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Power Management for Series Hybrid Electrical Vehicles via Power Split Strategy

Omar Said[1] , Ezzaddine Ahmed[2]
[1]Electrical and Computer Engineering Department, Garaboulli Faculty of Engineering, Elmergib University, Alkhoms, Libya
[2]Electrical and Electronic Engineering Department, Higher Institute of Sience and Technology Awlad Ali, Tarhouna, Libya
omsaid@elmergib.edu.ly[1] , ezzaddineahmed@gmail.com[2]

***Abstract*—Further to a previous study about power management for series hybrid electrical vehicles (SHEV) via on-off control strategy, using Matlab/Simulink, an attempt will be made through this paper to study another control strategy for SHEV called power-split control strategy. In case of the on-off control strategy, the combustion engine is operated at its optimal operating point which is based on minimization of fuel consumption or minimization of emissions or even a compromise on both. While the power split strategy is based on the optimal operating line of the engine, where the ICE needs to deliver different power demands, the corresponding optimal operating points represent the optimal operating line. The overall efficiency of the SHEV under this strategy has been presented and the effect of the initial state of charge (SOC) of the battery on the overall efficiency has been taken into consideration. Finally, a comparison for the overall efficiency of the SHEV under the two control strategies and the effect of the SOC on the overall efficiency has been presented.**

Keywords—Series Hybrid Vehicles, Power Split Strategy, Driving Cycle, State of Charge.

I. INTRODUCTION

Due to the variations in SHEV configurations, several power-control strategies are necessary to regulate the power flow to or from the different components of the vehicle. These control strategies are to achieve a number of goals such as maximum fuel economy, minimum emissions, and good driving performance. The design of power-control strategies for SHEVs involves different considerations. Some of them are summarized below [1]:

1) Optimal engine operating point: The best operating point of the ICE can be based on the maximization of fuel economy, the minimization of emissions, or even a compromise between fuel economy and emissions.

2) Optimal engine operating line: where the engine has to deliver different power demands, the corresponding optimal operating points form the optimal operating line. Fig.1 illustrates a typical optimal operating line of an engine in which the optimization is based on the minimum fuel consumption, which is equivalent to the maximum fuel economy.

3) Minimum engine dynamics: The engine operating speed needs to be regulated in such a way that any fast fluctuations are avoided, hence minimizing the engine dynamics.

4) Minimum engine speed: When the engine operates at low speeds; the fuel efficiency is very low. The engine should be cut off when its speed is below a threshold value.

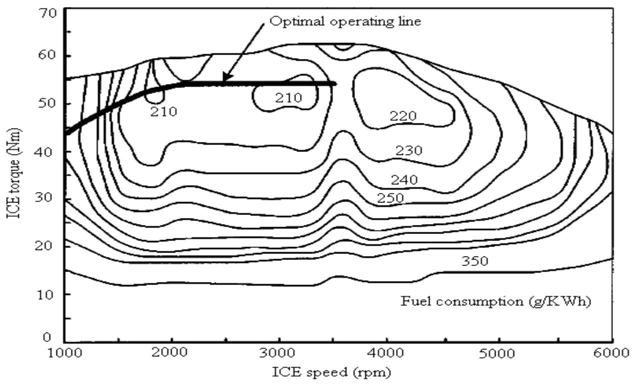

Fig. 1. Optimal operating line on an engine fuel consumption map [2].

5) Minimum engine turn on time: The engine should not be turned on and off frequently; otherwise, it results in additional fuel consumption and emissions. A minimum turn-on time should be set to avoid such drawbacks.

6) Proper battery available: The battery-available capacity needs to be kept at a proper level so that it can provide sufficient power for acceleration and can accept regenerative power during braking or downhill. When the battery-available capacity is too high, the engine should be turned off or operated idly. When the available capacity is too low, the engine should increase its output to charge the battery as fast as possible.

7) Safety battery voltage: The battery voltage may be significantly altered during discharging, generator charging, or regenerative charging. This battery voltage should not be overvoltage or under voltage; otherwise, the battery may be permanently damaged. Therefore, battery management is a critical issue.

8) *Relative distribution:* The distribution of power demand between the engine and battery can be optimized during the driving cycle.

The research area concerned with energy management has grown very fast in the recent years. Many computation methods of all kinds have been used to calculate the optimal energy management strategy, e.g. Model Predictive Control [3], Quadratic Programming [3], Rule Based Control [4], Fuzzy Logic control [5], Neural Networks and Adaptive Control [6]. These methods will not be discussed here because this paper focuses on another method which is

Logic Programming. In this paper, power split strategy for SHEV is investigated and results are compared with on-off strategy.Series hybrid electrical vehicle has the following operation modes which can be selectively used according to the driving condition and the desire of the driver [2], [7].

1. Pure electric mode: the engine is turned off and the vehicle is propelled only by the batteries. The arrows indicate the direction of energy flow.

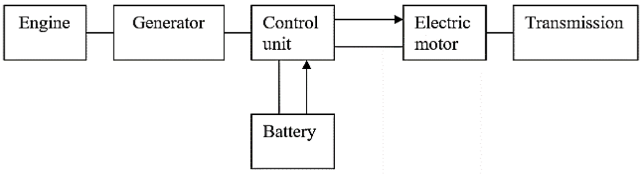

Fig. 2. Power flow in a pure electric mode.

2. Pure engine mode: the vehicle traction power only comes from the engine-generator, while the batteries neither supply nor draw any power.

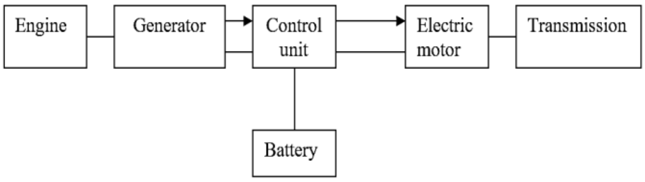

Fig. 3. Power flow in a pure engine mode.

3. Hybrid mode: the traction power is drawn from both the engine-generator and the batteries.

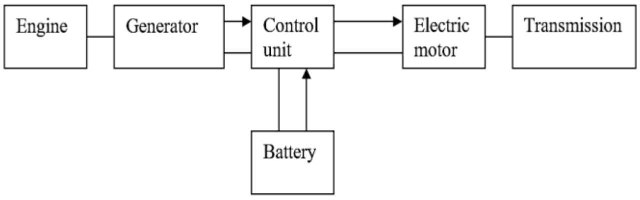

Fig. 4. Power flow in a hybrid mode.

4. Engine traction and battery charging mode: the engine generator supplies power to charge the batteries and to propel the vehicle.

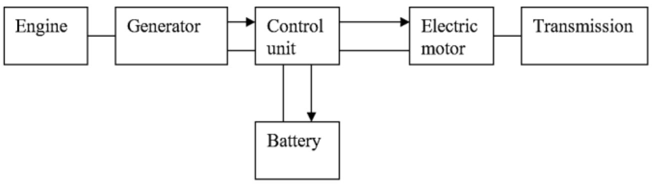

Fig. 5. Power flow in engine traction and battery charging mode.

5. Regenerative braking mode: the engine-generator is turned off and the traction motor is operated as a generator. The power generated is used to charge the batteries.

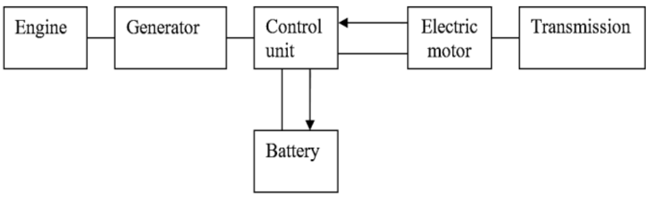

Fig. 6. Power flow in a regenerative braking mode.

6. Battery charging mode: the traction motor receives no power and the engine generator charges the batteries.

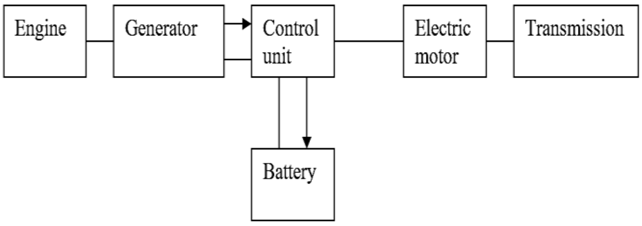

Fig. 7. Power flow in a battery charging mode.

7. Hybrid battery charging mode: both the engine-generator and the traction motor operate as generators to charge the batteries.

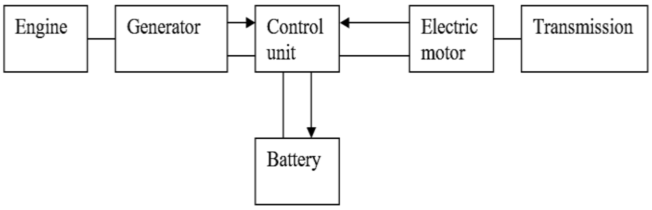

Fig. 8. Power flow in a hybrid battery charging mode.

II. SYSTEM MODELLING IN MATLAB/SIMULINK

Since the system model for both control strategies are same, the model constructed for a previous study about an on-off control strategy has been re-used for this study [8]. In table I, the efficiency from the diesel fuel energy to electrical output power is shown for different power levels. The efficiency is a combined efficiency for the engine, generator and the power converter. It is shown that the lower power output makes the lower efficiency and the power range of 35kW through 60kW has a flat efficiency. The maximum efficiency was found at high output power 50kW and the lower output power resulted in the lowest efficiency. When the output was 10kW, the system efficiency was 22.4%, and the peak output was 60kW, the efficiency was 30.2% [9]. In fact, as will be discussed later, the investigated control strategies are highly based on table I.

TABLE I. FUEL EFFICIENCY OF THE ENGINE/GENERATOR UNIT [8]

Operating Conditions		**Efficiency**	
[KW]	***[rpm]***	***[KWh/gl]***	***[%]***
10	1467	8.703	22.460
15	1535	9.228	23.815
20	1609	10.309	26.603
25	1673	10.711	27.643
30	1743	10.974	28.320
35	1816	11.470	29.599
40	1900	12.107	31.244
45	1974	12.166	31.396
50	2033	12.359	31.895
55	2118	11.838	30.550
60	2184	11.713	30.228

In any hybrid vehicle, due to the limitations of the battery, it is never possible to absorb all the regenerative power. This is because this power is in the form of high current for a very short time (impulse power).The battery can take in only a certain amount of power in a given period of time. Similarly, the output power is also limited by the power electronics of the traction motor [10].

Generally, the variation in the state of charge (SOC) is limited to a certain range during the battery operation. This is because the battery charging efficiency is very poor at high SOC and the discharge efficiency is poor at very low state of charge as can be seen in Fig. 9. Also the deep charging or discharging affects the battery life and performance. Therefore, it is assumed that the battery SOC should be maintained between 30% and 70% throughout the simulation as this ensures optimal battery life [10].

In reality, the internal resistance of the battery would be different during the charge and the discharge cycle, and varies depending on the state of charge of the battery [11].

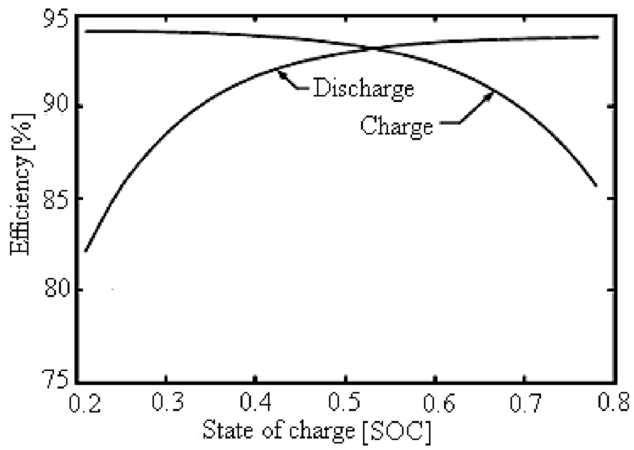

Fig. 9. Variation in charging and discharging efficiencies with state of charge [10].

In order to help with the simulation and analysis of the SHEV, certain typical driving schedule has been used. This driving schedule represents typical traffic environment for a particular range of time. The drive cycle is a plot of velocity and mechanical power demanded versus time. Same New European Driving Cycle (NEDC) shown in Fig. 10 was previously used for the on-off control strategy and reused now for the power split control strategy.

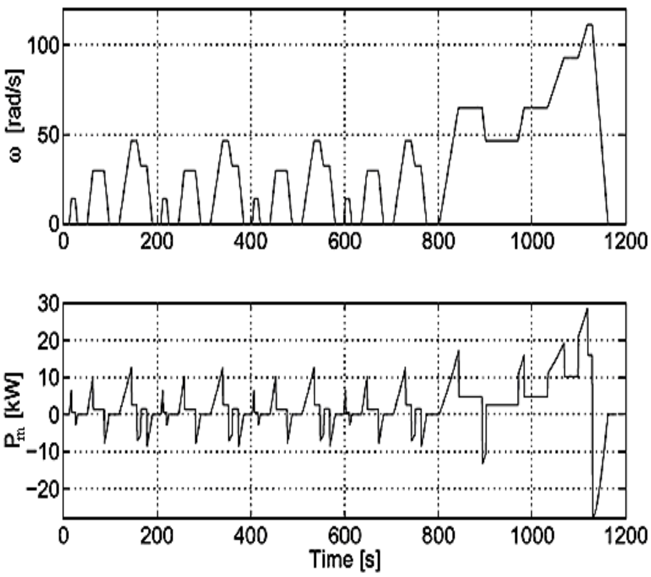

Fig. 10. Vehicle drive cycle [12].

As will be discussed later, the simulation is based on the electrical demanded power so equation (1) has been used to calculate the electrical power from the demanded mechanical power throughout the driving cycle.

$$P_e = P_m / \eta \quad (1)$$

Where: P_e = Electrical demanded power (kW)

P_m = Mechanical demanded Power (kW)

η = traction motor efficiency including power electronic losses (%).

Based on equation (1) the electrical demand power throughout the driving cycle has been calculated. Table II shows some of the calculated electrical power values.

TABLE II. ELECTRICAL POWER DEMAND VERSUS MECHANICAL POWER

Pm(kW)	ω (rad/sec)	T(Nm)	η (%)	Pe (kW)
6	10	600	0.625	9.6
-3	10	-300	0.5	-6
10	30	330	0.625	16
2	30	66	0.66	3
-8	30	-266	0.5	-16
12	45	266	0.625	19
4	40	100	0.66	7
-7	40	-175	0.6	-12
2	25	80	0.625	3.2
-9	25	-360	0.5	-18
17	65	261	0.66	26
5	65	77	0.714	7
-12	45	-266	0.625	-19
3	45	66	0.66	4.5

III. POWER SPLIT STRATEGY

This strategy is based on splitting the power demand between the engine/generator unit and the battery such that these power sources are operated at high efficiency operating points. These operating points are selected based on the efficiency map of these components. For the engine unit, a curve that connects the most efficient speed/torque operating points is defined as shown previously in Fig.1. This gives rang of powers which can be delivered by the engine when it is operated efficiently. Controlling the engine speed and torque to guarantee that the engine will operate at the desired power points is beyond the scope of this work [10].

Based on the status of the SOC, the power will be assigned to the engine/generator unit, to the battery, or to a combination of both. The engine will not be shut off under this strategy, it will be idle if no engine power is needed. This causes some extra fuel consumption, but there are advantages of this by limiting engine cycling on and off; moreover, the engine will be warm all the time which is better for emissions. The power to be charged or discharged from the battery at any moment will not exceed the maximum allowable value [10].

The Simulink file in Fig.11 shows the logic controller used for this strategy. By comparing the SOC to predetermined values the out power from engine/generator unit is obtained.

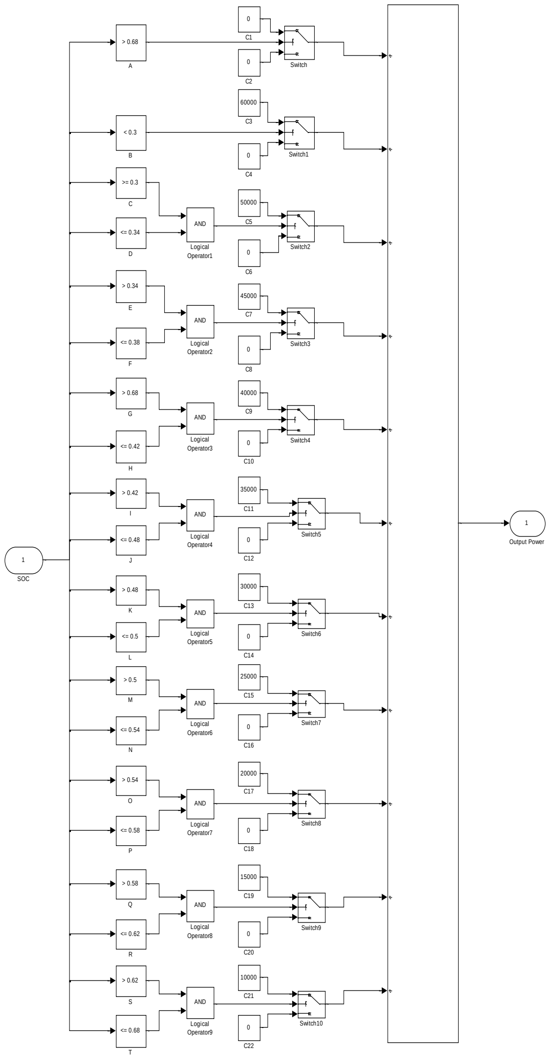

Fig. 11. Power split control subsystem.

For instance, if the SOC is less than 0.3, the engine/generator unit has to provide it is maximum power of 60kw and if it is greater than 0.68, then the engine should be put into an idle position giving zero power to the system.

When the SOC is between 0.5 and 0.54 then the engine/generator unit is assigned to produce a power of 25kW. Similarly, when it is between 0.54 and 0.58 then 20kw is derived to the system and so on.

It is important here to point out that to obtain more efficient power split control, this strategy should be based on both the SOC and the drive cycle requirements (e.g. power demanded, speed, etc.). However, for simplification purpose only SOC is considered.

The Simulink file in Fig.12 shows the Matlab/Simulink file for the overall system.

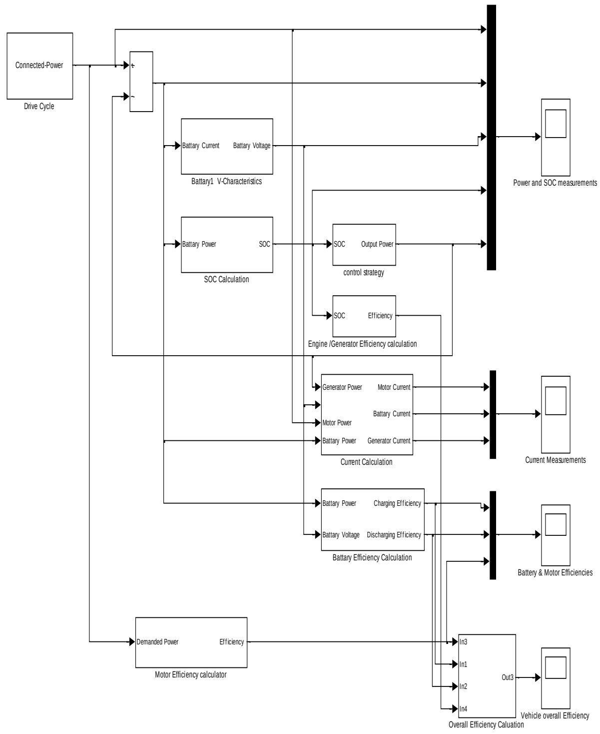

Fig. 12. Overall System For Power Split Control Strategy.

IV. RESULTS AND DISCUSSIONS

After the design had been completed, the vehicle was simulated for its performance over the NEDC of 1200 seconds for power split control strategy. Obtained results were compared to the performance of previous study about the on-off control strategy under same conditions.

As mentioned earlier, the power split strategy is based on the optimal operating line of the engine. It can be seen in Fig.13(c) that the engine runs at different power levels which constitute the optimal operating line. A difference in behaviour between the two strategies is that under the on-off strategy the generator power is either on or off while under the power strategy the generator power can come up at any time depending on the SOC and the power demanded as seen in Fig.13.

From Fig.13(d), the SOC of the battery is maintained so that the regenerative braking power can be absorbed by the battery as long as it is not in the form of impulse power as pointed out previously.

Fig.13 also shows a fast consumption of energy when the power demanded increases.

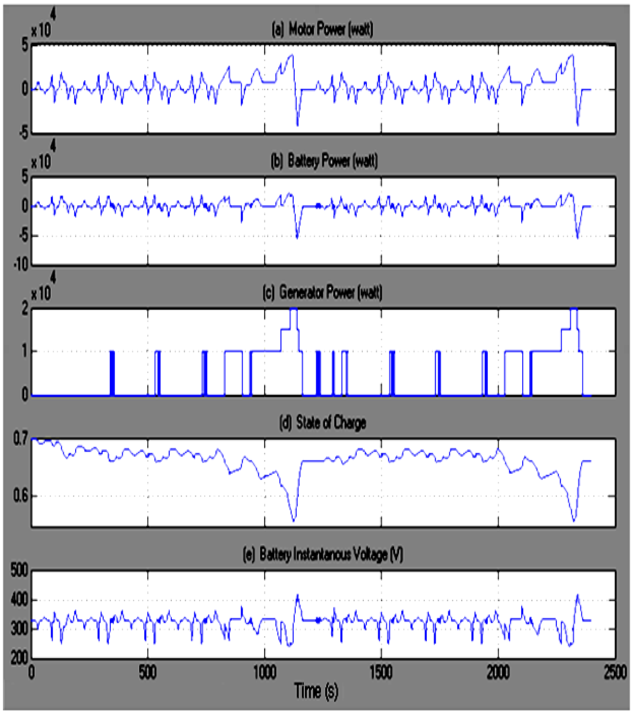

Fig. 13. (a) Motor electrical power (b) Battery power (c) Generatorpower (d) State of charge (e) Battery instantaneous voltage.

Fig.14 illustrates how the power split works in more detail. Three variables are shown in the figure: the motor current, the battery current and the generator current. All the modes of operation exist within a cycle using the power split strategy, as can be noticed from the current waveforms.

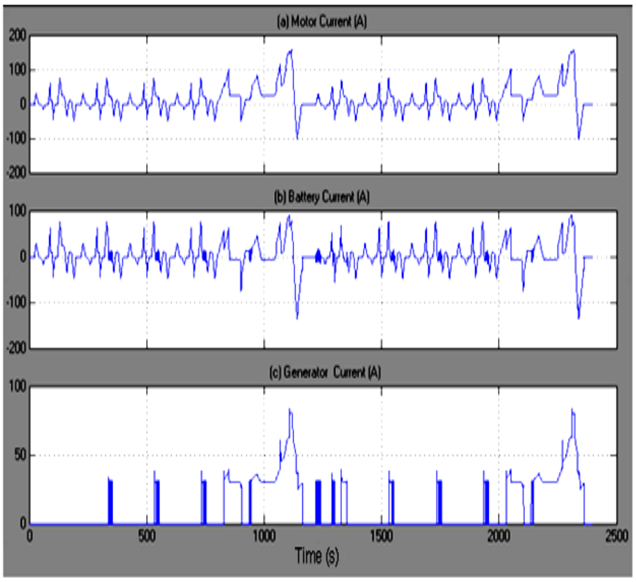

Fig. 14. (a) Motor current (b) Battery current (c) Generator current.

The overall efficiency has been achieved in the same way as in the on-off strategy. Firstly, the motor and battery charging and discharging efficiencies were simulated as shown in Fig.15 and then the average efficiency was plotted as shown in Fig.16. The overall efficiency of the vehicle under the power split strategy is 63.3% as seen in Fig.16. The overall vehicle efficiency in this case is reduced by 6.3% as the engine is running at different operating points with lower efficiency values.

Table III shows the overall efficiency over different initial SOC values for the power split control strategy compared to the on-off control strategy.

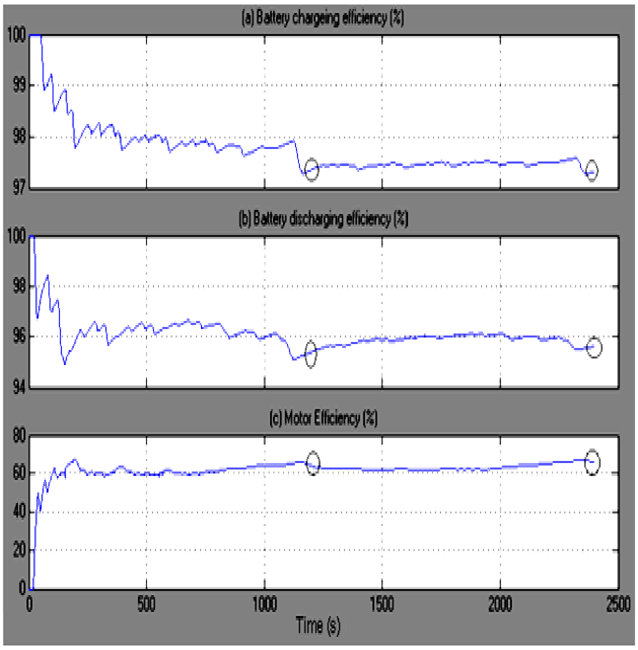

Fig. 15. (a) Battery charge efficiency (b) Battery discharge efficiency (c) Motor efficiency.

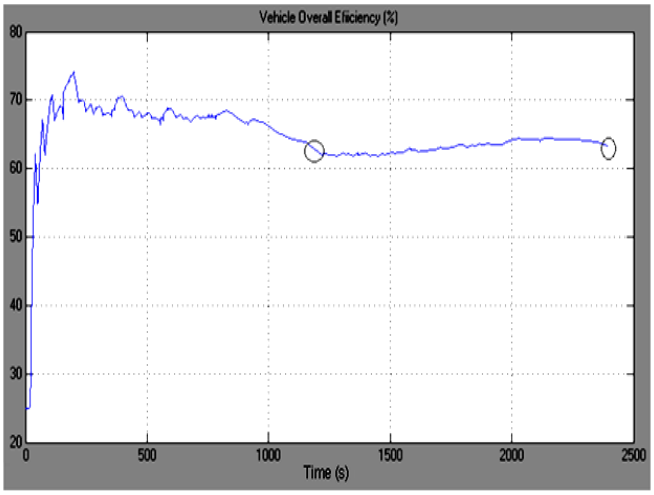

Fig. 16. Vehicle overall efficiency.

TABLE III. OVERALL EFFICIENCIES AGAINST SOC

On-off strategy			
SOC intial	0.3	0.5	0.7
η (%)	68.1	69.1	69.60
Power split strategy			
SOC intial	0.3	0.5	0.7
η (%)	60.4	61.1	63.3

It is clear that the higher the initial SOC the higher the efficiency because more initial energy is assumed to be already stored in the battery and hence less input energy is consumed leading to an increase in the overall efficiency.

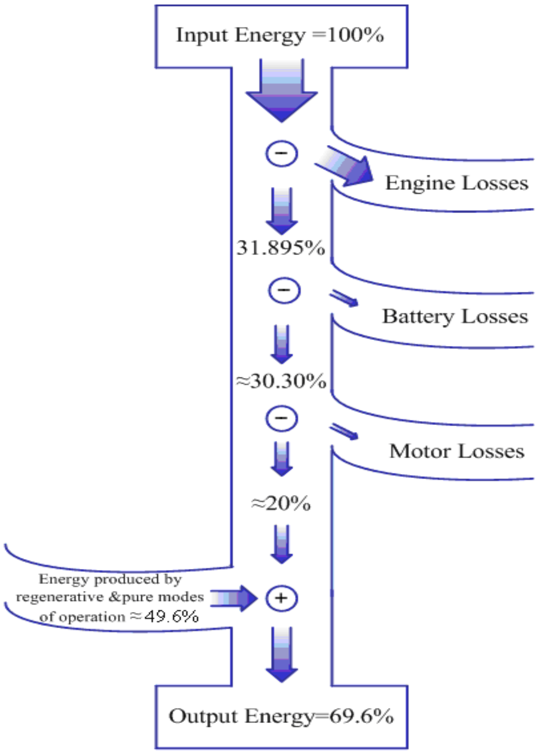

Fig. 17. Energy flow diagram under on-off control strategy with initial SOC=0.7

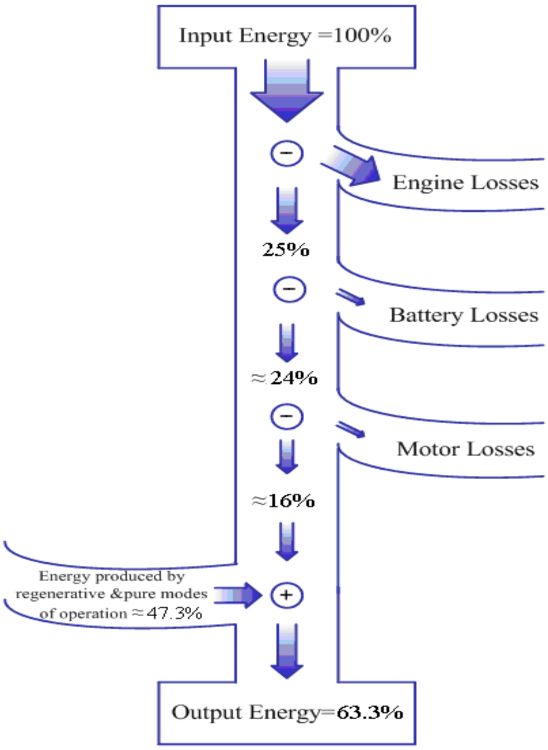

Fig. 18. Energy flow diagram under power split control strategy with initial SOC=0.7

Finally, Fig.17 and Fig.18 show a comparison between the two control strategy using Sankey diagrams which illustrate how the energy flows var for on-off and power split control strategies respectively. For instance, in Fig.17 (a) the initial SOC is assumed to be 0.7 and the input energy is 100%. Due to the engine/generator losses it is reduced to 31.895%. Having considered the battery losses the energy becomes 30.3% and when the motor Efficiency of 66% is included the remaining energy reaches as low as 20%. However, due to operating the vehicle under pure electric mode (i.e. engine is off) and that the driving cycle in Fig.10 shows considerable part of braking energy which is to be absorbed during the regenerative mode, the simulation shows that an increase of 49.6% of energy is achieved under these two modes of operation which results into an overall efficiency of 69.6%.

V. Conclusion

It is clear that when designing a series hybrid electrical vehicle, selecting a suitable size of the generator and storage devises are crucial. The overall efficiency of the vehicle is higher when the on-off strategy is used; while emissions are lower when the power split is applied. Therefore, choosing the most suitable control strategy is based on the industry requirements and the environment regulations. The performance of the overall system and each of its individual components could be predicted within a reasonable range using MATLAB/Simulink. Furthermore, computer simulation enables us to enhance the design prior to building actual prototypes, hence resulting in cost reduction. Finally, for more accurate results further testing is recommended to refine the utilized models of the vehicle components.

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