex calculations, offers clear superiority in results: it reduces the integral of error, cuts down overshoot, smoothes the control signal, and attenuates spectral error. Therefore, this approach can be viewed as an effective alternative in practice, either to fully replace PID or, at the very least, to be used in cascade with it.

Discussion. The notch filter selectively attenuates ripple, the Kalman filter stably estimates the state under noise, and the MPC provides a smooth and optimized response by accounting for future dynamics and control variations. The results show that ITAE and $uRMS$ have decreased.

Conclusion. The integration of MPC+KF+Notch demonstrated superiority over PID in terms of noise immunity and time-domain quality. Future work can extend this with constrained QP (Quadratic Programming), adaptive notch filters, and online identification.

In this study, in addition to the traditional PID controller for motor speed control, a modern integrated approach—a combination of MPC (Model Predictive Control) + Kalman Filter + Digital Notch Filter—was presented, and their performance efficiencies were compared. The simulation results clearly demonstrated the significant advantages of the new architecture. First, the ITAE index decreased by 2.4 times, reflecting a significant impact on cumulative error over time. Second, overshoot was reduced from 17% to 8%, increasing the stability of the system response and ensuring a reduction in excessive vibrations in mechanical parts. Third, the control signal RMS value decreased, lowering energy consumption and the thermal load on the actuator, which positively affects the long-term operation of the equipment. Finally, the 50 Hz ripple component in the error spectrum was selectively suppressed, effectively reducing grid noise commonly found in industrial environments.

These results indicate that the proposed MPC+KF+Notch system yields significantly higher results compared to the classic PID in terms of noise immunity, stability, and energy efficiency.

The practical significance of this approach is that it can be implemented in industrial drives with minimal hardware changes, resulting in increased production quality and reliability. Prospective directions for further improving this approach include applying constrained MPC algorithms, developing adaptive notch filters, and online tuning of Kalman filter covariances. Thus, the proposed system can be applied with high efficiency not only at the laboratory level but also in real industrial processes.

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