

Centralized Torque Controller for a Nonminimum Phase Phenomenon in a Powersplit HEV

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ABSTRACT

Torque controls for the engine and electric motors in a Powersplit HEV are keys to the success of balancing fuel economy, driveability, and battery power control. The electric variable transmission (EVT) offers an opportunity to let the engine operate at system-optimal fuel efficient points independently of any load. Existing work shows such a benefit can be realized through a decentralized control structure that translates the driver inputs to independent engine torque and speed control. However, our study shows that the decentralized control structures have a fundamental limitation that arises from the nonminimum phase (NMP) zero in the transfer function from the driver power command to the generator torque change rate, and thus not only is it difficult to obtain smooth generator torque but also it can cause violations on battery power limits during transients. Additionally, it adversely affects the driveability due to the generator torque transients reflected at the ring gear. This study investigated a novel centralized torque controller to enhance smart coordination between the engine and generator. We first analyzed the theoretical limitations of the decentralized control and then presented a centralized strategy with a theoretical proof. Simulation results also verified that the centralized control can effectively smooth the generator torque and eliminate the inverse response of the generator torque during rapid vehicle accelerations/decelerations. Further it prevents battery power spikes by reducing generator torque transients, thus enhancing the battery durability. Finally it smoothes the mechanical torque spikes transmitted to the planetary ring gear, and therefore helps reduce NVH.

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INTRODUCTION

Typical examples of eCVT (electronic Continuously Variable Transmission)-equipped Hybrid Electric Vehicles are the Series HEV [1] and the Power Split HEV [2]. The eCVT systems have direct control over the engine speed, independent of the wheel speed through an electric machine directly coupled with the engine. Torque control in the eCVT system is a challenging task that involves coordination of both torques from the engine and the electric machine in all driving conditions including aggressive and rapid transients.

Figure 1 shows a typical power-split hybrid powertrain configuration. The powertrain consists of two power sources - combination of engine, generator and planetary gear set, and combination of motor and battery. The planetary gear set provides interconnection between the engine, generator and motor, with the carrier gear connected to the engine, the sun gear to the generator, and the ring gear connected to the motor thru the counter shaft that is connected to the wheel thru the final drive. This planetary gear configuration offers

the possibility of decoupling the engine speed from the vehicle speed, which provides the potential to achieve improved engine operation efficiency. The figure also depicts the vehicle control system for the power split hybrid powertrain, which consists of Vehicle System Controller (VSC), Engine Controller Module (ECM), Transaxle Controller Module (TCM), High Voltage Battery Controller Module (BCM), and a Regenerative Braking System (BSM) are part of the control.

It is the VSC of any hybrid vehicle that interprets the driver's accelerator pedal and brake pedal commands, determines the a set of independent control variables [1][2][3][4] (Note that for a power split powertrain there are two degree of freedom [2]), calculates the actuator commands, and subsequently performs the torque coordination among the subsystems. It is the torque control and torque coordination that eventually determines which power source delivers how much to meet the driver's demand in a smooth manner while whole powertrain system is running optimally with subsystem constraints complied.

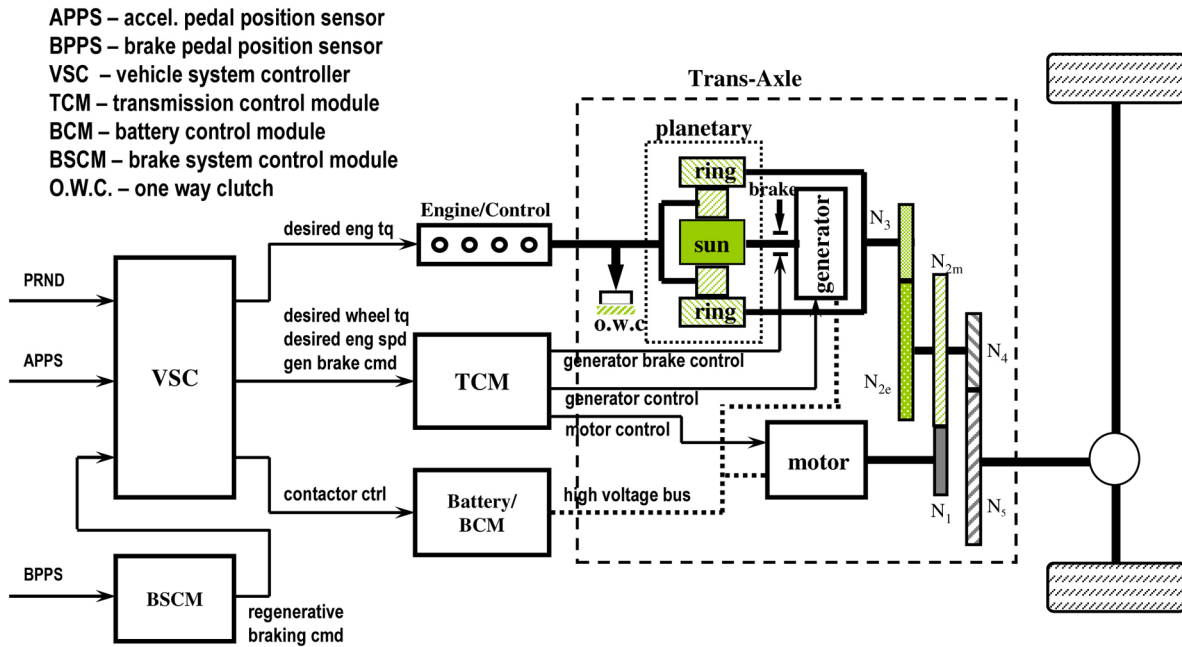


Figure 1. Power Split Powertrain System Configuration [2]

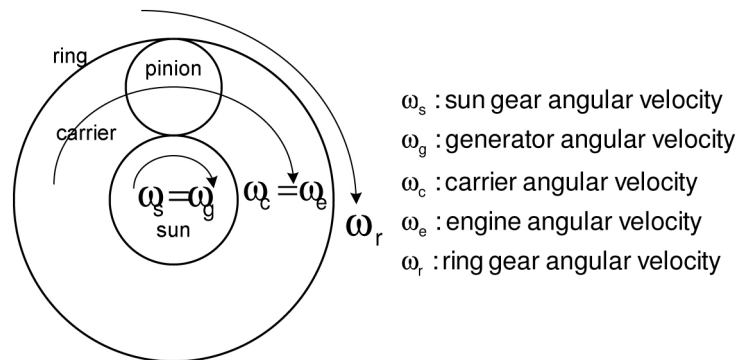


Figure 2. Planetary Gear Schematic

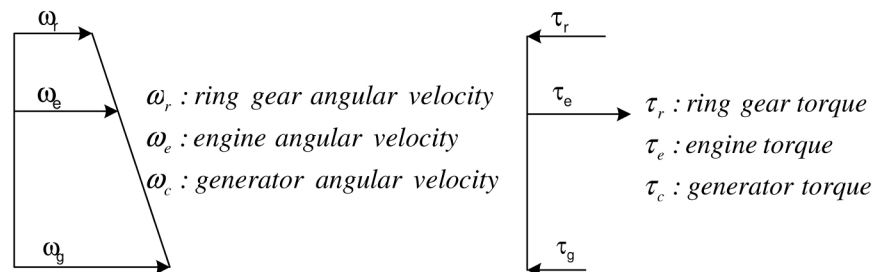


Figure 3. Planetary Torque/Speed Relationship

Figure 2 and Figure 3 shows the detailed schematic of a planetary gear with defined speed and torque conventions in a Powersplit HEV [2], where the gearset connects the engine to a generator. This allows the engine speed to vary continuously and smoothly towards its efficient operation points.

The torque relationship among the planetary ring gear, carrier and sun gear is fixed between any of the two regardless of their speed relationship. If the engine torque is positive (or 'clockwise'), the steady state generator torque has to be counterclockwise to provide engine reaction torque and balance the planetary system.

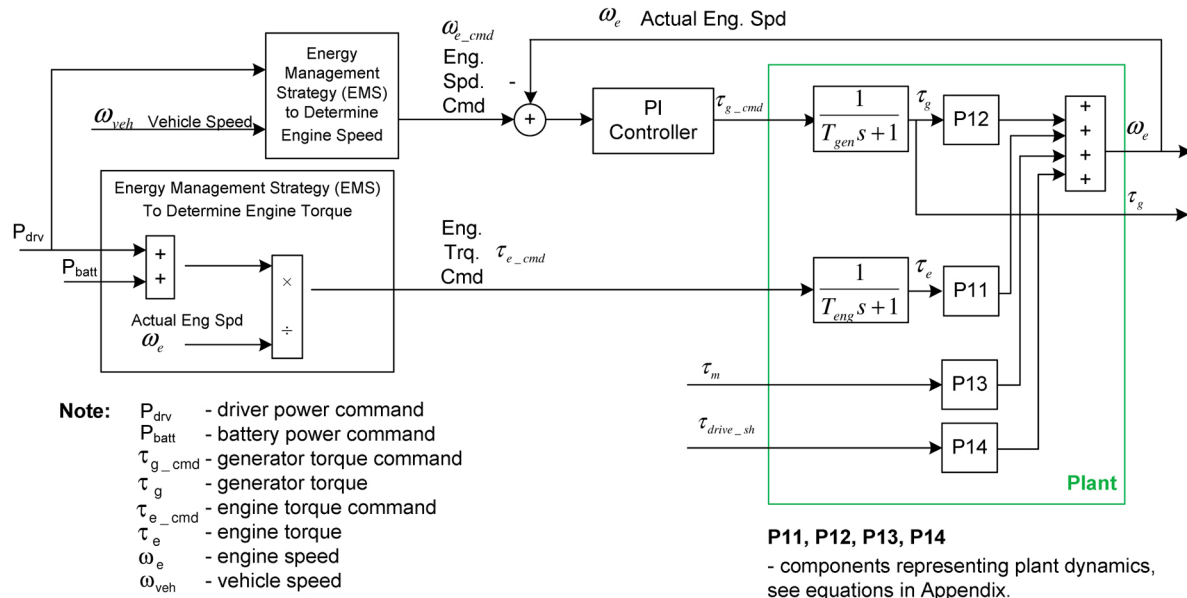


Figure 4. A Decentralized Controller for Engine Torque and Speed (Note: The Powersplit plant dynamics P12, P11, P13 P14 are derived in the Appendix)

The optimal engine speed can be maintained by the engine speed control itself, or the generator speed feedback control, or more complicated torque coordination. In any of the approaches, the planetary torque - speed relationship shown above always holds and it serves as the underpinning base in our mathematical derivation, which will be thoroughly analyzed in this paper, on how a centralized torque controller and decentralized controller differ in terms of causing nonminimum phase (NMP) in the Powersplit HEV.

On the other hand any torque perturbation or spike in the planetary are not isolated from the wheel torque path due to the existed rigid connection between the ring gear and the motor shaft in a Powersplit HEV. This connection contributes more additional challenges to the engine and generator torque coordination, particularly due to concerns on driveability and battery power.

The following sections of the paper start from a design of the decentralized torque controller, and then analyze its limitations using both test data and theoretical analysis, and finally present a centralized torque controller for more intelligent coordination between the engine and generator to eliminate a NMP zero. Simulation results are finally included to show the effectiveness of the centralized controller in eliminating the inverse torque response and the battery power spikes.

THE DECENTRALIZED TORQUE CONTROLLER

First we present a decentralized Hybrid Vehicle System Controller (VSC) which separates the engine speed control and engine torque control as shown in Figure 4. It should be

noted that the two 'EMS (Energy Management Strategy)' blocks in Figure 4 represents the core of the hybrid optimal decision-making for energy management. More details on EMS based on Degree of Freedoms on the HEVs can be found in [1][2][3]. The EMS comprises algorithms and lookup tables developed by optimizing the total system efficiency by considering various vehicle operating modes, driver's requirements (speed and traction force requirement) and the efficiencies of the individual subsystem. In this paper, we simplify the EMS into simple mathematic forms as static mapping factors q and p (Figure 7) in later derivations.

The engine speed is controlled by a PI closed-loop controller, while the engine torque command is determined in open loop. If the total engine power command varies, the corresponding target engine speed and target engine torque both will change.

The decentralized controller has limitations in obtaining a monotonic and smooth generator torque if given a step input driver power command (Figure 5). The generator torque initially heads in a way opposite to its steady-state direction as highlighted in Figure 5. This characteristic in controls is known as the nonminimum phase (NMP) zero phenomenon which ends in a typical transient response of undershoot [5] [6][7][8].

To illustrate, in event of an abrupt driver command change, e.g. an aggressive tip-in, the target engine torque increases quickly. The generator torque amplitude must increase in an opposite direction to react to the engine torque. In the meantime, since the target engine speed changes, the initial generator torque will reduce in amplitude to assist fast engine speedup under the PI control. Such an interaction causes an obvious initial undershoot (or negative overshoot) as illustrated in Figure 5. The theoretical cause of the sudden

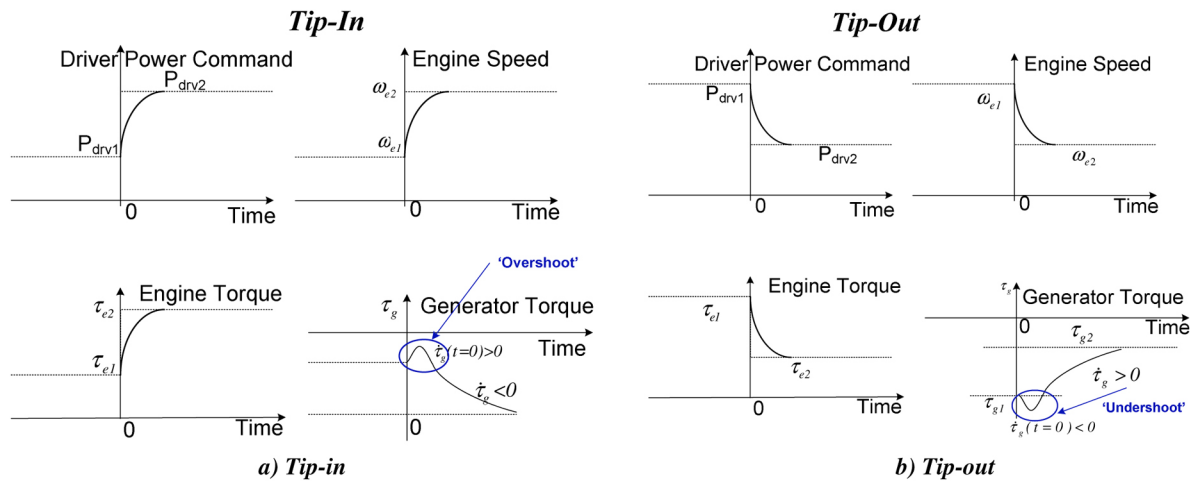


Figure 5. Illustration of the Inverse Response of the Generator Torque

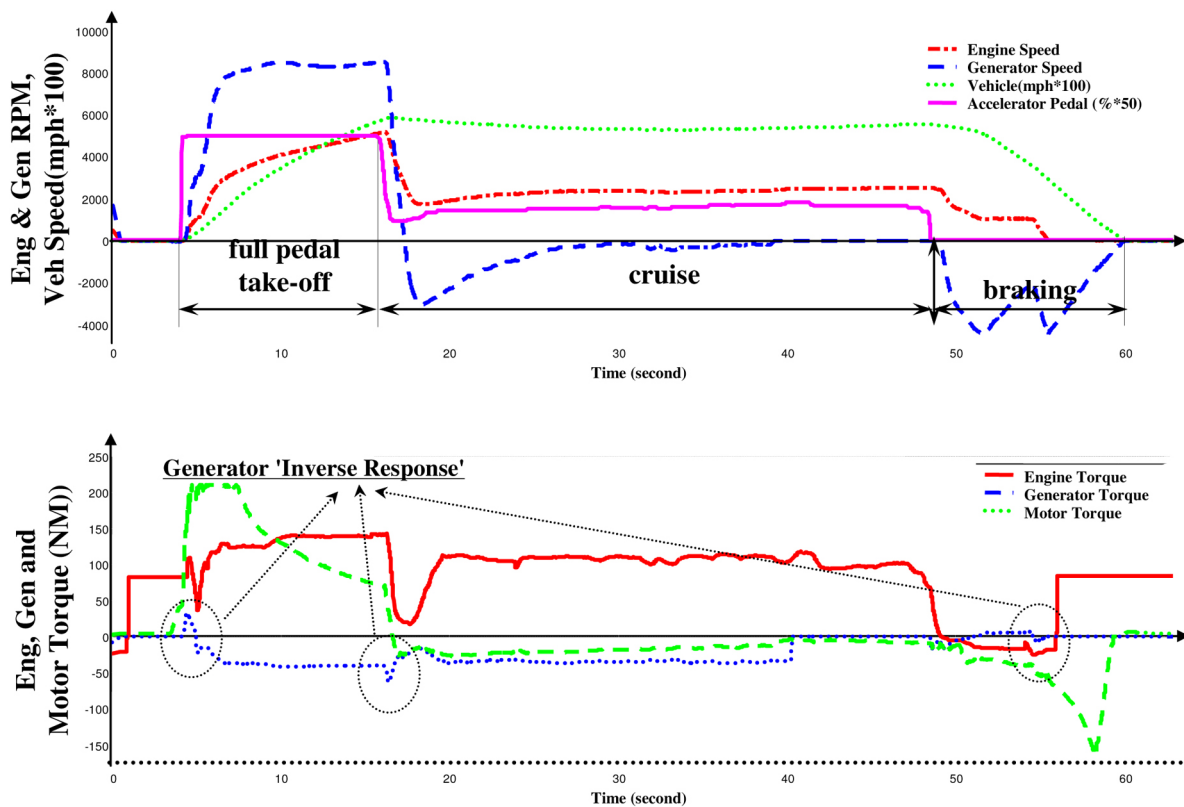


Figure 6. Inverse Response of the Generator Torque in a Ford Escape Powersplit HEV (Vehicle Test Data)

inverse response in the decentralized controller is mathematically identified in the next section.

Due to the decentralized control structure, the generator torque inverse responses exist in all driving situations in the Powersplit HEVs. The phenomenon can be illustrated using vehicle test data of a Ford Escape Powersplit Hybrid. Figure 6 captures some typical tip-in and tip-out events. As highlighted in red circles, when the engine speed accelerates or decelerates, the generator torque first responds in an inverse

manner and then monotonically reacts to the engine torque for speed control.

In short the decentralized controller has the following limitations:

- During rapid vehicle acceleration deceleration transients, the generator torque overshoots or undershoots could end in current spikes at the battery, which can impact battery durability especially when battery power limits are low.

• The spiky and ragged generator torque during aggressive driving will be reflected at the planetary ring gear and finally transmitted to the driveshaft. This torque behavior can adversely affect the driveability, and could degrade more when

• The battery power limits are low,

• The motor torque capacity is limited or the motor torque response is not fast enough to compensate the generator torque behavior.

THE NONMINIMUM PHASE (NMP) ZERO

The modeling of the Powersplit HEV dynamics can be summarized as below. (The detailed mathematical derivation is also attached in the [Appendix](#)). To study the generator torque response, we pick two variables (engine speed and generator torque) as the plant outputs. The two state variables are picked as engine speed and motor speed.

$$X = \begin{bmatrix} \omega_e \\ \omega_m \end{bmatrix}; u = \begin{bmatrix} \tau_e \\ \tau_g \\ \tau_m \\ \tau_{drive_sh} \end{bmatrix}; Y = \begin{bmatrix} \omega_e \\ \tau_g \end{bmatrix} \quad (1)$$

$$A = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}; C = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}; D = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \quad (2)$$

$$B = \begin{bmatrix} J_{eng\&carrier} + J_{gen\&sun} T_{e2g}^2 & (T_{e2g} J_{gen\&sun} T_l T_2 \frac{1}{\rho}) \\ -(T_l T_2 \frac{1}{\rho} J_{gen\&sun} T_{e2g}) & (J_{mot_lumped} + \frac{T_l^2 T_2^2}{\rho^2} J_{gen\&sun}) \end{bmatrix}^{-1} \begin{bmatrix} 1 & T_{e2g} & 0 & 0 \\ 0 & -\frac{T_l T_2}{\rho} & 1 & -\frac{T_2}{T_g} \end{bmatrix} \quad (3)$$

$$\text{Let's define } \begin{bmatrix} J_A & J_B \\ J_C & J_D \end{bmatrix}^{-1} = \begin{bmatrix} J_{eng\&carrier} + J_{gen\&sun} T_{e2g}^2 & (T_{e2g} J_{gen\&sun} T_l T_2 \frac{1}{\rho}) \\ -(T_l T_2 \frac{1}{\rho} J_{gen\&sun} T_{e2g}) & (J_{mot_lumped} + \frac{T_l^2 T_2^2}{\rho^2} J_{gen\&sun}) \end{bmatrix} \quad (4)$$

From [equations 1, 2, 3, 4](#), the system transfer function can be derived as,

$$G(s) = \frac{Y(s)}{U(s)} = C(sI - A)^{-1}B + D = \begin{bmatrix} \frac{J_A}{s} & (\frac{J_A T_{e2g} \rho - J_B T_l T_2}{s \rho}) & \frac{J_B}{s} & -\frac{J_B T_2}{s T_g} \\ 0 & 1 & 0 & 0 \end{bmatrix} \quad (5)$$

$$\text{Therefore, } Y = \begin{bmatrix} \omega_e \\ \tau_g \end{bmatrix} = \begin{bmatrix} \frac{J_A}{s} & (\frac{J_A T_{e2g} \rho - J_B T_l T_2}{s \rho}) & \frac{J_B}{s} & -\frac{J_B T_2}{s T_g} \\ 0 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} \tau_e \\ \tau_g \\ \tau_m \\ \tau_{drive_sh} \end{bmatrix} \quad (6)$$

For simplicity of illustration, let us use P_{ij} to represent the plant dynamics as follows:

$$\begin{bmatrix} P_{11} & P_{12} & P_{13} & P_{14} \\ 0 & P_{21} & 0 & 0 \end{bmatrix} = \begin{bmatrix} \frac{J_A}{s} & (\frac{J_A T_{e2g} \rho - J_B T_l T_2}{s \rho}) & \frac{J_B}{s} & -\frac{J_B T_2}{s T_g} \\ 0 & 1 & 0 & 0 \end{bmatrix} \quad (7)$$

We get,

$$\omega_e = P_{11} \tau_e + P_{12} \tau_g + P_{13} \tau_m + P_{14} \tau_{drive_sh} \quad (8)$$

Based on the above derivation, we can simplify our existing decentralized controller and plant dynamics ([Figure 4](#)) into the diagram below ([Figure 7](#)). Note p and q are the Energy Management Strategy transformations that map driver power into target engine speed and target engine torque

commands, while $\frac{1}{T_{gen}s + 1}$ and $\frac{1}{T_{eng}s + 1}$ represent the generator and engine dynamics respectively.

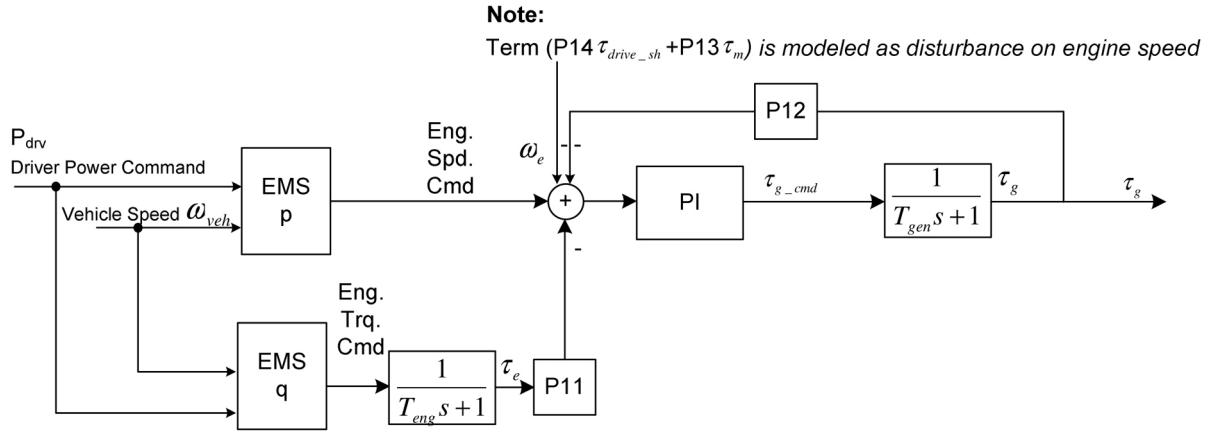


Figure 7. Existing Controller with Plant

From Figure 7, we can derive the transfer function,

$$G(s) = \frac{\tau_g(s)}{P_{drv}(s)} = \left(p - \frac{qP_{11}}{T_{eng}s+1} \right) \left(\frac{\frac{PI}{T_{gen}s+1}}{1 + \frac{PI P_{12}}{T_{gen}s+1}} \right), \quad (9)$$

It can be proven that $G(s)$ contains a nonminimum phase (NMP) zero if all terms $(P_{11} P_{12}, p, q)$ in the transfer function are fully expanded. (See complete derivations in the next section). However, to avoid the excessive steps in algebraic transformation due to the complexity of the Powersplit HEV dynamics, here we take another approach to prove the initial inverse response arises from the nonminimum phase zero.

We keep $G(s)$ in the simple form without expanding all the terms. If we assume a step input driver power command, $P_{drv} = u(t)$, and use the Initial Value Theorem, the initial value of the derivative (or 'change rate') of the generator torque is,

$$\begin{aligned} \dot{\tau}_g(t=0) &= \lim_{s \rightarrow \infty} s^2 G(s) u(s) \\ &= \lim_{s \rightarrow \infty} s^2 \left(p - \frac{qP_{11}}{T_{eng}s+1} \right) \left(\frac{\frac{PI}{T_{gen}s+1}}{1 + \frac{PI P_{12}}{T_{gen}s+1}} \right) \frac{1}{s} \end{aligned} \quad (10)$$

$$\text{where } P_{11} = \frac{J_A}{s}; P_{12} = \frac{J_A T_{e2g} \rho - J_B T_l T_2}{s \rho},$$

$$PI = K_p + \frac{K_i}{s}$$

$$\text{Finally we can get, } \dot{\tau}_g(t=0) = \frac{pK_p}{T_{gen}} \quad (11)$$

p is the transformation which maps driver power into engine speed command.

K_p is the proportional gain of the engine speed PI controller.

T_{gen} is the time constant in the generator torque dynamics.

In the above equations 9, 10, 11, p , K_p , T_{gen} are all positive, thus the initial value of 'the derivative of the generator torque' $\dot{\tau}_g(t=0)$ is positive for a step input P_{drv} . However, we know from the lever diagram that the change rate of the generator torque must be negative (see the gradients of τ_g in Figure 5) in order to react the increasing engine torque. This contradiction inevitably ends in an initial torque undershoot.

So far our derivation has explicitly identified the cause of the initial generator torque undershoot during a tip-in event. To eliminate this inverse response, we need to design a centralized controller so that $\dot{\tau}_g(t=0)$ is negative during a step input P_{drv} . Likewise for a negative step input (tip-out event), $\dot{\tau}_g(t=0)$ needs to be positive.

THE CENTRALIZED TORQUE CONTROLLER

It is well known that the nonminimum phase (NMP) zero dynamics in control system design imposes limit on closed-loop performance [5][6][7][8]. The undershoot phenomena occurs because of the unstable zeros. It is a difficult task to cancel the characteristics by using linear control techniques [5]. There are available techniques in the literature such as pole-zero cancellations, adding additional measurement in the system, or varying the control structure [7]. Considering the implementation challenges to alleviate the closed-loop bandwidth limitations associated with the NMP zero in the