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Energy-efficient control of electric vehicles based on linear quadratic regulator and phase plane analysis

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HIGHLIGHTS

- A phase plane-based energy-efficient controller is proposed for electric vehicles.
- A self-stable boundary is developed for vehicle stability identification.
- The gain scheduling on two LQR modes is designed for better vehicle performance.
- The vehicle stability and power consumption are integrated in torque allocation.
- The proposed controller saves up to 9.68% and 3% energy at two typical maneuvers.

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ABSTRACT

Electric vehicles (EVs) have advantages in the aspect of energy, environment, and vehicle motion control. However, it is still not competitive enough to conventional vehicles because of the limited driving range and the high cost of the battery. Therefore, the energy efficiency is of the most importance for the control of EVs. Existing range extension control systems on EVs mostly focus on longitudinal front and rear axle torque distribution or lower-level yaw moment allocation. It is a challenge to maintain the vehicle's stability at the cost of the minimum energy when the vehicle is cornering, this paper proposes a phase plane-based controller for EVs, focusing on the energy-efficient upper-level yaw stability control. The phase plane-based controller is automatically adaptive to driving situations through the optimization of weights on the performance of the vehicle handling and stability. Firstly, a friction constrained desired model is presented for the model-following control. Secondly, β–$\dot{\beta}$ phase plane analysis is conducted based on a nonlinear vehicle model to graphically identify the vehicle lateral stability in real time. The self-stable region can be determined by the vehicle velocity, the road friction coefficient, and the wheel steering angle. Then, energy optimizing (i.e. gain scheduling of LQR controllers) rules are designed based on the vehicle lateral stability identification. Finally, the proposed phase plane-based controller is evaluated and the yaw moment costs are compared to other controllers' in a realistic 7-DOF vehicle model. The results demonstrate that the proposed controller presents an excellent yaw stability control capability, and compared to the widely used Shino's controller, the proposed controller reduces the energy consumption by 9.68% and 3% at the 'light' and 'severe' maneuver, respectively.

1. Introduction

As the transportation sector accounts for a significant share of energy consumption and greenhouse gas (GHG) emissions in most countries, especially in developed economies, EVs have been proposed as an energy-saving and environment-friendly alternative to internal combustion engine vehicles (ICVs), mainly because of the higher efficiency of electric motors and their tailpipe zero emissions peculiarity. Despite the undeniable higher efficiency of electric motors, the improvement in overall energy consumption efficiency of EVs also depends on the relative efficiency of the supply-chain from the electricity generation plant to the charging station compared to that from the well to the gas station [1,2]. For other reasons that motivate the utilization of EVs are, the simple structure involved in manufacturing (only a battery, a power electronic drive, and electric motors), the potential to support grid operation as they can store energy in their batteries [3,4], and the

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Nomenclature

DYC	direct yaw-moment control
EECA	energy-efficient control allocation
EV	electric vehicle
GHG	greenhouse gas
HCC	holistic corner controller
ICV	internal combustion engine vehicle
LQR	linear quadratic regulator
MFC	model-following control
PMSM	permanent magnetic synchronous motor
TCS	traction control system
VSC	vehicle stability control
V2G	vehicle-to-grid system
2WD	two-wheel-driving
4WD	four-wheel-driving
A_D	vehicle frontal projected area
a	distance from the center of gravity to front axle
a_x	vehicle longitudinal acceleration
a_y	vehicle lateral acceleration
b	distance from the center of gravity to rear axle
C_D	coefficient of aerodynamic resistance
C_r	coefficient of rolling resistance
$C_{\alpha f}$	cornering stiffness at front tire
$C_{\alpha r}$	cornering stiffness at rear tire
e_i	parameters of vehicle self-stable boundary
F_a	aerodynamics resistance
F_{DR}	driving resistance
F_g	road grade resistance
F_r	tire rolling resistance
F_{xij}	tire longitudinal force
F_{yij}	tire lateral force
F_{zij}	vertical loads at each wheel
h_g	height of the center of gravity
I_w	tire/wheel rolling inertia
I_z	yaw moment of inertia
l	distance from the front axle to rear axle
m	vehicle mass
M_z	direct yaw moment requirement
n_{ij}	motor rotational speed
P_{bloss}	motor power loss in regenerative braking mode
P_{dloss}	motor power loss in driving mode
P_{total}	total energy consumption rate
R_e	tire/wheel rolling radius
R_{sta}	radius of the stable circle in β–$\dot{\beta}$ phase plane
T_{ij}	motor torque on each wheel
T_t	total longitudinal torque
$T_{t\,ij}$	motor torque on each wheel to meet T_t
ΔT_{ij}	motor torque on each wheel to meet M_z
t_{w1}	front track width
t_{w2}	rear track width
V	vehicle velocity
V_x	vehicle longitudinal velocity
V_y	vehicle lateral velocity
W_{hand}	weight on handling-oriented mode
W_{sta}	weight on stability-oriented mode
α	road grade angle
α_f	tire slip angle of the front wheels
α_r	tire slip angle of the rear wheels
β	side slip angle in vehicle body
γ	yaw rate in vehicle body
λ	Lagrange multipliers
ρ	air density
η_b	discharging efficiency of a lithium ion battery
η_c	efficiency of an on-board charger
η_i	efficiency of inverter
μ	road friction coefficient
δ_f	front wheel steering angle from driver
ω_{ij}	wheel angular velocity

capability of generating and using power of its own. Moreover, compared to ICVs, the four-wheel-driving (4WD) EVs with four in-wheel motors have remarkable advantages in motion control as follows [5],

1. In-wheel motors enable EVs to independently control and drive four wheels.
2. Electric motors response faster and more accurate to the driver's demand than engines.
3. Motor torque can be precisely measured by the motor current.

These advantages contribute greatly to Vehicle Stability Control (VSC) such as Direct Yaw-moment Control (DYC) [6–8], Traction

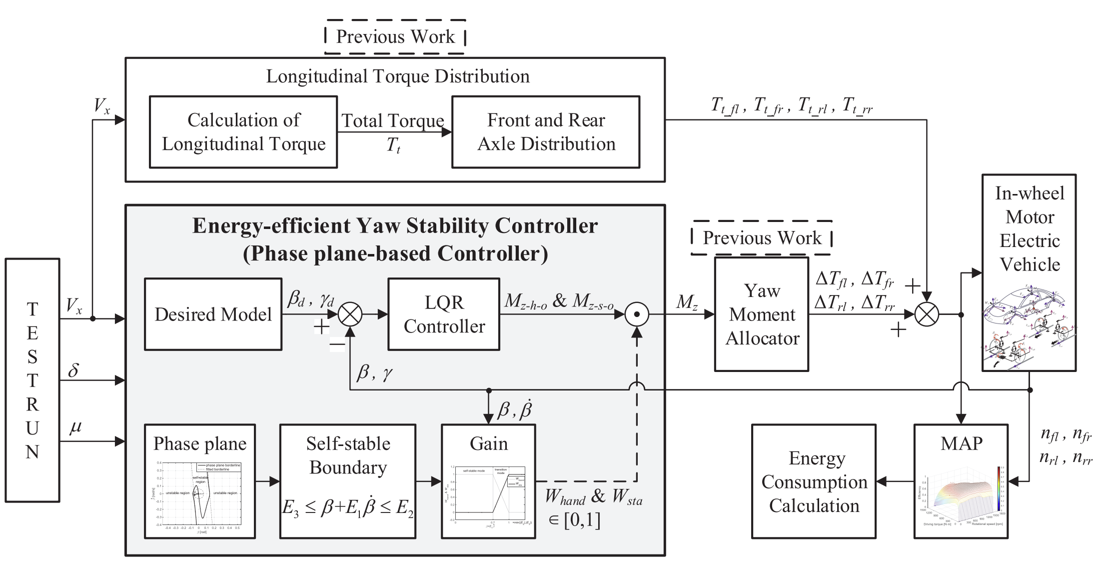

Fig. 1. Energy-efficient control system of electric vehicles.