Feedforward-feedback shift control with disturbance compensation of a two-speed transmission for electric vehicles

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Motivation

- **Overall objective**
  - To develop a gear shifting controller for a two-speed transmission for *electric vehicles* (EV)
  - **Output torque** of the transmission is **to be kept constant** during shifting
- **Background**
  - Most EVs in the market are equipped with reduction gears providing merely one fixed speed ratio
  - The use of transmission will improve both the power efficiency and the drivability of the vehicle

Motivation

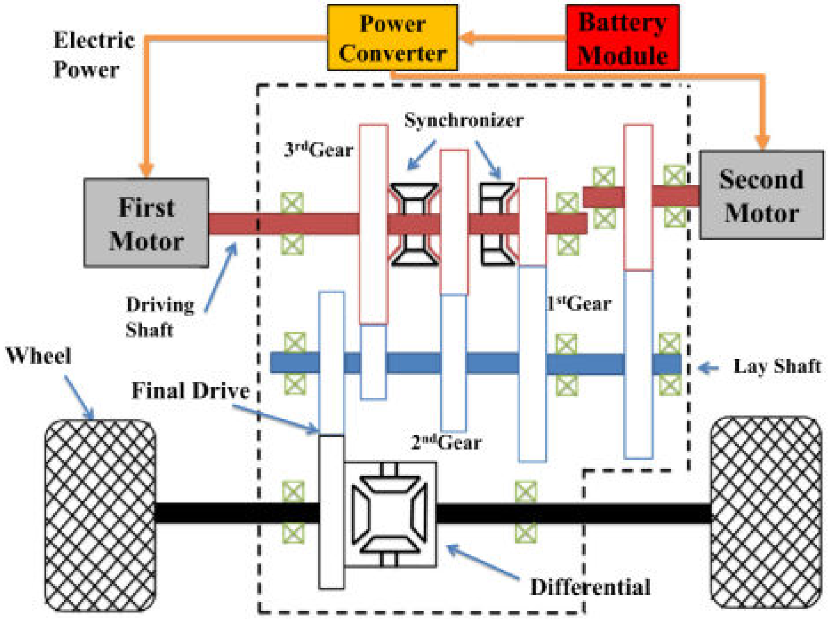
Company	Model	Powertrain	Speed ratio	0-100 km/h (s)	High speed (km/h)	Motor maximum speed (rpm)	Picture
Nissan	Leaf	Reduction	7.94	7.5	145	11000	
Renault	Zoe	Reduction	/	8.1	140	/	
Tesla Motor	Model S	Reduction	9.73	5.4	225	20000	
BMW	i3	Reduction	9.665	7.2	150	12000	
GM	Chevrolet Bolt	Reduction	7.05	6.5	146	9100	
Exagon Motors	Furtive-eGT	**3-speed transmission**	/	3.5	250	10000	
SGMW	Baojun e100	Reduction	/	/	100	/	
BAIC Motor	EC	Reduction	/	/	100	/	
BYD	e6	Reduction	/	/	140	/	

Motivation

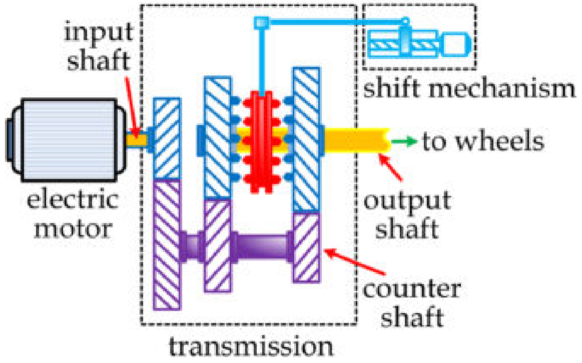
- **2-3 speeds are sufficient** for transmissions for EV, because of the high efficiency of modern traction motors

- Most of applications of transmissions for EV are based on **AMT** with single input, which causes power interruption during gear shifting

- **Power interruption is generally unacceptable** for high-performance models like Model S by Telsla



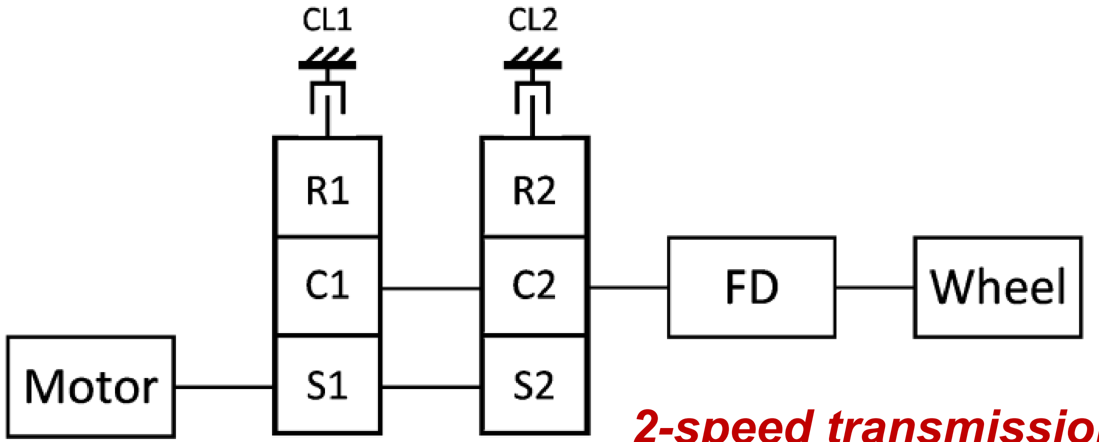
AMT with dual input



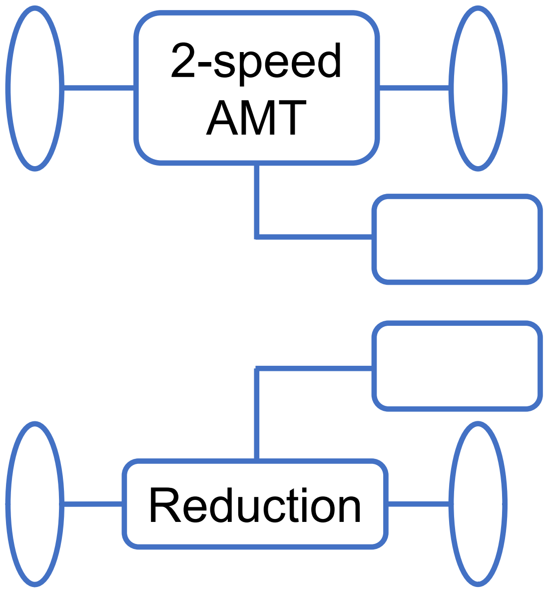
AMT with single input

Motivation

- What can be done to avoid power interruption during gear shifting on transmissions for EV?
  - For AMT-based powertrains, equip the vehicle with two or several propulsion sources.

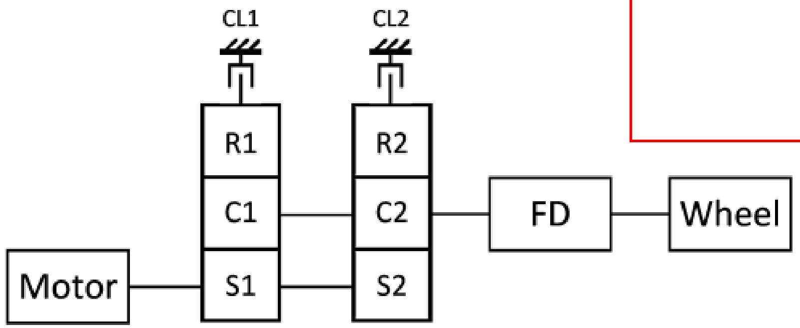


2-speed transmission

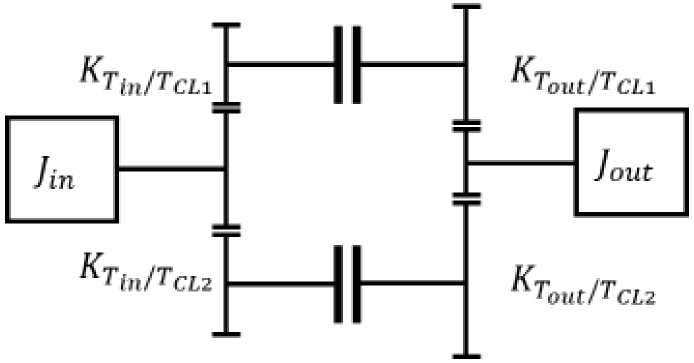


Dynamic model

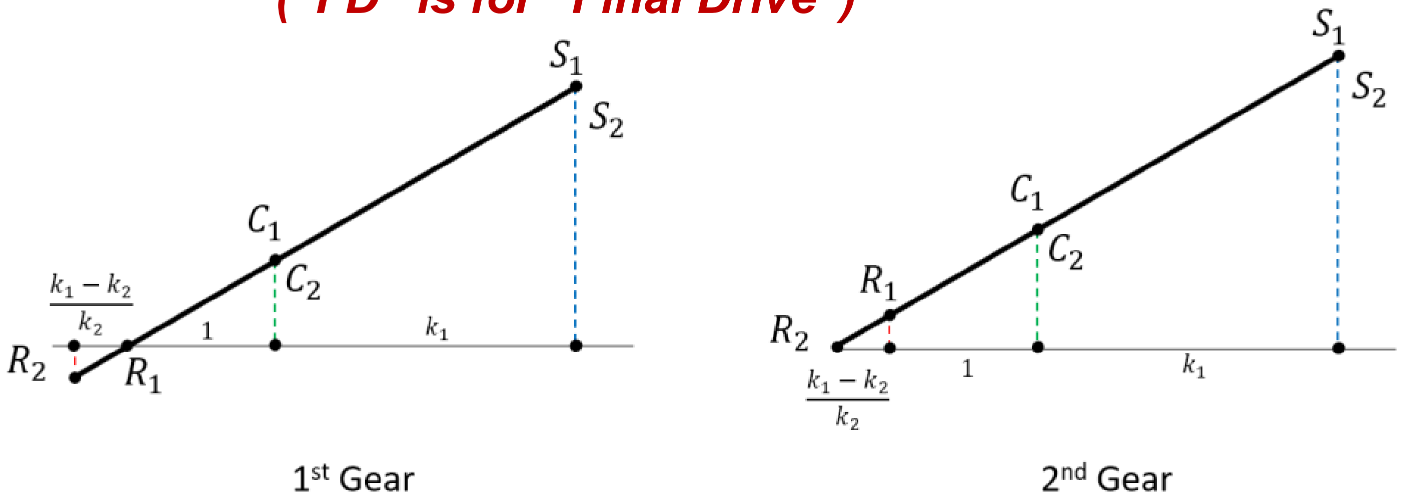
Recommended for PG modeling:
the `autoEQ` function



Schematic of the two-speed transmission (“FD” is for “Final Drive”)



Generic dual-clutch model



Lever Diagram

Ignoring the inertias not connected with inputs/outputs

⇩

$$\dot{\omega}_{S1} = \frac{1}{J_{S1S2}} T_{in} - \frac{1}{J_{S1S2} k_1} T_{CL1} - \frac{1}{J_{S1S2} k_2} T_{CL2}$$

$$\dot{\omega}_{C2} = \frac{1}{J_{C1C2}} T_{out} + \frac{k_1 + 1}{J_{C1C2} k_1} T_{CL1} + \frac{k_2 + 1}{J_{C1C2} k_2} T_{CL2}$$

Constant-output-torque shift control

- The shifting process of 1-2 upshift is considered

- **General requirements**
  - Duration of the whole process can be easily manipulated
  - Jerks on both the input and output shaft are small enough
  - Output torque of the transmission is constant during shifting

Torque phase

- In the torque phase, the load on the motor shaft is gradually transferred from the off-going clutch to the on-coming one

- **Requirements**
  - The off-going clutch should be **kept engaged** during the torque phase and no slip occurs
  - The load and the effective pressure on the off-going clutch should be reduced to zero **at the same time**

Torque phase

CL1 is locked

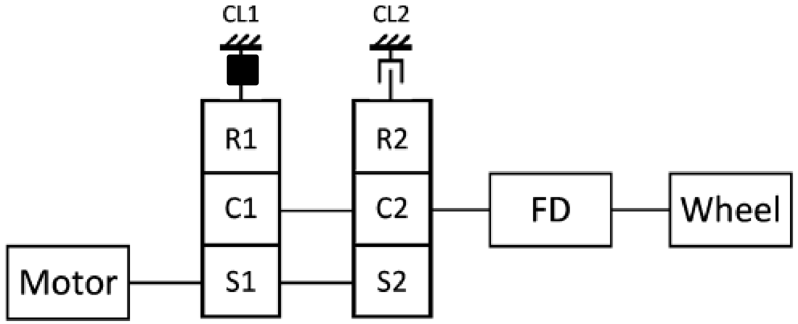
⇩

$$\dot{\omega}_{S1} = (1 + k_1)\dot{\omega}_{C2}$$

Simplified dual-clutch model

$$\dot{\omega}_{S1} = \frac{1}{J_{S1S2}}T_{in} - \frac{1}{J_{S1S2}k_1}T_{CL1} - \frac{1}{J_{S1S2}k_2}T_{CL2}$$

$$\dot{\omega}_{C2} = \frac{1}{J_{C1C2}}T_{out} + \frac{k_1 + 1}{J_{C1C2}k_1}T_{CL1} + \frac{k_2 + 1}{J_{C1C2}k_2}T_{CL2}$$

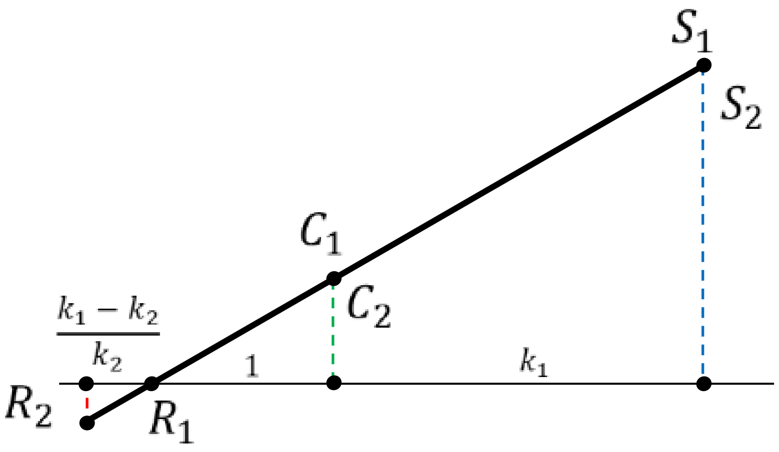


⇩

$$\dot{\omega}_{C2} = \frac{k_2^2}{temp}T_{out} - \frac{(k_1 - k_2)k_2}{temp}T_{CL2} + \frac{(k_1 + 1)k_2^2}{temp}T_{in}$$

⇨ T_{driv} (the driving torque on the output shaft)

$$temp = J_{C1C2}k_2^2 + J_{S1S2}(1 + k_1)^2 k_2^2$$



1st Gear

Torque phase

Simplified dual-clutch model

$$\mathbf{0} = \frac{1}{J_{S1S2}} T_{in} - \frac{1}{J_{S1S2} k_1} T_{CL1} - \frac{1}{J_{S1S2} k_2} T_{CL2}$$

$$\dot{\omega}_{C2} = \frac{1}{J_{C1C2}} T_{out} + \frac{k_1 + 1}{J_{C1C2} k_1} T_{CL1} + \frac{k_2 + 1}{J_{C1C2} k_2} T_{CL2}$$

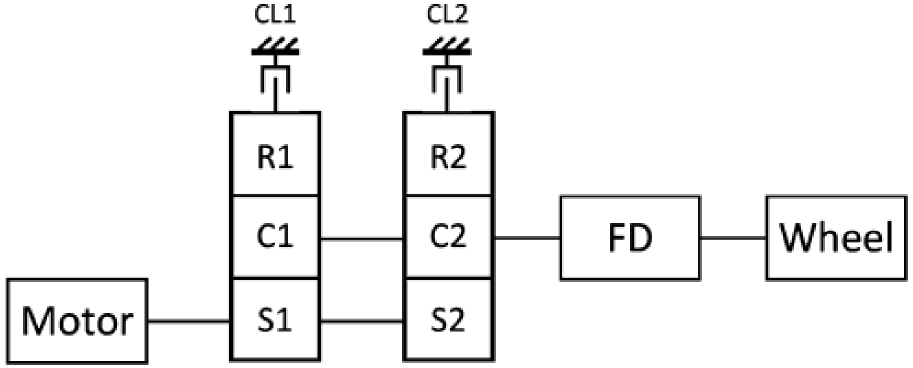
- Load on the motor shaft is constant
- Assume constant input torque

$$T_{CL1} = T_{in} k_1 - T_{CL2} \frac{k_1}{k_2}$$

$$T_{driv} = -\frac{(k_1 - k_2) k_2}{temp} T_{CL2} + \frac{(k_1 + 1) k_2^2}{temp} T_{in}$$

⇨ (the driving torque on the output shaft)

$$temp = J_{C1C2} k_2^2 + J_{S1S2} (1 + k_1)^2 k_2^2$$



Torque phase

$$T_{driv} = -\frac{(k_1 - k_2)k_2}{temp} T_{CL2} + \frac{(k_1+1)k_2^2}{temp} T_{in}$$

$$T_{CL1} = T_{in}k_1 - T_{CL2}\frac{k_1}{k_2}$$

- T_{driv} is the *required* driving torque on the output shaft
- T_{in} is the input torque from the traction motor
- T_{CL1} and T_{CL2} are the transmitted torque by CL1 and CL2

Initial values (should be determined carefully to avoid sudden change):

$T_{cap1}(t_0) = T_{in}(t_0)k_1$

$T_{cap1}(t_0) = \frac{T_{CL1}(t_0)}{\gamma} = \frac{T_{in}(t_0)k_1}{\gamma}$

$T_{driv}(t_0) = (k_1+1)T_{in}(t_0)$

$T_{CL2}(t_0) = 0$

Control strategy for the torque phase:

t_0: start of the torque phase; t_1: end of the torque phase

$T_{cap1}(t) = T_{cap1}(t_0) - \frac{T_{cap1}(t_0)}{t_1 - t_0}(t - t_0), t_0 \le t \le t_1$

$T_{CL1} = \gamma \cdot T_{cap1}$, $0 < \gamma < 1$ to ensure $T_{CL1} \le T_{cap1}$ and avoid slipping of CL1

$T_{CL2} = -\frac{k_2(k_1+1)}{k_1(k_2+1)}T_{CL1} + \frac{k_2}{(k_2+1)}T_{driv}$

$T_{in} = \frac{k_2 - k_1}{k_1(k_2+1)}T_{CL1} + \frac{1}{(k_2+1)}T_{driv}$

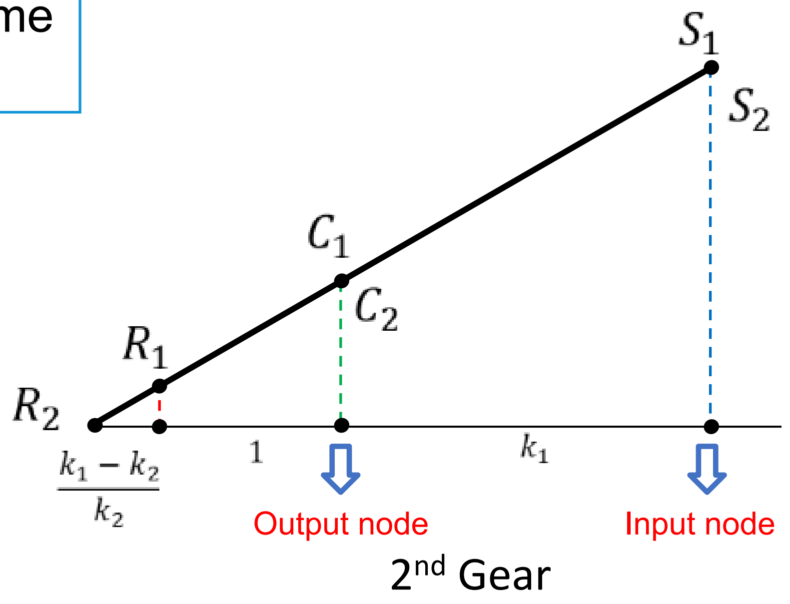
Inertia phase

- **At the end of the *torque phase*:**
- $T_{CL2} = -\frac{k_2(k_1+1)}{k_1(k_2+1)} T_{CL1} + \frac{k_2}{k_2+1} T_{driv}$
- $T_{in} = \frac{k_2-k_1}{k_1(k_2+1)} T_{CL1} + \frac{1}{k_2+1} T_{driv}$
- **During normal driving (2nd gear):**

$$T_{CL2} = \frac{k_2}{k_2+1} T_{driv}$$

$$T_{in} = \frac{1}{k_2+1} T_{driv}$$

This means that at the end of the torque phase, the torque transmitted by CL2 is the same as that of normal driving



Inertia phase

- **At the end of the *torque phase*:**
- $T_{CL2} = -\frac{k_2(k_1+1)}{k_1(k_2+1)}T_{CL1} + \frac{k_2}{k_2+1}T_{driv}$
- $T_{in} = \frac{k_2-k_1}{k_1(k_2+1)}T_{CL1} + \frac{1}{k_2+1}T_{driv}$
- **During *normal driving* (2nd gear):**

$$T_{CL2} = \frac{k_2}{k_2+1}T_{driv}$$

$$T_{in} = \frac{1}{k_2+1}T_{driv}$$

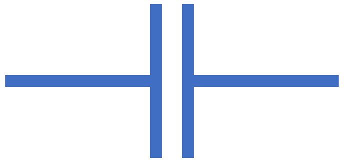
This means that at the end of the torque phase, the torque transmitted by CL2 is **the same as** that of normal driving

Fact:
During the inertia phase, the output torque is solely determined by T_{CL2}

Requirement:
The output torque should be kept constant during gear shifting

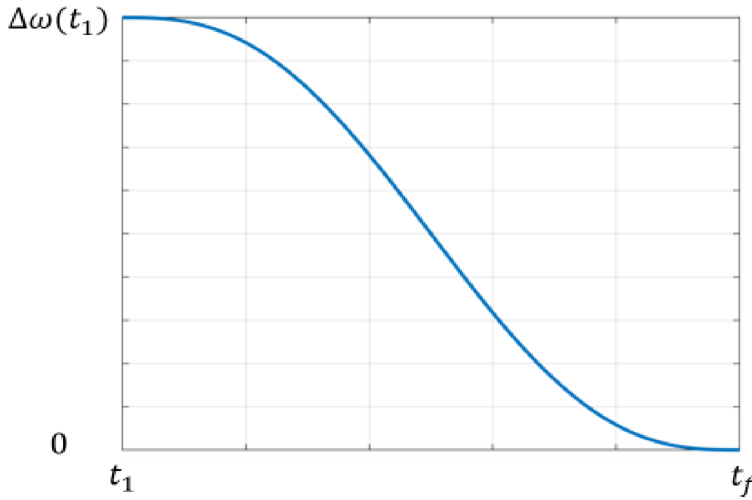
⇨

Conclusion:
- T_{CL2} should be kept constant during the inertia phase.
- Elimination of the speed difference on CL2 should be fulfilled by the motor


CL2

Inertia phase

- **Speed synchronization through feedforward-feedback control**
  - The reference speed is a 3-4-5 polynomial



Reference speed

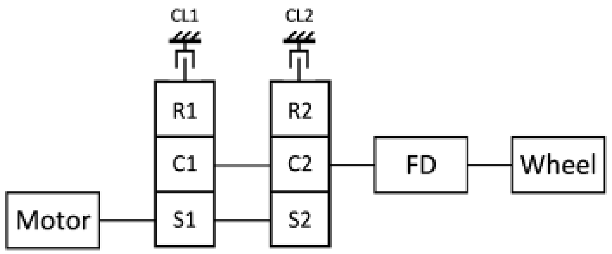
  - **Feedforward control law:**

$$T_{in} = \frac{1}{k_2+1}T_{driv} + \dot{\omega}_{S1}\left[J_{R1}\frac{k_2-k_1}{k_1^2(k_2+1)} + J_{S1S2}\right] - \dot{\omega}_{R2}\left[J_{R2}\frac{1}{k_2} + J_{R1}\frac{k_2(k_1+1)}{k_1^2(k_2+1)}\right]$$

⇩ (for continuity and simplicity)

$$T_{in} = \frac{1}{k_2+1}T_{driv} + \dot{\omega}_{S1}\left[J_{R1}\frac{k_2-k_1}{k_1^2(k_2+1)} + J_{S1S2}\right] - \dot{\omega}_{R2}\left[J_{R2}\frac{1}{k_2} + J_{R1}\frac{k_2(k_1+1)}{k_1^2(k_2+1)}\right]$$

$$T_{in}(t_1) = \frac{1}{k_2+1}T_{driv}$$
$$\dot{\omega}_{R2}(t_1) = 0$$



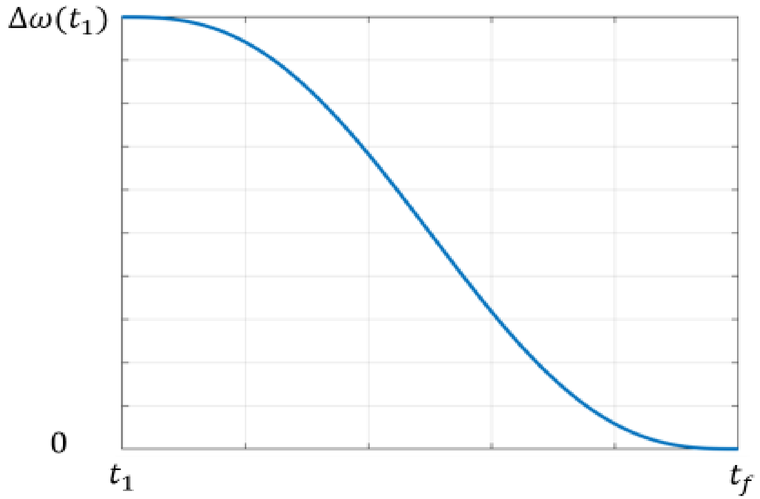
CL2

Inertia phase

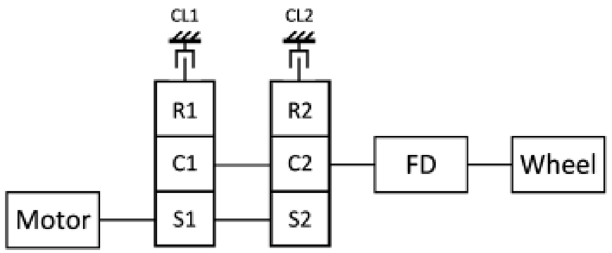
- **Speed synchronization through feedforward-feedback control**
  - **Feedback control law**

$$u_{feedback} = -F(x - r)$$

- x is the state variable, namely ω_{R2}
- F is the feedback gain
- r is the reference signal

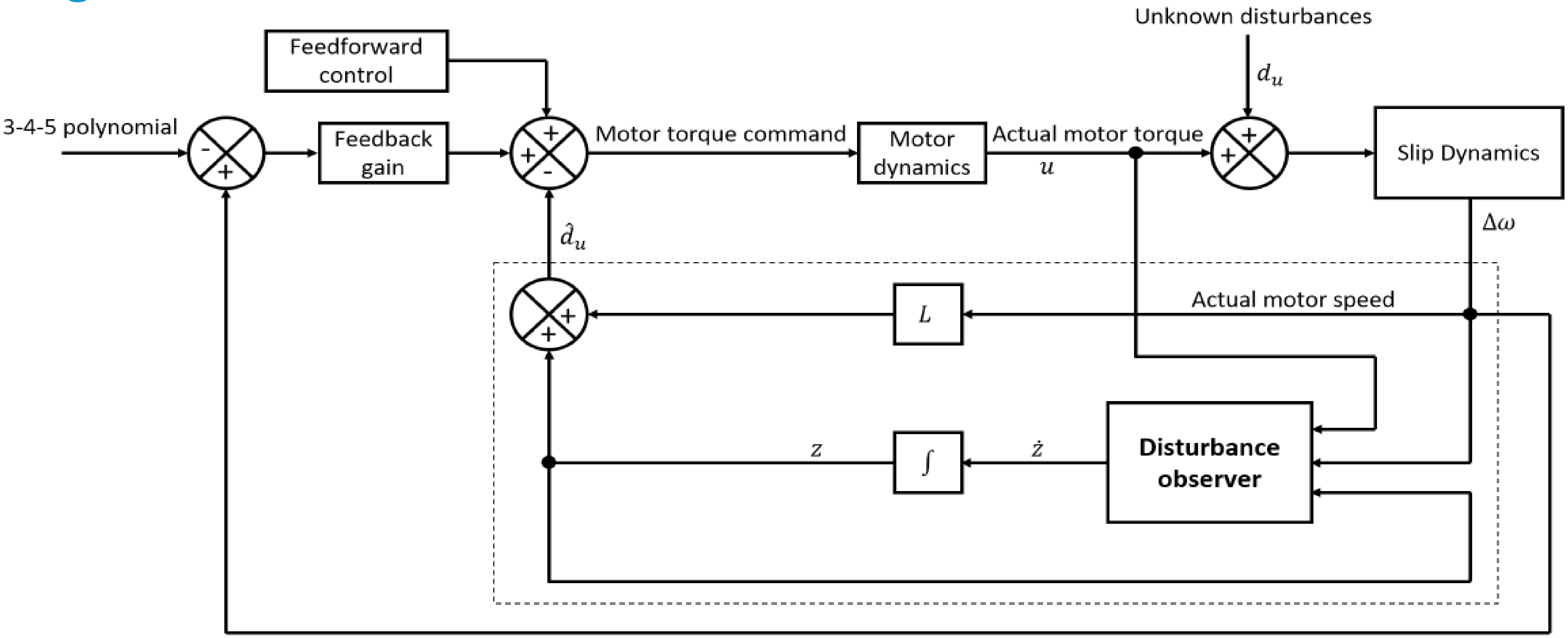


Reference speed

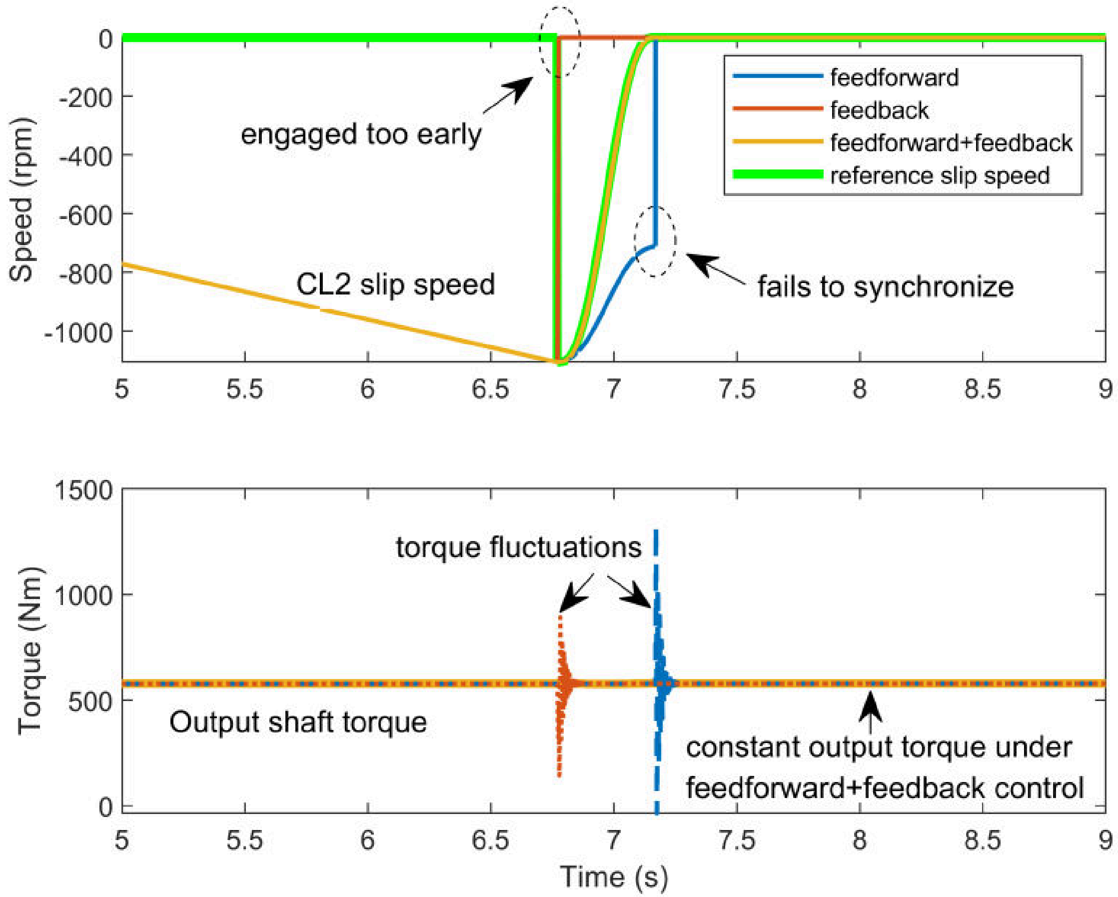


Inertia phase

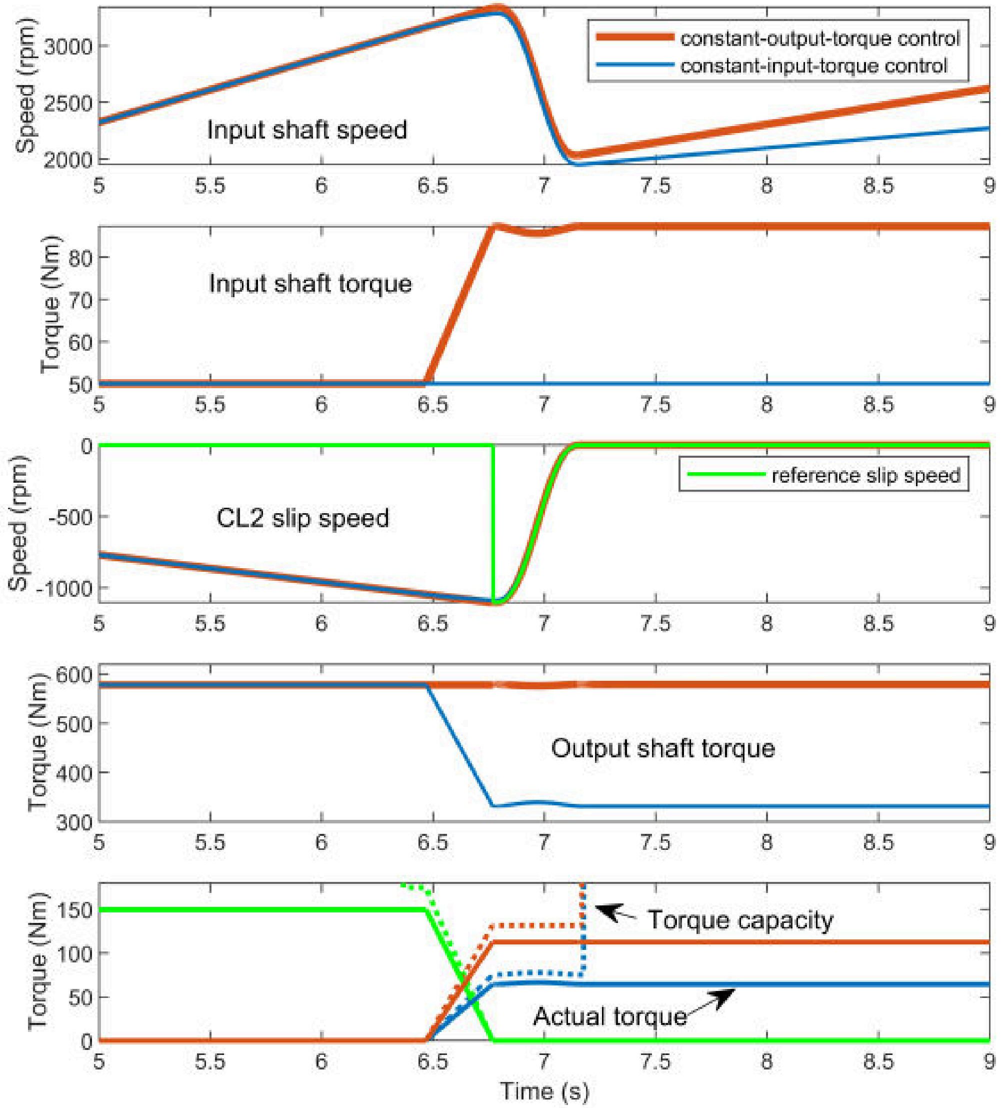
- **Integration of the disturbance observer**



Simulation results

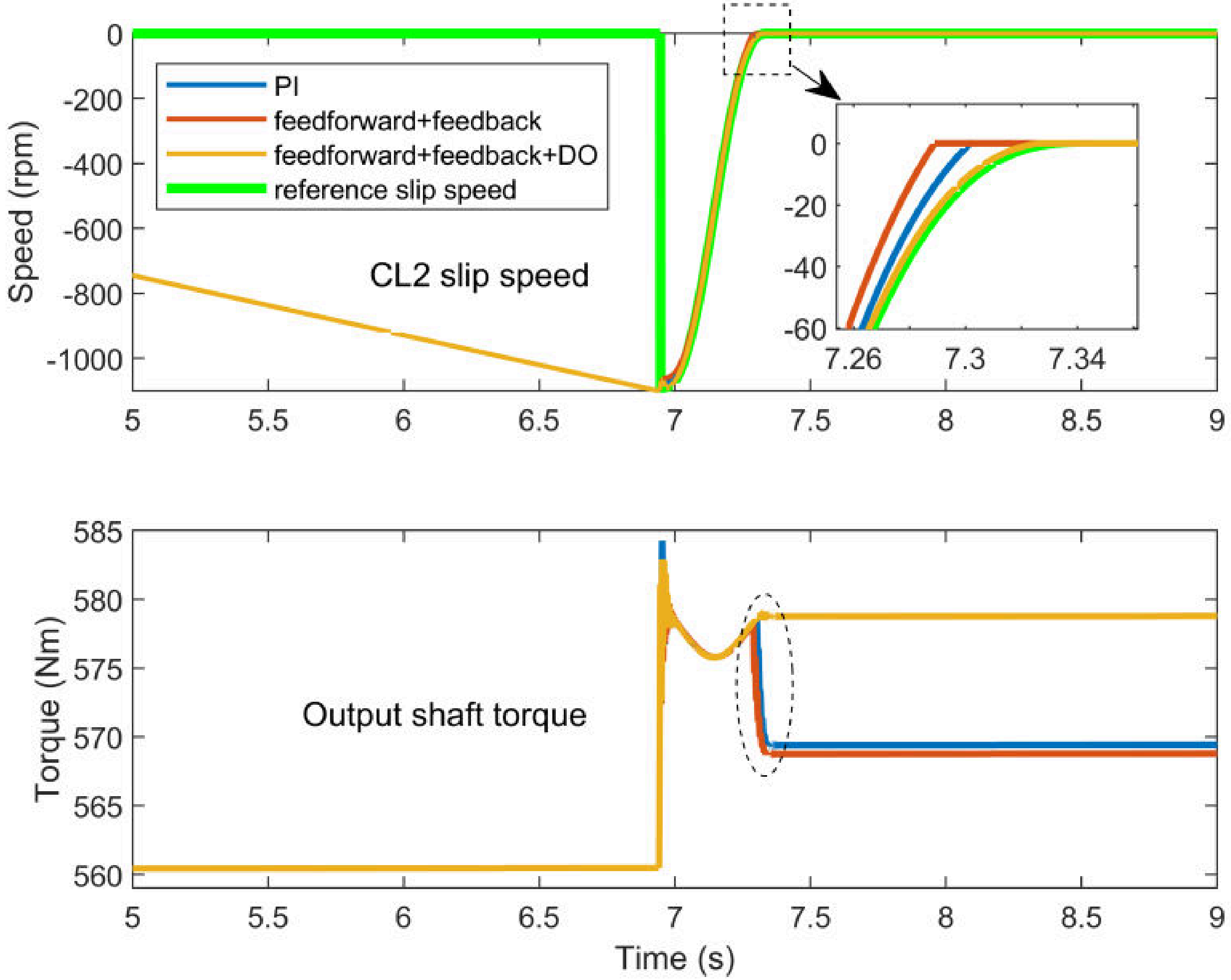


Comparison with pure feedforward and feedback controller



Comparison with constant-input-shaft torque control

Simulation results



Comparison with non-DO-based controllers

Summary

- **A gear shifting strategy for a two-speed transmission for EV is proposed**
  - Output torque of the transmission is kept constant during the whole shifting process
  - Control law for the torque phase is purely feedforward
  - Feedforward-feedback control with disturbance observer for the inertia phase is used

- **Simulation results suggest significant advantages over pure feedforward or feedback control as well as non-DO-based solutions**

Thank you!