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A Rule-Based Energy Management Strategy for Plug-in Hybrid Electric Vehicle (PHEV)

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Abstract—**Hybrid Electric Vehicles (HEV) combine the power from an electric motor with that from an internal combustion engine to propel the vehicle. The HEV electric motor is typically powered by a battery pack through power electronics. The HEV battery is recharged either by the engine or from regenerative braking. The electric drive mode is very limited for an HEV due to the limited battery power. A more powerful battery will increase the electric drive range of the vehicle, thus improving fuel economy. However, the battery will need to be recharged using an electric outlet since the regenerative braking and limited engine usage will not be sufficient to fully recharge the larger battery pack. In this paper, a rule-based energy management strategy for a Plug-in Hybrid Electric Vehicle (PHEV) is presented. Since large amount of electric energy is stored in the battery from the electric power grid, the fuel consumption is reduced significantly as compared with HEV counterpart. The proposed energy management strategy is implemented on a PHEV model in ADVISOR and the model is then simulated for a number of predefined drive cycles. The proposed PHEV algorithm results are compared with those for HEV with similar battery capacity as PHEV.**

I. INTRODUCTION

In today's world, the demand of the Hybrid Electric Vehicles (HEV) is rising with the rising gasoline prices. A HEV is powered from two sources of energy: an electric motor via battery and an internal combustion engine. As these vehicles have two degrees of freedom for energy flow controls, it has been of greater area of interest for researchers in the past years. In the Hybrid Electric Vehicles, the battery is charged through the engine and the regenerative braking while decelerating the vehicle. But as the engine is used to charge the battery and then the battery is used to drive the vehicle, there are large losses in this loop while using the fuel. The electric drive mode is very limited for an HEV due to the limited battery power. A more powerful battery will increase the electric drive range of the vehicle, thus improving fuel economy. But the battery will need to be recharged using an electric outlet since the regenerative braking and limited engine usage will not be sufficient to fully recharge the larger battery pack. For a configuration, it is therefore necessary that the battery be charged from some source other than the engine / regenerative braking. The PHEV configuration has the promise of significantly improving the fuel economy and reducing harmful emissions over its HEV counterpart.

For the past few years, a lot of research has been performed on the next generation of Hybrid Electric Vehicles called Plug-in Hybrid Electric Vehicles (PHEV). In these vehicles, higher capacity batteries are used that can store charge from the electrical outlet along with the onboard engine charging and regenerative brake charging. The energy management system is responsible for managing the energy flow. Since there are two sources of energy, the energy management system directs the flow of energy in the most efficient way and performance of vehicle can be improved significantly.

In the past, a number of research work has been done on the hybrid electric vehicles. However, since PHEV concept is relatively new, the literature available on its energy management strategies is not extensive. Gong [1] investigated to optimize the Plug-in Hybrid Electric Vehicle using Dynamic Programming by using intelligent transportation system GPS, GIS and advanced traffic flow modeling techniques. Pritchard [2] using the ADVISOR showed that by using plug-in feature in HEV school buses significant savings in fuel can be done. Ceraolo [3] showed the General approach to optimize both the series and parallel powertrains and studied effect of different functions on management strategies including plug-in rechargeable capabilities.

Since both the HEV and PHEV are very similar in approach to each other, HEV studies are also helpful in understanding the PHEV. Wu [4] used the Particle Swarm Optimization technique to optimize the Parallel HEV powertrain. Valerie [5] implemented the Real Time optimization of parallel HEV using ADVISOR for optimum Fuel Economy and Emissions.

In this paper, we make use of the ADVISOR software from National Renewable Energy Laboratory with the PHEV models. These models are modified for different Rule-Based Control strategies and then the results are compared with the results of ADVISOR model Control strategies for both PHEV and HEV.

II. REVIEW OF RULE BASED ENERGY MANAGEMENT CONTROL STRATEGY(RBS) IN ADVISOR FOR PRIUS AND PARALLEL MODEL

Prius is a combination of both parallel and series Powertrains. In this kind of Powertrain,, the continuous variable transmission (CVT) is used which consists of Planetary Gear set connected to the Motor, Generator and Engine. The planetary gear set acts as a speed coupler between the Engine and Generator. Also there exists a torque coupling between the Engine and Motor.

In the Rule Based Energy Management Control strategy which is being used by the ADVISOR Model for Prius, the power generated by the Engine is controlled power while remaining power is provided by the Motor. The Engine is ON/OFF condition is dependent on the State of Charge (SOC) of Battery, Power Requested, Vehicle speed and Engine Coolant Temperature.

The various Engine Operating modes are selected based on the following set of rules:

a) If SOC of battery is enough, Power requested can be provided by battery, Vehicle operating at low speed and Coolant temperature is acceptable then only Vehicle is operated in Electric mode.
b) If the Engine is ON and the state of charge of battery is above the targeted state of charge then Engine and Motor both provide the requested power demand.
c) If the state of charge of the battery goes below the targeted state of charge then the Engine provides the extra power to charge the battery and also powers the Vehicle.
d) If the Power requested by the vehicle goes negative and the Engine is OFF then entire negative requested power is stored in the battery using the Regenerative braking.

In Rule Based Strategy (RBS) Energy Management control strategy used for the Parallel powertrain model the Engine power is controlled and the remaining power is delivered by the Motor. But in the Parallel powertrain the Gear box is used instead of Continuous Variable Transmission. Here the following control strategy is used.

a) If the Vehicle speed is below Electric Launch speed limit and state of charge of battery is greater than lower limit then it will be powered entirely by Motor in EV mode.
b) If the power required by the vehicle exceeds the maximum power that can be provided by Engine and state of charge of battery is more than its lower limit then the remaining power is provided by Motor.
c) When the power required by vehicle goes negative all the negative power is stored by the Battery via regenerative braking.
d) The engine also may turn off if the torque required drops below a limit i.e. off torque limit in the figure shown below if state of charge is greater than lower limit of state of charge.

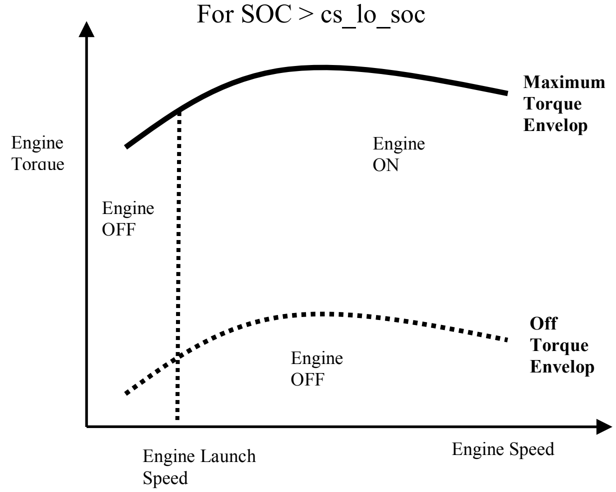

Fig 1: Charge Depletion Strategy for Parallel Strategy [9]

e) If the state of charge of battery drops below its lower limit then Engine provides the extra power which is used to charge the Battery as shown in the figure below while operating above the min Torque Envelope.

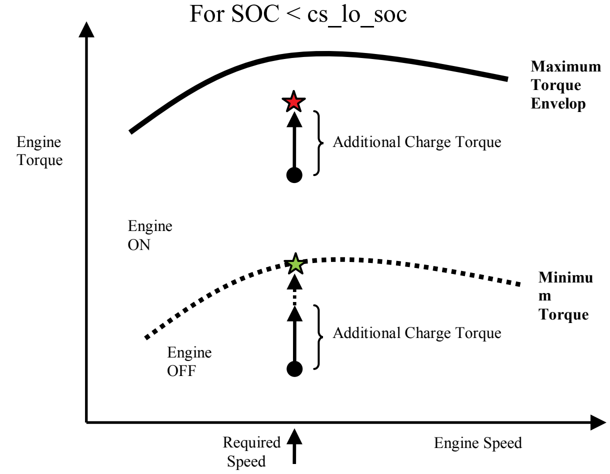

Fig 2: Charge Sustaining strategy for Parallel strategy [9]

III. PROPOSED RULE BASED ENERGY MANAGEMENT STRATEGY FOR PHEV

It can be seen from above that the RBS of ADVISOR is an Electric Assist Strategy. Since the PHEV has a higher capacity battery that is initially charged through an electric outlet, maximum use of this battery should be done to reduce the Fuel Consumption. So in this rule based strategy the maximum power is drawn from battery via motor to drive the vehicle and the rest of power is provided by the Engine.

As mentioned above the continuous variable transmission is used in the power train so that engine can be operated at desired optimal speed. Here we also control the operating torque of the engine to provide the battery charging power and the vehicle driving power as a function of speed. The engine ON/OFF condition is controlled by the following set of rules.

1. If state of charge of the battery is below the lower limit of state of charge and positive power is required by the vehicle then the Engine must be turned ON.
2. If the state of charge of the battery is above its lower limit and the power requested by the vehicle is less than the maximum power that can be provided by the Motor but positive then the Engine must be turned OFF.
3. If the state of charge of the battery is above its lower limit and the power requested by the vehicle is more than the maximum power that can be provided by the Motor but positive then the Engine must be turned ON.
4. If the Power requested by the vehicle is negative and the state of charge of the battery is below its upper limit then the Engine must be turned OFF.

These above set of rules are used to define the operating modes of the vehicle. The vehicle operating modes are based on the charge depletion and the charge sustaining operation. The following rules define the operating modes of the vehicle:

a) If the state of charge of the battery is above its lower limit and the power required by the vehicle can be fulfilled by the Motor alone then the Vehicle is driven in Electric Vehicle Mode.
b) If the state of charge of the battery is above its lower limit and the power required by the vehicle cannot be provided by the Motor alone then the Engine is used to provide the rest of power to drive the vehicle.
c) If the state of charge of the battery is below its lower limit and the power required by the vehicle is lesser then the power that can be generated by the engine at optimal operating point then while operating the Engine at its optimal operating point the rest of the power is used to charge the Battery.
d) If the state of charge of the battery is below its lower limit and the power required by the vehicle is more than the power that can be generated by the vehicle at optimal operating point then the engine power is alone used to drive the vehicle.
e) If the state of charge of the battery is lower than the upper limit and the required power is negative then this negative power is used to charge the battery directly through regenerative Braking.

IV. SIMULATION RESULTS

The simulation for rule based control strategy for Prius model is done using the existing model of Prius in the ADVISOR. It is simulated for Plug-in Hybrid Electric Vehicle using Prius control strategy in ADVISOR. To match the battery capacity of a PHEV, the energy capacity of the stock Prius battery was significantly increased from 6 Amp-Hr to 26 Amp-Hr. and the initialization of control parameters and battery models is done as shown in the Table 1 below:

Table 1: Models and Parameter values used for Priuis Model and Prius Control Strategy

Variable/Model	Value/Name
Engine	FC PRIUS JPN 57kw
Motor	MC PRIUS JPN 50kw
Battery	ESS LI7 temp
Max Battery Capacity	26 Amp-Hr
Initial Conditions	Hot Temp Conditions
Init SOC	95 %
SOC High	90%
SOC Low	35%
Eng On SOC	35%
Target SOC	45%
Eng On Min Power Req	18,000 W
Electric Launch Speed Limit	34 MPH

The simulation for the proposed rule based energy management strategy for PHEV is done using Prius model in the ADVISOR. Here the battery energy capacity is kept at 26 Amp-Hr. It's engine ON/OFF conditions were modified according to the PHEV control strategy. Here the engine is operated at a selected speed which depends on the required power. Engine is also operated on maximum engine torque which is selected as an efficient operating point according to the strategy. Thus engine is being operated at specific speeds and torques. The models and the control parameters are initialized as mentioned in following Table 2:

Table 2: Model and Parameter values used for Prius vehicle with proposed RBS

Variable/Model	Value/Name
Engine	FC PRIUS JPN 57kw
Motor	MC PRIUS JPN 50kw
Battery	ESS LI7 temp
Max Battery Capacity	26 Amp-Hr
Initial Conditions	Hot Temp Conditions
Init SOC	95 %
SOC High	90%
SOC Low	35%

These two models are then simulated for the input of five consecutive UDDS or EPA drive cycle (Fig. 3) since 1 drive cycle would not show good comparison and maximum capability of PHEV vehicle. The total distance traveled by vehicles is 37.2.

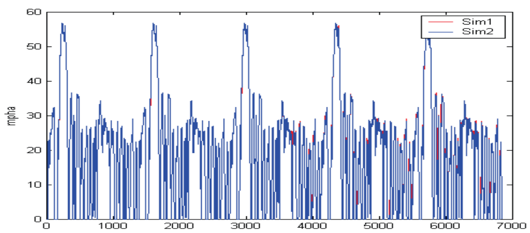

Fig 3: 5 EPA drive cycles.

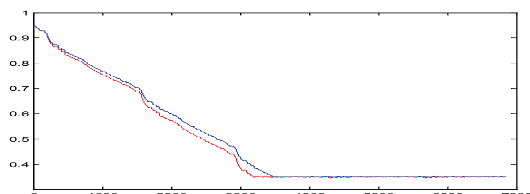

Fig 4: SOC of Prius strategy (blue) and SOC of proposed strategy (Red and dotted).

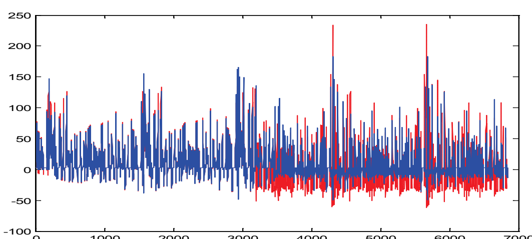

Fig 5: Current drawn for Prius strategy (blue) and current drawn for proposed strategy (RED and dotted) from battery.

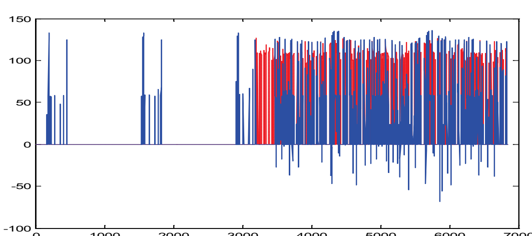

Fig 6: Engine Torque for Prius strategy (Blue) and Engine Torque for proposed strategy (Red and dotted).

Figures 4 through 6 show the simulation results for SOC, battery current draw, and engine torque for both Prius strategy and proposed strategy. The Fig 4 shows that the Proposed strategy makes maximal use of the battery for about first 3000 seconds compared to Prius strategy. Fig 5 reveals that this proposed strategy stores more charge into the battery compared to the Prius strategy while operating engine in efficient region. From Fig 6 we can ascertain that the Engine torque is much more constant about the efficient point. Hence it also improves the efficiency of Engine. The Prius control strategy for PHEV resulted in a gas mileage of 74.8 MPG while the proposed rule based control strategy for PHEV provided mileage of 87.6 MPG for the drive cycle of 37.2 miles. Also the engine working efficiency for the Prius strategy is 29% and the engine working efficiency for the proposed RBS strategy on Prius model increased to 35%. Furthermore, the comparison of MPG for different distances also shows the advantage of proposed strategy over Prius strategy as shown below:

Table 3: MPG comparison for different distance of Prius Strategy and Proposed Strategy

No. of Drive Cycle (Distance in Miles)	3 (22.4)	5 (37.3)	7 (52.2)	10 (74.5)	15 (112)
Prius Strategy MPG	202.9	74.8	59	51	45.9
Proposed Strategy MPG	234	87.6	68.7	59.3	53.6

Similarly, the comparison between the proposed ruled based PHEV strategy and the Parallel strategy is also done on the Parallel Powertrain Model of the ADVISOR.

For simulating the Parallel Strategy on the Parallel Powertrain Model the control parameters were modified as shown in below Table 4:

Table 4: Model and Parameter values used for Parallel model and its Control strategy

Model\Variable	Name\Value
Engine	FC SI41 emis 41kw
Motor	MC AC75
Battery	ESS LI7 temp
Battery Max Capacity	26 Amp-Hr
Initial Conditions	Hot Temp Conditions
Initial SOC	95%
SOC High	90%
SOC Low	35%
Electric Launch Speed Limit	30 MPH
OFF Torque Fraction	20%
Min Torque Fraction	40%
Charge Torque	15.25 Nm

The proposed RBS strategy is also implemented in the Parallel Powertrain model after some modifications in the model. The engine ON/OFF condition and the torque control to the engine is modified according to the strategy. Also the power routing in the planetary gear set is modified. The control parameters for this strategy are set as mentioned in Table 5 below:

Table 5: Model and Parameter values used for Parallel model and Proposed RBS

Model\Variable	**Name\Value**
Engine	FC SI41 emis 41kw
Motor	MC AC75
Battery	ESS LI7 temp
Battery Max Capacity	26 Amp-Hr
Initial Conditions	Hot Temp Conditions
Initial SOC	95%
SOC High	90%
SOC Low	35%

These two energy management strategies for Parallel Powertrain model are run for the five EPA drive cycles (Fig. 7) and the total distance traveled by the vehicles is 37.2 Miles since 1 drive cycle would not show good comparison and maximum capability of PHEV vehicle..

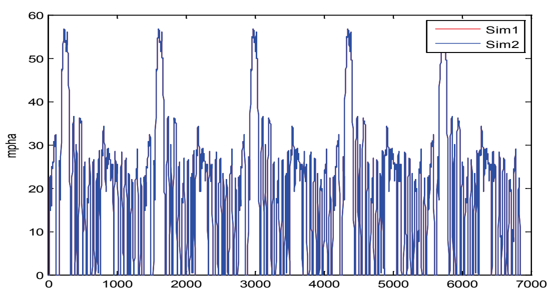

Fig 7: 5 EPA drive cycles.

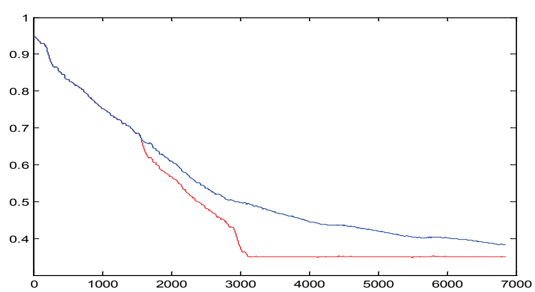

Fig 8: SOC of Parallel strategy (blue) and SOC of proposed PHEV strategy (Red and dotted).

Figures 8 through 10 show the simulation results for SOC, battery current draw, and engine torque for both parallel strategy and proposed strategy.

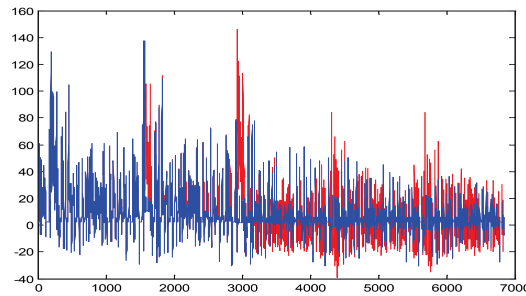

Fig 9: Current drawn for Parallel strategy (blue) and current drawn for Proposed strategy (RED and dotted) from battery.

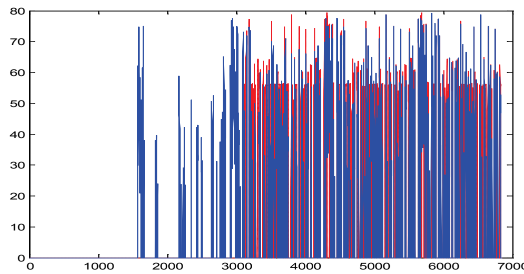

Fig 10: Engine Torque for Parallel strategy (Blue) and Engine Torque for proposed PHEV strategy (Red and dotted).

The Fig 8 also shows that the proposed strategy makes maximal use of the battery for about first 3000 seconds compared to parallel strategy. Fig 9 reveals ample of current drawn and stored in the battery during the entire drive cycles compared to parallel strategy making its maximal use while operating engine in efficient region. From Fig 10 we learn that the Engine torque for most part is about efficient operating point hence increasing the Engine efficiency. For these simulations on the Parallel Powertrain the Parallel strategy provided 75.9 MPG while the proposed PHEV strategy provided the 80.9 MPG and both the times vehicle ran for the distance of 37.3 Miles. The Engine working efficiency for Parallel strategy is 28% but for the PHEV strategy on the parallel Model is 29%. Moreover, the comparison of MPG for different distances also shows the advantage of proposed strategy over Parallel strategy as shown below:

Table 6: MPG comparison for different distance of Parallel Strategy and Proposed Strategy

No. of Drive Cycle (Distance in Miles)	**3 (22.4)**	**5 (37.3)**	**7 (52.2)**	**10 (74.5)**	**15 (112)**
Parallel Strategy MPG	124.6	74.6	62	54.3	48.4
Proposed Strategy MPG	194.2	80.9	64	55.5	50.4

Even though the rule based energy management strategy presented above shows very promising results, there is room for further improvement in the fuel economy and performance of a PHEV. Such improvements can be achieved via mathematical optimization and developing the energy management strategy based on this optimization.

V. CONCLUSION

In this study, the proposed RBS strategy was implemented on two different vehicle models i.e. Prius model and Parallel model. The results of this RBS strategy were then compared to the Prius energy management strategy and the Parallel Powertrain energy management strategies in ADVISOR for different distances travelled. It was observed that with the proposed RBS energy management strategy, the gas mileage of the PHEV increased by 16% over the Prius control strategy. The gas mileage with RBS strategy was also better than that for Parallel Powertrain control strategy in ADVISOR by about 6%. The engine efficiency with the proposed RBS strategy also increased significantly over that for Prius and Parallel control strategies. It is therefore concluded that the charge depletion and charge sustaining strategies along with electric assist strategy (the proposed RBS) is more effective on the PHEV compared to HEV energy management strategies on PHEV for the same battery energy capacity.

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