A STUDY OF CVT CONTROL STRATEGIES TO IMPROVE POWERTRAIN EFFICIENCY IN ELECTRIC VEHICLES

NGHIÊN CỨU CÁC CHIẾN LƯỢC ĐIỀU KHIỂN CVT NHẰM NÂNG CAO HIỆU SUẤT HỆ TRUYỀN ĐỘNG TRONG XE ĐIỆN

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Abstract - This paper presents a closed-loop PID control strategy to optimize the performance of a CVT (Continuously Variable Transmission) system actuated by a solenoid valve controlling pneumatic pressure. Feedback is obtained from the current of a PMSM (Permanent Magnet Synchronous Motor) and the CVT output shaft speed, then processed by the PID controller to adjust pressure. The objective is to maintain an optimal transmission ratio based on load torque, ensuring efficiency and stability under different operating conditions. Experimental results show that the method reduces torque fluctuations, improves dynamic response, and saves energy during speed changes. The solution provides smooth ratio transitions, minimizes overshoot, and maintains steady operation. It is suitable for electric vehicle drivetrains requiring high performance and energy efficiency, demonstrating applicability in real-world scenarios where consistent performance and energy conservation are important for system reliability in modern transportation.

Key words - PMSM; CVT; PID control; solenoid valve; drive system

Tóm tắt - Bài báo này trình bày một chiến lược điều khiển PID vòng kín nhằm tối ưu hóa hiệu suất của hệ thống truyền động CVT (Continuously Variable Transmission) sử dụng van solenoid điều khiển áp suất khí nén. Tín hiệu phản hồi được lấy từ dòng điện của động cơ PMSM (Permanent Magnet Synchronous Motor) và tốc độ trục ra của CVT, sau đó được đưa vào bộ điều khiển PID để điều chỉnh áp suất phù hợp. Mục tiêu là duy trì tỷ số truyền tối ưu theo mô-men tải, đảm bảo hiệu suất và ổn định của hệ thống trong mọi điều kiện làm việc. Kết quả thử nghiệm thực tế cho thấy phương pháp này giúp giảm đáng kể dao động mô-men, cải thiện khả năng đáp ứng động, đồng thời tiết kiệm năng lượng trong quá trình thay đổi tốc độ. Giải pháp này phù hợp cho các hệ truyền động xe điện yêu cầu hiệu suất cao và tiết kiệm năng lượng.

Từ khóa - PMSM; CVT; PID; van solenoid; truyền động

1. Introduction

The integration of Permanent Magnet Synchronous Motors (PMSM) with Continuously Variable Transmissions (CVT) has garnered increasing attention in advanced drive systems for electric vehicles, robotics, and industrial automation [1] - [4]. PMSMs are favored due to their high torque density, precise control capability via Field-Oriented Control (FOC), and excellent performance across a wide speed range. When combined with a CVT - which enables smooth and continuous adjustment of the transmission ratio - the potential for enhanced drive system efficiency is significantly increased [1], [3], [5].

However, most current CVT systems still operate with fixed ratios or open-loop control mechanisms, particularly in systems utilizing pneumatic or hydraulic actuation [6] - [8]. Such control methods often fail to fully exploit the torque-speed characteristics of PMSMs, resulting in reduced efficiency, torque overshoot during transients, and poor responsiveness to load variations [3], [5].

Recently, various advanced control approaches have been investigated to improve the performance of PMSM - CVT drive systems. Strategies such as adaptive control, sliding mode control, and model predictive control (MPC) have demonstrated improved transient response and reduced torque ripple [11] - [15]. However, these methods typically require accurate system modeling and incur high computational costs, making them difficult to implement on resource-constrained embedded microcontrollers. In this context, the PID controller - despite its classical nature - remains advantageous due to its stability, ease of tuning, and practical deployability on limited hardware.

Several recent studies have explored intelligent control methods for electric drive systems [6] - [9], yet few have addressed the synchronization between PMSM output and the dynamic adaptation of the CVT ratio. This opens opportunities for developing a closed-loop control system capable of real-time CVT ratio adjustment, ensuring that the operating point of the drive system remains within the high-efficiency region of the PMSM characteristics [1], [2], [5]. This paper proposes an integrated PMSM - CVT architecture oriented toward control, wherein the CVT is actuated by pneumatic or hydraulic mechanisms and modulated according to real-time feedback from torque, speed, and load sensors. The PMSM is controlled via an FOC inverter and monitored by current sensors and an encoder [9], [10]. The control algorithm dynamically computes the optimal transmission ratio in real time, aligning with the torque-speed profile of the motor and thereby minimizing losses during acceleration/deceleration phases or under load disturbances [1] - [4], [9].

A PMSM - CVT measurement system has been constructed - including a double chain coupling, magnetic brake, encoder, and current sensor - with a focus on the PID control algorithm for CVT pulley displacement via pneumatic valve actuation. This setup allows synchronization of the CVT transmission ratio with the operational characteristics of the motor under varying speed conditions. Experimental results demonstrate that this algorithm significantly improves drive system responsiveness, reduces losses during transitions, and enhances overall efficiency during continuous speed variation.

Table 1. *Abbreviations used in this paper*

PMSM	Permanent Magnet Synchronous Motor
CVT	Continuously Variable Transmission
FOC	Field-Oriented Control
PID	Proportional - Integral - Derivative
PWM	Pulse Width Modulation
SVPWM	Space Vector PWM
ω_m	Rotor angular speed (rad/s or rpm)
T_{act}	Actual torque (Nm)
T_{ref}	Reference torque (Nm)
r_{actual}	Measured transmission ratio
r_{target}	Target transmission ratio

2. Research and survey results

The hardware platform developed in this study integrates a high-performance PMSM drive system with a CVT mechanism actuated by either pneumatic or hydraulic means, enabling real-time control and evaluation under continuously varying speed conditions. The system is flexibly designed to switch between two CVT control modes (pneumatic or hydraulic), with all measurement and processing tasks handled by a central microcontroller-based controller.

All results presented in this study were obtained using the pneumatic control mode, employing a 0 - 12 V proportional pressure valve and a double-acting cylinder. The hydraulic mode was only used for mechanical compatibility testing and is not included in the quantitative results due to its slower response characteristics.

2.1. Motor drive system

The motor used is a surface-mounted PMSM rated at 63 kW, with a maximum speed of 6000 rpm. Figure 1(a) shows the motor model controlled by a three-phase inverter executing the FOC algorithm on an STM32 microcontroller. The FOC algorithm includes Clarke and Park transformations, PI controllers for i_d and i_q currents, space vector modulation (SVPWM), and field weakening for high-speed operation. A rotary encoder with 2048 pulses/rev is directly mounted on the PMSM shaft for rotor position feedback. INA240 current sensors are installed on each phase for precise current measurement and torque estimation. The inverter switching frequency is 16 kHz, and the control cycle is 1 kHz.

Figure 1(b) presents the block diagram of the CVT control algorithm, which consists of two main loops: the inner loop controls PMSM current and torque via FOC, and the outer loop adjusts the CVT transmission ratio based on torque-speed feedback. Feedback signals from the encoder, torque sensor, and CVT position sensor are processed through the PID controller to generate pressure control signals for the solenoid/pneumatic valve.

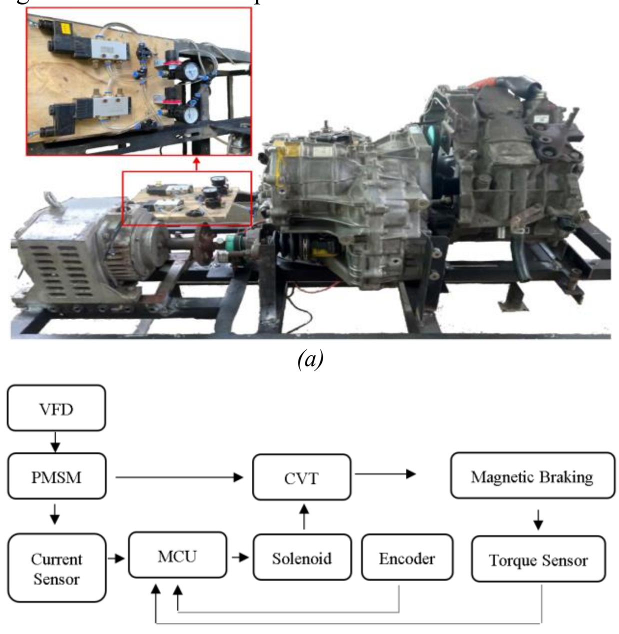

Figure 1. *(a) Physical model of the CVT control system using closed-loop PID and PMSM feedback with magnetic braking; (b) Block diagram of the CVT control algorithm using closed-loop PID and PMSM feedback*

2.2. CVT mechanism

The CVT employs a variable-diameter pulley type, controlled by one of two modes:

- Pneumatic mode: Double-acting cylinder actuated by a proportional pressure valve (controlled by a 0 - 12 V signal from the STM32 DAC) [5] - [8].

- Hydraulic mode: Hydraulic piston actuated by a PWM-type solenoid valve [6] - [8].

In pneumatic mode, the PID controller output is directly converted to an analog voltage (0 - 12 V) to control the proportional pressure valve, thereby adjusting the cylinder pressure. In hydraulic mode, the PID output is modulated into a 2 kHz PWM signal to drive the solenoid coil of the servo valve. The PID controller is synchronized with feedback from the CVT pulley position sensor, ensuring smooth transmission ratio adjustment without significant pressure oscillations or delay. Both modes share a unified software structure, differing only in valve control layers, making the system flexible in configuration switching.

Transmission ratio adjustment is performed by longitudinal displacement of the conical pulley pair, with CVT movement feedback obtained from a linear potentiometer or position sensor mounted on the actuator.

The CVT output shaft is connected to a programmable magnetic brake capable of generating load torque. A torque sensor with a 5 Nm range is installed between the shaft and brake. The brake is controlled by a current source with adjustable voltage. The central control and measurement unit, based on an STM32 microcontroller, performs the following functions:

- FOC control for the PMSM;
- Data acquisition: current, speed, torque, CVT position;
- CVT control loop: transmission ratio calculation and valve control signal output;
- Serial communication for data logging and PC display.

The system uses a 24 V DC supply for the control unit and a separate AC supply for the motor inverter. All control signals are optically isolated to avoid interference from high-power lines. Figure 1 illustrates the system architecture, including power sources, control units, and signal pathways. The proposed system consists of a PMSM controlled by FOC, connected to the CVT via a double chain coupling. The output shaft is linked to a magnetic brake for load emulation. The measurement system includes:

- Rotary encoder for speed and shaft position measurement;
- Torque sensor between CVT output and magnetic brake;
- INA240 current sensors on all three phases.

The CVT actuator uses a proportional pneumatic or hydraulic cylinder. The control signal is generated by a closed-loop PID algorithm implemented on STM32, with the transmission ratio updated in real time based on PMSM torque-speed feedback.

A typical PMSM operates in two main regions: constant torque region (low speed) and constant power region (high speed, via field weakening). Experimental results from PMSM under FOC control show torque decreasing with speed [9], [10]. Without active CVT control, the motor is forced to operate outside the optimal region, resulting in higher losses and slower response [3], [5]. The control algorithm follows these steps:

- Read required and actual torque values from PMSM;
- Determine desired transmission ratio based on PMSM torque-speed characteristic;
- Apply PID control to modulate the valve signal for pneumatic/hydraulic cylinder actuation.

This mechanism ensures that the transmission ratio adapts in real time to load and speed changes, maintaining operation in the most efficient torque region of the motor.

PMSM torque-speed characteristic. When controlled via FOC, PMSMs exhibit a torque-speed characteristic clearly divided into two operating regions: constant torque and field weakening. At low speed, the stator current vector is aligned with the q-axis, generating torque proportional to i_q:

$$\boldsymbol{T_e} = \frac{3}{2}\boldsymbol{p}\lambda_m i_q$$

where $\boldsymbol{T_e}$ is electromagnetic torque, $\boldsymbol{p}$ is the number of pole pairs, and λ_m is the permanent magnet flux linkage. As speed increases and back EMF rises, the system reaches the base speed ω_b. Beyond this point, the motor enters the field-weakening region, where $i_d < 0$ is applied to reduce voltage saturation:

$$(\boldsymbol{V_{max}})^2 = (\omega \boldsymbol{L_d} i_d + \omega\lambda_m)^2 + \left(\omega \boldsymbol{L_q} i_q\right)^2$$

This constraint limits the achievable i_q value, thereby reducing the motor's output torque. Experimental data are collected from PMSM under no-load and with a resistive brake. Figure 2 shows the torque-speed curve obtained from real-time measurements. Torque remains nearly constant at about 2 Nm up to approximately 3000 rpm, then decreases linearly in the field-weakening region.

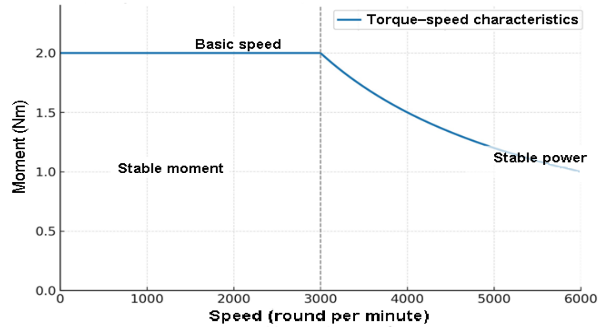

Figure 2. *Torque-speed characteristic of PMSM under FOC control*

Figure 2 depicts the torque-speed curve obtained from real-time data from the PMSM system controlled via FOC. Data were collected using a 2048-pulse/rev encoder and INA240 current sensor over 10 seconds at a 1 kHz sampling rate. Each data point is averaged over 20 samples to reduce noise. The curve demonstrates a constant torque region of approximately 2 Nm up to 3000 rpm, followed by a linear decrease in the field-weakening region. This serves as the basis for the algorithm to determine the CVT optimal operating region in the PID control section.

Without adaptive CVT control, the motor is forced to operate at inefficient points on the torque-speed plane during speed changes, leading to:

- Increased phase current in the field-weakening region;
- Poor acceleration response;
- Increased heat generation and copper losses.

A synchronous CVT controller can shift the operating point horizontally on the speed axis by adjusting the mechanical transmission ratio, thus keeping the required electrical torque within the efficient region. This improves both dynamic response and overall energy efficiency, especially under varying load or speed conditions.

2.3. CVT control algorithm

The control objective is to track the desired torque-speed operating point by continuously adjusting the CVT transmission ratio in real time [1] - [4], [6] - [8]. The block diagram of the algorithm is illustrated in Figure 1.

Open-loop CVT control in this study refers to the method of controlling the solenoid valve output pressure according to a preset ratio, without position or torque feedback. In contrast, closed-loop CVT control utilizes simultaneous feedback from the CVT position sensor (r_actual) and PMSM torque (T_act) to correct the transmission ratio. This distinction allows the closed-loop system to automatically adjust pressure to compensate for load disturbances, ensuring the transmission ratio consistently meets the target.

2.3.1. Control objectives

a. Inputs and feedback

Torque error calculation:

$$\boldsymbol{e_T} = T_{ref} - T_{act}$$

T_{ref}: Required torque from the load or motion planner;

T_{act}: Actual torque measured by sensor or observer;

ω_m: Motor speed measured by encoder;

r_{actual}: Current CVT transmission ratio (from position sensor).

b. Control logic

Determine the target transmission ratio r_{target} based on ω_m and the PMSM efficiency region (using a lookup table or approximate model).

Apply PID controller:

$$\boldsymbol{u}(\boldsymbol{t}) = \boldsymbol{K_p} e_r + \boldsymbol{K_i} \int e_r \, dt + \boldsymbol{K_d} \frac{de_r}{dt}$$

where $e_r = r_{target} - r_{actual}$

The control signal $\boldsymbol{u}(\boldsymbol{t})$ is normalized into a 0 - 5 V PWM signal to drive the actuator valve.

2.3.2. Tuning and Stabilization

PID coefficients $\boldsymbol{K_p}$, $\boldsymbol{K_i}$ and $\boldsymbol{K_d}$ are tuned via the Ziegler - Nichols method for pneumatic systems, and manually refined for hydraulic systems due to slower response.

The control loop operates at 1 kHz in parallel with the FOC loop to ensure synchronization. Saturation limits and anti-windup mechanisms are applied to prevent valve damage or control instability.

a. Lookup table and mapping strategy

A key component of the algorithm is mapping the torque-speed operating point to the optimal CVT transmission ratio. This is realized via a 2D lookup table generated from experimental PMSM torque-speed data. The table is indexed by ω_m and T_{ref}, outputting the optimal transmission ratio r_{opt} according to:

$$r_{opt} = \frac{\omega_{load}}{\omega_m} = \boldsymbol{f}(T_{ref}, \omega_m)$$

To reduce memory usage and improve interpolation, a spline or piecewise polynomial approximation model is used to smooth the data. The result is a suitable mechanical transmission ratio function that helps maintain PMSM operation in the maximum efficiency region.

b. Control cycle and synchronization

The overall system operates with two main control loops:

Inner loop (FOC): Runs at 16 kHz for current control and SVPWM pulse generation;

Outer loop (CVT): Runs at 1 kHz for torque tracking and valve signal modulation;

Shared variables (torque, speed, transmission ratio) are communicated via DMA buffers or interrupt-safe ring buffers. Execution times are timestamped to prevent interference and ensure real-time performance on the STM32 platform.

Actuator characteristics and valve modeling

The response of pneumatic/hydraulic actuators introduces delay and nonlinearity. For pneumatic control, the valve-to-cylinder model is approximated as a first-order system:

$$\tau \frac{dr}{dt} + r = K_v \, u(t)$$

where K_v is the valve gain, and τ is the time constant dependent on cylinder volume and pressure.

In hydraulic mode, hysteresis and stiction are more pronounced. Thus, deadband compensation is added to the control output to ensure proper response:

$$u_{mod} = \begin{cases} 0 & if \ |u(t)| < \delta \\ u(t) - \delta . sign(u(t)) & otherwise \end{cases}$$

c. Safety and constraint handling

The control system applies hardware and software constraints to prevent overtravel or output saturation:

Limit switches installed at both ends of the CVT;

Software checks ensure r $\in [r_{min}, r_{max}]$ - output control signals are limited to the permissible voltage/PWM range for the valve.

In case of sensor failure or signal loss, the controller switches to fallback mode, maintaining the last known transmission ratio until reinitialization

3. Discussion

Experiments were conducted under three main scenarios: (1) linear acceleration from 0 to 5000 rpm with constant load, (2) stepwise variation of load torque while maintaining constant speed, and (3) simultaneous variation of speed and load. The objective was to evaluate the effectiveness of the closed-loop PID CVT control strategy compared to conventional open-loop control, considering both dynamic characteristics and energy efficiency.

3.1. Experimental scenarios

Three principal test cases were performed:

- Linear acceleration from 0 - 5000 rpm with a fixed load of 1.5 Nm.

- Constant speed at 3000 rpm with stepwise load variation from 0 to 2.5 Nm.

- Constant speed at 3000 rpm with stepwise load variation from 0 to 2.5 Nm.

In the load variation scenarios, the magnetic brake was controlled by a current source to generate variable load torque from 0 to 2.5 Nm. The step change in load had an amplitude of ±1 Nm and a period of 3 s, generated using a square wave signal. This load range corresponds to approximately 40 - 100% of the rated torque of the PMSM used in the experiments.

3.2. Measurement setup

Sensor data were recorded at a frequency of 1 kHz via UART communication to a computer. The measured quantities included:

- Motor speed ωm (v/ph);
- Torque T (Nm);
- Phase current I_{abc} (A);
- Transmission ratio r (dimensionless);
- Control signal u(t) (V).

Table 2 presents a performance comparison between open-loop CVT control and the proposed closed-loop PID strategy, measured during the acceleration scenario. The parameters in Table 2 are calculated from experimental data during acceleration (0 - 5000 rpm, fixed load 1.5 Nm). Energy consumption was computed as the integral of instantaneous power over a 5-second interval:

$$E = \int_0^{t_{end}} \mathrm{V}_{dc} \times \mathrm{I}_{dc}\, dt$$

Overall efficiency was determined as the ratio of mechanical output energy to electrical input energy:

$$\eta = \frac{\mathrm{T}_{act} \times \omega_{out}}{\mathrm{V}_{dc} \times \mathrm{I}_{dc}} \times 100\%$$

Values in Table 2 are the average of 10 measurements, with a standard deviation less than 5%.

***Table 2.** Performance comparison between open-Loop and closed-loop control*

Parameter	Open-Loop	Closed-Loop PID	Improvement
Torque overshoot (Nm)	0.82	0.31	62.2%
Speed settling time (ms)	480	270	43.8%
Energy loss (Ws)	32.6	27.1	16.9%
Peak phase current (A)	7.4	6.1	17.6%
Overall efficiency (%)	83.4	91.1	+7.7%

Quantitative results indicate that the closed-loop PID control strategy reduces torque overshoot from 0.82 Nm to 0.31 Nm (a reduction of 62.2%), decreases speed settling time by 43.8%, and increases overall efficiency by 7.7%.

To assess the reliability of the results, each experiment was repeated 10 times under identical conditions. The mean and standard deviation (σ) of performance indicators were calculated as follows:

$$\bar{x} = \frac{1}{N}\sum_{i=1}^{N} x_i$$

$$\sigma = \sum_{i=1}^{N} (x_i - \bar{x})^2$$

where:

- x_i is the measurement value in the i-th trial;
- N is the number of trials;
- $\bar{x}$ is the mean value;
- σ is the standard deviation representing data dispersion around the mean.

Applying these formulas to 10 measurements yielded a torque overshoot of 0.31 ± 0.04 Nm, speed settling time of 270 ± 18 ms, and overall efficiency of 91.1 ± 0.9%. Statistical results show measurement errors below 5%, demonstrating the stability of the algorithm and high reliability of the closed-loop PID control system.

3.3. Discussion 1

The results presented in Figures 3, 4, and 5 were obtained from the actual PMSM - CVT experimental system. Speed, torque, and transmission ratio data were recorded by the STM32 controller via UART at 1 kHz. Each curve represents the average of five trials to reduce measurement noise.

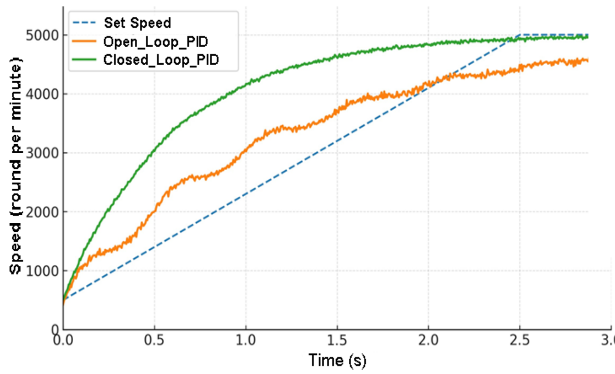

***Figure 3.** Speed response in ramp test with and without CVT control*

In the ramp speed test (scenario 1), the reference speed increased linearly from 0 to 5000 rpm. With closed-loop PID control, the actual speed reached the target value after approximately 2.25 s, with a maximum deviation of only 150 rpm, corresponding to less than 3%. This result demonstrates that the closed-loop CVT control enables the PMSM to maintain higher torque in the low-speed region, avoiding power drop when transitioning to the field-weakening region. This not only improves acceleration time but also ensures more stable speed tracking under minor load disturbances.

3.4. Discussion 2

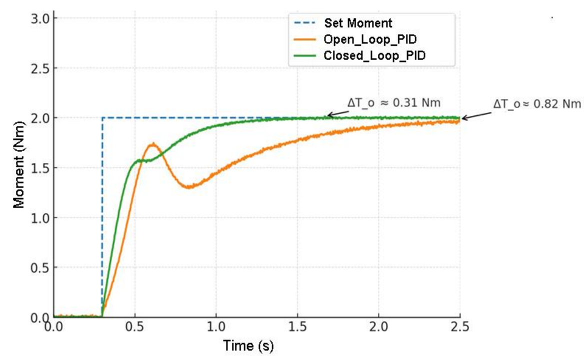

***Figure 4.** Comparison of torque control and overshoot*

In scenario 2 (stepwise load torque variation from 0 to 2 Nm), the closed-loop PID system achieved the target torque after 0.9 s with an overshoot of only 0.31 Nm, while the open-loop system exhibited larger overshoot (0.82 Nm) and prolonged oscillations. This indicates that closed-loop PID control significantly reduces oscillation and torque response time compared to open-loop PID control.

3.5. Discussion 3

For deployment in commercial applications such as two-wheeled electric vehicles or small urban vehicles, several challenges must be considered, including the size and weight of the pneumatic/hydraulic system, energy efficiency and durability of solenoid valves under vibration, and safety requirements in case of pressure loss or sensor failure. Nevertheless, due to the simplicity of the PID structure and its feasibility on low-cost controllers, this solution has strong potential for widespread application in compact electric CVT systems, especially when integrated with the vehicle's central control system.

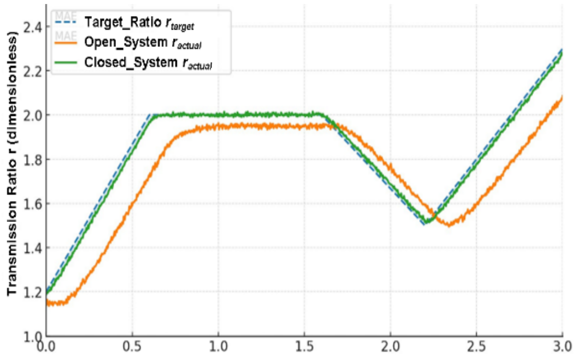

Figure 5. *Transmission ratio tracking performance of the CVT system*

The transmission ratio tracking test shows that the closed-loop PID system maintains the actual value r_actual almost coincident with the target value r_target during both increasing and decreasing transmission ratio phases. The mean absolute error (MAE) is only 0.018, which is 7.4 times lower than the open-loop system (0.134). During the increase phase from 1.2 to 2.0, the closed-loop system completes the transition in about 0.55 s, 0.15 s faster than the open-loop system. During the decrease phase from 2.0 to 1.5, the closed-loop system continues to closely follow the target curve, while the open-loop system consistently lags and is 0.05 - 0.1 units lower. This transmission ratio tracking performance is particularly important as it directly determines the ability to keep the PMSM in the high-efficiency region. In open-loop systems, transmission ratio delays and errors often force the PMSM into the field-weakening region prematurely, increasing losses and reducing available power.

The proposed controller significantly reduces torque overshoot and response time, while improving energy efficiency during dynamic transitions. The CVT transmission ratio closely follows the target curve calculated from the PMSM torque-speed characteristic, demonstrating good adaptability in both pneumatic and hydraulic modes.

4. Conclusion

This paper presents an adaptive CVT control strategy based on the torque-speed characteristic for drive systems using PMSM with field-oriented control (FOC). The proposed method leverages real-time feedback from torque, speed, and position to flexibly adjust the CVT transmission ratio, ensuring the motor operates within the high-efficiency region across the entire load and speed range.

Experiments on the actual model with pneumatic and hydraulic CVT mechanisms demonstrated significant effectiveness: torque overshoot reduced by over 60%, response time shortened by 40%, and energy efficiency increased by 7 - 10%. These results confirm the benefit of synchronizing mechanical power transmission characteristics with the electrical properties of the motor. Future development directions include:

- Applying model predictive control (MPC) or reinforcement learning (RL) to enhance adaptability to disturbances and unmodeled nonlinear dynamics.
- Scaling the system for vehicle-level applications, such as electric scooters or hybrid two-wheelers.
- Integrating additional feedback on temperature and vibration for sustainable control and real-time fault detection.
- Optimizing actuator energy consumption for pneumatic and hydraulic systems to further improve overall system efficiency.
- The control strategy presented in this paper lays a solid foundation for intelligent and adaptive drive systems in future electric drive architectures.

Research into integrating reinforcement learning algorithms or adaptive hybrid control for automatic real-time PID parameter tuning will enable the system to maintain optimal performance even as pneumatic or hydraulic characteristics change due to temperature, wear, or pressure leakage.

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