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Developmentof mode selection map for multi-mode powersplit hybrid electric vehicle basedon offline optimization Huanqing WangDepartmentof Mechanical Engineering_Engineering MechanicsMichiganTechnological UniversityHoughton, MI 49931 —This paper presents anoffline optimization strategy to be used for multi-mode hybrid electric vehiclepowertrain control. A novel method of using equivalent consumption minimizationstrategy (ECMS) to determined best mode is explained and a mode selection mapis created. The performance of offline optimized map control is compared withrule based control from data provided by Argonne national lab. Keywords—hybridelectric vehicle; optimal control; powersplit; ECMS

I.

Introduction With higher regulationson emission and fuel economy, electric vehicle and hybrid electric vehicle aretaking over the market quickly. With EV charging infrastructure and batterytechnology takes time to develop, internal combustion engine is still thedominate force. Electrification could significantly reduce the inefficient useof engine, for example, during low speed, and city stop and go situation. Electric motor can do the majority of the work during low speed situation, avoiding running engine at low BSFC point. Motor is also capable of regeneratebraking where charge can be brought back to the battery. The powersplit vehicleis capable of being a series or parallel, it can used one motor as a propellingmotor the other used as generator.

The combination aims to use engine at mostefficient point, whether directly propelling the vehicle or charged battery forfuture use. Majorcontrol strategy for hybrid electric vehicles are: rule based control, instantaneousoptimization, model predictive control and global optimization. Rule basedcontrol are widely applied in automotive industries where rule extraction arebased on calibration tasks.

Instantaneous optimization is suitable for realtime control since the algorithm try to minimize the cost at each time step. Equivalent consumption minimization strategy would fall in the category ofinstantaneous optimization. Dynamic programming is a global optimizationmethod, where it determines the state trajectory of a given solution. Itutilizes bellman principle of optimality and the cost is calculated backwards, therefore prior knowledge of entire drive cycle is require.

Model predictivecontrol is a dynamic programming break in shorter intervals, instead ofrequiring entire drive cycle; it could uses only short predicted speed chunksof 5 seconds or 10 seconds to perform dynamic programing for optimal control. ECMS hasbeen a popular method for instantaneous optimization in single mode series, parallel and powersplit vehicle, but not for multi-mode vehicle control. Thispaper proposes of method applying ECMS for multi-mode vehicle powertraincontrol. The powersplit is generated in a lookup table offline for each mode. All modes are compared for all driving conditions and the mode with lowestequivalent fuel cost would be selected. The best mode map is generated offlinebut it can be used for online application. The control strategy is tested inUDDS drive cycle and optimized map based control is compared with rule basedcontrol data by Argonne national lab.

Section II introduces thespecs of vehicles and kinematic relationship in each operating mode. SectionIII explains the problem formulation, powersplit optimization, and modeoptimization and control strategy. Section IV compares the results withexperimental data from Argonne national lab. Section V concludes this paper.

II. VehiclemodelingA.

VehiclelayoutGM volt 2 uses a 1. 4-liter engine and two motors and twoplanetary gear set. Different operating modes can be achieved by opening andclosing of the two clutches 3. MGB is ideal for low speed high torqueapplication where MGA is more suitable for high-speed low torque. There is aone way clutch on connected to the engine to prevent engine spinning backwardsduring EV mode. Clutch one connects sun gear of PG1 and ring gear of PG2. Fig.

1Architecture of Chevy Gen II Volt B. ModedynamicsThere are five modes introduced by GM. Different mode canbe achieved by opening and clutches. The summary and equations are presentedfor each mode. The governing equation for speed relation is Willis’ equation.

Where is the angular velocity of the ring gear, is the angular velocity of the sun gear, is the angular velocity of the planetarycarrier. S is the teeth number of sun gear and R is the teeth number of sungear. 1EV: During one motor EV mode, clutch 1 is open andclutch2 is closed. Motor A and Motor B both spins and react to vehicle speed, but only Motor B provides torque.

EV2: During two motor EV mode, clutch 1 is open andclutch2 is closed. Both Motor and Motor can provide torque. This mode canprovide maximum amount of torque. LER: During LER mode, clutch 1 is open and clutch 2 isclosed. Part of engine power is used to charge the battery. Motor A acts as agenerator and motor A torque is directly coupled to engine torque. FER: During fixed extended range, clutch 1 and clutch 2are both closed.

Only in this mode. Motor A is grounded and it does not providetorque. All engine power is used to propel the vehicle. The engine speed isdirectly proportional to vehicle speed since the gear ratio between engine andwheels is fixed. Motor B can assist propelling the vehicle when large axletorque is required. HER: During high extended range, clutch 1 closes andclutch 2 is open.

By closing clutch 1, sun gear of PG1 is connected to ringgear of PG2. This gives a higher ratio and makes it efficient for high speeddriving. Engine speed is independent from wheel speed. By adjusting motor A andmotor B rpm, the engine rpm can run at efficient operating points. Where is the angular velocity of motor A, is the angular velocity of motor B, is the angular velocity before final drive. S1is number of teeth of the sun in the first planetary gearset. R1 is the numberof teeth of the ring in the first planetary gearset.

S2 is number of teeth ofthe sun in the second planetary gearset. R2 is the number of teeth of the ringin the second planetary gearset. is the torque of motor A, is the torque of motor B, is the torque of engine.

III. optimalcontrolInstantaneous optimization is used for this equivalentminimization strategy approach. At every operating point, the cost of fuel andcost of electricity is being minimized. Since electric and fuel is not directlycomparable, electric consumption is converted to equivalent fuel1.

Bruteforce algorithm is used to determine best motor and engine operatingcombinations and results are stored in maps. 3. 1. EVbest operating pointsDuring EV operation, the goal is to reduce battery energy consumption. It is achieved by using both motors at the most efficient combination.

The costfunction is defined: Where is the battery power consumption; is the Motor A torque, is the Motor A angular speed, is the Motor B torque, is the Motor B angular speed, is the Motor A efficiency, is the Motor A efficiency , is the Motor A power electronics efficiency, is theMotor B power electronics efficiency. All driving condition can considered interms of axle torque and speed4. For each, torque and speed combination, all motoroperating conditions are examed, and the control with lowest cost is recordedand shown in the graph. , Fig. 2 MotorB best operating torque for EV mode. Fig.

3 MotorA best operating torque for EV mode. 3. 2. Hybridmode best operating pointsDuring hybridoperation, the equivalent fuel consumptionis

being minimized at eachinstant. The equivalent fuel consists of instantons fuel consumption andelectricity converted into fuel by multiply average bsfc factor. The equivalentfuel factor is a BSFC equivalent factor, represent how efficient engine wouldoperate if those motor power are provided by engine.

For every speed and torquepoint, all engine and motor operating combinations are examed and control withthe lowest operating cost is selected. Where is the equivalent fuelconsumption, which is the sum of engine fuel consumption and equivalent fuel consumption from electricmotor . is the equivalence factor ofconverting battery power to fuel consumption, it represents how efficient theengine would operate if those electric power are otherwise provided by engine, the detailed of determination of this factor can be found in 2. is the Motor A power, is the Motor B power.

is -1 when MGA acts as generator and 1 whenacts a motor. is -1 when MGB acts as generator and 1 whenacts a motor. All driving condition can bemapped into axle torque and speed combination, sweeping through allcombinations, the best control in terms engine speed, engine torque, motor Btorque, motor B speed, motor A torque, and motor A speed are shown in Fig. 4-9. Fig. 4 Enginebest operating torque for LER mode. Fig.

5 Enginebest operating rpm for LER mode. Fig. 6 MotorB best operating torque for LER mode. Fig. 7 MotorB best operating speed for LER mode. Fig. 8 MotorA best operating torque for LER mode. Fig.

9 MotorA best operating speed for LER mode. 3. 3. Bestmode mapFor each mode, the equivalent fuel cost can be determined forall operating conditions and is generated in map with respect to axle torque andspeed.

The fuel consumption map for LER mode is shown in Fig. 10. Fig. 10Equivalent fuel consumption for LER mode. There are total of four maps (EV, LER, FER, HER), afteroverlay 4 modes fuel consumption together, for each axle torque and speed, themode with the lowest fuel cost is selected. The mode selected will be recordedinto our new map best mode map. The results are shown in Fig. 11.

It shows EVmode is most efficient during low speed operation. During extreme high torquerequirement, it is also selected since it exceeds other mode’s torque capability. Fig. 11 bestoperating mode map.

A. Control strategyWhen determining best operatingpoints and extracting mode map, all control combinations are examined; it iscomputationally expensive and the map is developed offline. Although the modemap and operating map are generated offline, it is suitable for onlineapplication. In Fig.

12, any drive cycle can be discretized into vehicle’s axletorque requirement and speed. At each discrete time step, the pair goes throughmode selection lookup first. Then, the two points going into the mode selectiontable to select the mode.

The according best operating points from that mode islooked up and send to the vehicle model. Fig. 12 the control strategy frombest mode map

IV. ResultsThe drive cycle being used is UDDS and it is compared withexperimental data of the same cycle from Argonne National Lab5. The offlineoptimized map method uses the best mode map and best operating points, whererule based control method used experimentally recorded mode shift andpowersplit. Both control strategies are used and fed into the model and resultsare recorded. Fig. 13 shows the engine operating points of the optimized mapmethod.

The inefficient use of engine is avoided in this method whereas thereare low BSFC points recorded in rule-based control in Fig. 15. Fig. 13Engine operating points in UDDS cycle from offline optimization map. Fig. 14 Simulationresults of UDDS cycle from offline optimization map. Fig. 14 shows that by running engine at low BSFC point, lower fuel consumption can be obtained.

The mode shift of the optimized mapeliminated the use of two motor EV mode, since it is determined there are lessloss using one motor during UDDS driving, which is a relative low torquerequirement driving cycle. Rule based control almost has a charging anddepleting behavior. As shown in Fig. 15, when battery state of charge becomesrelatively high, it uses EV to drain the battery for the next 250s.

Fig. 15Engine operating points in UDDS cycle from ruled based control. Fig. 16 Simulationresults of UDDS cycle from ruled based control. After the drive cycle, the simulation shows the rule basedcontrol strategy control strategy consumes 0. 304 gallons of gasoline and theoptimized map control strategy consumes 0.

246 gallons of gasoline. The fuelsaving is achieved by running the engine at efficient point where BSFC valuesare
low.

V. ConclusionsThis paper introduces the architecture of Chevy gen2 volt, explained an offline optimization strategy to determine vehicle best operatingpoints and best mode map. The offline optimized map control strategy comparedwith rule based control strategy from data provided by Argonne National Lab. References1 G.

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