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Research Article

# An Investigation of Inverse-Automatic Mechanical Transmission of EV Using Gear Downshift Approach

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**Abstract:** Utilizing a two-speed I-AMT (Inverse-Automatic Mechanical Transmission) with a rear friction clutch as the research object, a gear shift strategy was developed to enhance the driving dynamics and comfort of electrical vehicles (EVs). This strategy combines the open-loop clutch position approach with the closed-loop drivetrain approach. proposal for regulating motor velocity. A two-degree-of-freedom (DOF) Smith predictor with feedforward input is developed to monitor the desired speed of the drive motor despite the system's intrinsic time delay and external disturbances. A feedback speed tracking approach is utilized to realize the speed tracking performance with the existence of time delay and external disturbance, while feedforward input is employed to remove the influence of clutch sliding friction on the speed approach of the motor. To ensure the effectiveness of the gear shift approach strategy and the precision of the two DOF Smith approach with the feedforward approach, a comparison of simulation results is performed first. Then, the most challenging working scenario to approach the transmission, downshifting at high throttle, was tested using an I-AMT-equipped lightweight pure electric vehicle. The results of the experiments show that the two-degree-of-freedom (DOF) Smith approach can remove the time-delay effect from the closed-loop approach and that the proposed whole gear shift approach strategy can limit the clutch slippage time to less than 1.5 s, resulting in a smaller shift jerk and ensuring both driving dynamics and riding comfort.

**Keywords**: Electric Vehicle; Smith Approach; I-AMT; Gear Downshift

## 1. Introduction

The energy density of batteries plays a critical role in ensuring sufficient range for battery electric vehicles (BEVs). In recent years, there has been a notable increase in the energy density of EV batteries. High-performance battery cells now boast energy densities surpassing 300 Wh/kg, a significant improvement compared to the 100-150 Wh/kg range observed just a decade ago. This advancement means that electric cars can now travel twice the distance with the same battery mass [1,2]. The continuous improvement in battery chemistry and cell design has been instrumental in achieving this progress. Notable examples include Tesla's upcoming 4680 cells and LG Energy Solution's Ultium cells. These advancements in energy density are driving the expansion of BEVs and revolutionizing the electric vehicle industry. In 2021, the global consumer expenditure on electric vehicle (EV) purchases reached an estimated USD 250 billion [2,3]. This surge in EV sales has prompted substantial investments in electrification, accounting for over 65% of total end-use investment in the transport sector. According to recent analysis by the International Energy Agency (IEA), this share is projected to rise to more than 74% in 2022. This investment is not limited to passenger cars alone; it also encompasses the electrification of buses and heavy-duty trucks. An excellent example of this trend is India's recent tender for the procurement and deployment of over 5,000 electric buses in five major cities. Moreover, the global production capacity of batteries is expected to witness a significant increase, rising from below 200 GWh in 2019 to over 1,200 GWh in 2024. This boost follows substantial capital expenditures by listed battery manufacturing companies in 2021, rebounding from the pandemic-induced dip. These companies are now investing three times more than they did in 2020. As of 2021, China leads the world in battery manufacturing capacity, accounting for approximately 75% of the global total. The United States, Hungary, and Germany follow closely behind in terms of battery production capacity. This rapid expansion in battery manufacturing capacity is a clear indication of the growing significance and momentum of the electric vehicle market worldwide [2,3].

Electric vehicles (EVs) have advanced fast and dramatically due to the increasingly stringent energy consumption and car pollution restrictions in various nations throughout the world, as well as the fast advancement of technology on batteries, motors, etc. Increased efficiency, decreased energy usage, low noise, and so on are just a few of the many benefits that EVs offer over their Internal Combustion Engine (ICE)-powered counterparts. However, the majority of current-generation EVs feature a fixed-gear transmission, reducing their flexibility in the workplace. However, the two-speed transmission is one of the most important strategic directions for the future of EVs because it can maximize the drive motor's performing range, enhance the vehicle's maneuverability, and increase its cruising range [4-7].

From a structural perspective, two-speed transmissions of EVs are either of the planetary gear type or the parallel shaft type. Automatic transmissions (ATs) are simplified into the planetary gear type. This type of gearbox is expensive and difficult to build, yet it has a good quality of shifting for its age. The parallel shaft category, on the other hand, has been simplified from the dual-clutch transmission (DCT) or the automatic mechanical transmission (AMT), thus it has a more straightforward design and lower cost. Two-speed EV transmissions are typically either planetary gear or parallel shaft designs. The planetary gear type is the simplest form of automatic transmission. Although costly and labor-intensive to produce, this gearbox design has held up well in terms of shifting quality over the years. However, the parallel shaft category is easier to manufacture and less expensive because it borrows less from the complex designs of the dual-clutch transmission and the automatic mechanical transmission (AMT) [8-12].

The torque phase and inertia phase are frequently employed ways to describe the transition between gears. The drive motor torque and clutch position are adjusted using feedforward approach techniques during the torque phase, and the drive motor's speed is tracked using a proportional integral derivative (PID) approach during the inertia process phase, all of which contribute to the exceptional shift quality. By moving the synchronizer to the transmission's second shaft, the speed differential between the synchronizer's two sides is minimized, resulting in faster gear transitions. I-AMT is one of the most promising multi-speed gearboxes for electric vehicles in the future [13-15].

Additionally, the I-AMT with an overrunning clutch is proposed, in this structure, when the friction clutch is disengaged and the overrunning clutch is synchronized, the gearbox will operate according to the first gear, and when the friction clutch is activated and the encircling clutch is synchronized, the gearbox can employment according to the second gear. The inverse-automatic mechanical transmission in electric vehicles using a gear downshift approach plays a crucial role in optimizing the performance and efficiency of the vehicle. the significant contributions of this article can be written as follows:

- Improved energy efficiency: By intelligently managing the gear shifts, the system can optimize the power delivery from the electric motor, reducing energy consumption and extending the driving range of the vehicle.
- Enhanced driving experience: Smooth and timely gear shifts contribute to a more comfortable and responsive driving experience. The downshift control ensures that the vehicle is always in the optimal gear for the given driving conditions, providing better acceleration and deceleration.
- Regenerative braking: During deceleration or braking, the downshift control can help maximize the regenerative braking effect, which captures kinetic energy and converts it back into electrical energy to recharge the battery. This not only improves the overall efficiency of the vehicle but also extends the life of the braking system.

- Reduced wear and tear: By managing the gear shifts more effectively, the downshift control can reduce the stress on the transmission components, leading to lower maintenance costs and increased longevity of the vehicle.
- Improved safety: Proper gear downshift control can contribute to better vehicle stability and control, especially during challenging driving conditions, such as steep inclines or declines, and in situations that require rapid deceleration.

Overall, the gear downshift control of inverse-automatic mechanical transmission in electric vehicles is an essential component in enhancing the performance, efficiency, and safety of these vehicles. The remaining sections of the paper are organized as follows: In **Section 2**, the framework of inverse-automatic mechanical transmission (I-AMT) is explored. **Section 3** presents the Smith approach employed in the study. Moreover, **Section 4** deals with application of the two-degree-of-freedom smith control technique in the design of a speed tracking approach for dynamic systems. Finally, **Section 5** provides a summary of the conclusions reached in the paper.

## 2. Framework of I-AMT

To begin with, Dog clutches are utilized in this setup so that the vehicle can achieve a reverse gear with the same ratio as the first gear. Transmissions can be made more cheaply and with less disruption to the driving experience thanks to the use of an electronic usually closed wet multi-plate clutch. The multi-plate clutch is gradually engaged from its release condition throughout the torque portion of the gear-upshift process. Thus, the torque transmitted by the multi-plate clutch grows over time, while the torque transmitted by the encircling clutch gradually drops until it is zero [16-20]. Figure 1, depicts the architecture of the I-AMT with two gear ratios.

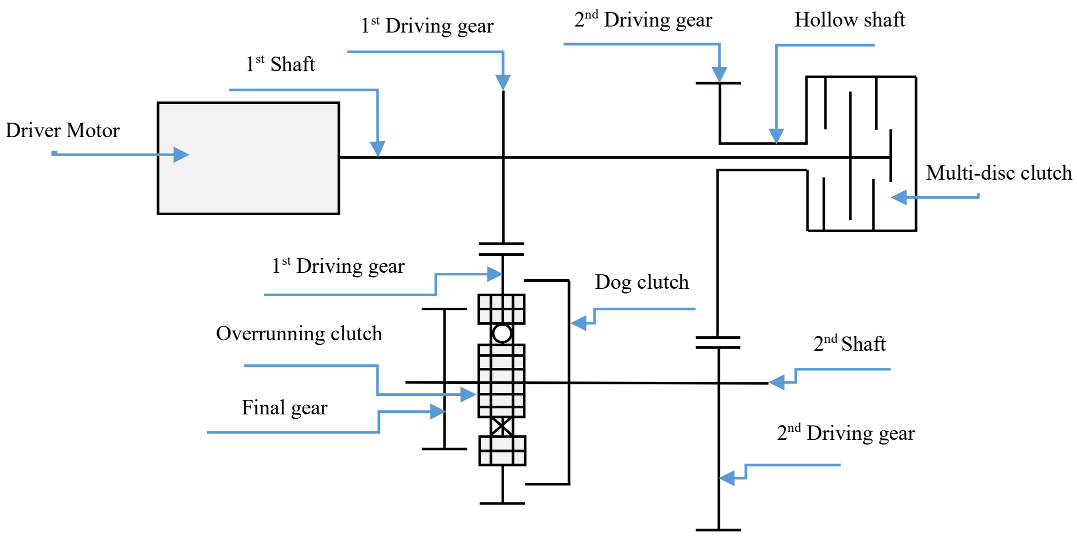


**Figure 1**. The diagram of I-AMT.

The gear-shifting operation then enters its inertial phase, during which the multi-disc clutch remains engaged until it has completely merged. In contrast, the downshifting process begins with the inertia phase, during which the multi-disc clutch is initially combined with the gearbox and then gradually disengaged. At this stage, the overrunning clutch's inner and outer rings need to be synchronized in speed, which requires torque output from the drive motor. Next, you'll move from the inertia phase to the torque phase as the multi-disc clutch continues to disengage. Given the transmission's reliance on a single friction the aspect and the inertia phase required for speed synchronization throughout the downshift procedure, it's clear that maintaining a smooth and synchronous approach of the overrunning clutch presents a significant challenge. Because of this, approaching the downshift in an I-AMT is far more challenging than the upshift [21-24].

$T_m$, $T_c$, $T_1$ are the torque that is produced by the motor, the gearbox torque of the multi-disc clutch and the load torque of those who are driven part of the multi-disc clutch, respectively, and are used to simulate the dynamics of the I-AMT as illustrated in Figure 2. The kinematics equation of the transmission is developed as shown in Eq. (1).

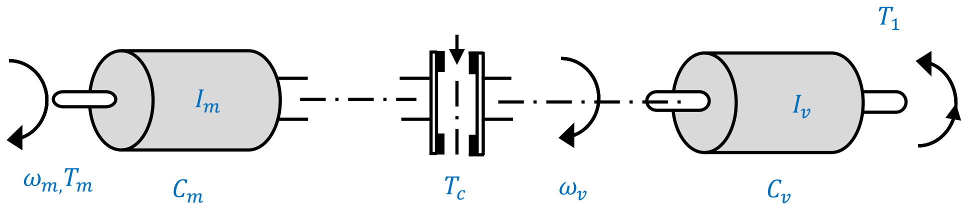


**Figure 2**. The two-mass dynamic model of I-AMT.

$$T_m - T_c - C_m \omega_m = I_m \dot{\omega}_m \tag{1}$$

where $I_m$ is the comparable moment of inertia of the engaged part of the multi-disc clutch. $C_m$ and $C_v$ are the corresponding damping coefficients of the primary and prompted parts of the multi-disc clutch, accordingly. $\omega_m$ and $\omega_v$ are the speeds of the primary and caused parts of the clutch. Torque $T_m$ is produced by the motor approach output on the stator winding's three-phase form of alternating current (AC), and the torque approach input u is the motor torque load factor (referred to Fig. 3 for a visual representation of the relationship between the motor torque load component and the pedal) as shown in Eq. (2).

$$\dot{T}_m + aT_m = bu(t - \tau) \tag{2}$$

wherein $a$ and $b$ are the unknown coefficients. While the vehicle is in the inertia phase of a gear downshift, the multi-disc clutch is falling. Additionally, the clamping force of the clutch is proportional to the clutch compression as shown in Eq. (3). $k$ indicates the clutch compression depth and $F$ belongs to the clutch clamp force.

$$T_c \propto F \propto k \tag{3}$$

The following list of external disturbances collectively has the following effects on the drive motor's speed-tracking efficiency: The mechanical linkage mechanism in the multi-disc clutch actuator exhibits nonlinearity in its motion relationship. Additionally, the correlation between the compression force and the displacement of the compression spring of the multi-plate clutch is not strictly linear. The multi-disc clutch's friction coefficient is not constant and is dependent on different factors, such as the speed differential between the driving and driven components and the temperature of the clutch surface. Long-term operation of the multi-disc clutch actuator and clutch friction plate results in wear and tear, leading to corresponding changes in the clutch spring stiffness [25-32]. The aforementioned disturbances have a detrimental impact on the drive motor's speed tracking performance, resulting in prolonged clutch slip time or increased vehicle jerk during the gear shift process. Such factors can impair the quality of downshifts. Consequently, it is imperative to devise an approach to mitigate these adverse effects.

## 3. Smith Approach

The Smith approach, also known as a Smith predictor, makes a significant contribution to approach system design by addressing the issue of time delay. In practical applications, time delays are often present due to physical limitations, measurement and processing times, and communication delays. These delays can cause a system to become unstable or lead to poor performance. The Smith approach helps overcome these issues by introducing a predictive compensator that can anticipate future changes in the system and adjust the approach signal accordingly, thus improving approach system performance [33-38].

*A. Conventional Smith Approach*

In practical applications, there is inevitably a time lag between the calculated and actual applied approach values, resulting in a pure delay in the approach system. This may result in significant overshoot and system shock. To address this issue, O.J.M. Smith introduced the Smith predictor in 1958 [39-46], as depicted in Figure 3. The core principle of the Smith predictor involves transferring the pure delay element outside the closed-loop of the approach system through the addition of a predictive compensator in parallel to the original approach system.

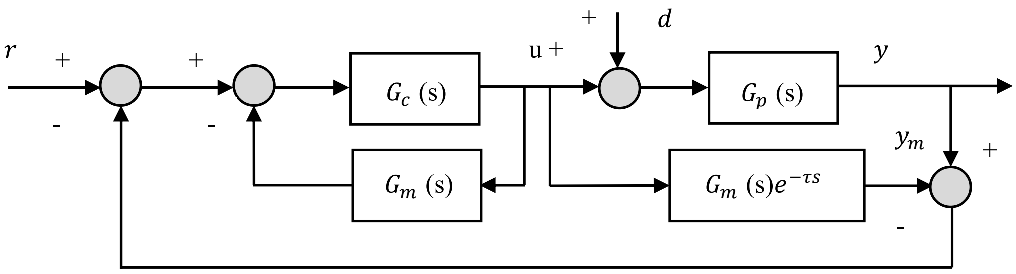


**Figure 3**. Flow chart of conventional Smith approach.

This approach can mitigate the adverse effects of pure delay on the system approach. $G_s$ $(s)$ indicates a digital approach.$G_p$ $(s)$ = $G_{p-}$ $(s)$ $e^{-ts}$ shows plant model, $G_{p-}$ $(s)$ indicates removing delay from the system model. $G_m$ $(s)$ represents the model of $G_{p-}$ $(s)$ $\tau$. Moreover, the $\tau_m$ deals with delay time.$d$ demonstrates system external disturbance.

*B. Two-degree-of-freedom Smith approach*

As previously noted, the conventional Smith approach features two feedback links: one involving output feedback from the identification system for tracking approach, and the other involving deviation feedback resulting from external disturbances and model uncertainties. Both feedback links are accounted for in the approach system after the adjustment of $G_c$ $(s)$. As a result, ensuring simultaneous tracking performance and disturbance rejection performance of the approach system can be challenging. To address this problem, a two-degree-of-freedom Smith approach design, depicted in Figure 4, can decouple the aforementioned performance approach processes. This approach enables the achievement of both superior tracking performance and disturbance rejection performance simultaneously, thereby enhancing system robustness [47-51].

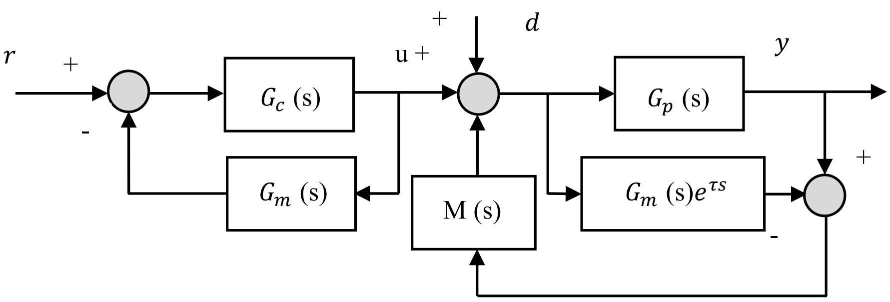


**Figure 4**. Flow chart of two-degree Smith approach.

## 4. Application of the Two-Degree-of-Freedom Smith Approach

In the present section, a gear shift approach is developed employing a two-degree-of-freedom Smith predictor, as illustrated in Figure 5. The target motor speed is denoted by $\omega_{e0}^{*}$, whereas the actual motor speed is represented by $\omega_{e0}$ . The clutch slip torque after a time delay is indicated by $T_{c+}$. The transfer functions (1) and (2) are respectively demonstrated in Eq. (4) and Eq. (5).

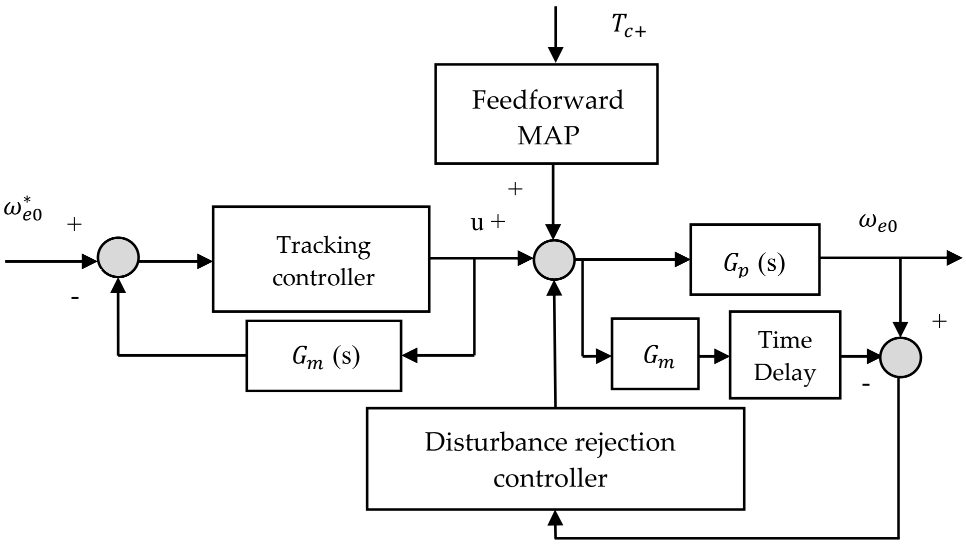


Figure 5. Approach scheme of I-AMT gear downshift.

$$G_{P2}\ (S) = \frac{\omega\ (S)}{T_m\ (S)} = \frac{1}{I_m\ S + c_m} \tag{4}$$

$$G_{P1}\ (S) = \frac{T_m\ (S)}{u\ (S)} = \frac{b}{as + 1}\ e^{-\tau s} \tag{5}$$

Given the importance of the slip torque approach in multi-disc clutch systems for ensuring desirable gear shift quality, the feedforward approach is employed to account for the inherent clutch characteristics. This feedforward approach is represented in a MAP form. In the multi-disc clutch, a "fast-slow-fast" open-loop position approach logic is utilized, which artificially establishes varying clutch position change rates for different stages [52-60].

## 4. Conclusion

This article proposes an approach strategy for the gear shift process in the two-speed I-AMT of pure electric vehicles. The strategy involves a combination of an open-loop multi-disc clutch position approach and a closed-loop drive motor speed approach. By employing the two-degree-of-freedom Smith approach, this approach decouples the tracking approach and the disturbance rejection approach, representing an improvement over the conventional Smith approach. The article presents the design of a motor speed-tracking approach with feedforward input. The approach comprises both a speed tracking approach and a disturbance rejection approach, thereby ensuring both tracking approach and disturbance suppression performance. Simulation and experimental results demonstrate that the proposed approach achieves smooth shifting performance under power downshift conditions with large throttle openings. Furthermore, the two-degree-of-freedom Smith approach with feedforward can eliminate the impact of time delay and independently suppress the external disturbance interference to the closed-loop speed approach. The current approach scheme may require improvement. Specifically, there is a natural delay between the torque command and the actual motor output torque, which causes the motor output torque to remain relatively high during the delay period after the inertia phase commences. If the clutch is rapidly disengaged during this period, the vehicle may experience a significant jerk that could negatively impact drivability.

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