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The Effect of the Operating Point Choice On Fuel Economy in Series Hybrids

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Abstract

This paper investigates the effect of the choice of operating points for series hybrid configurations in power generation, especially for the case of heavy duty hybrid drive applications. Using the genetic algorithm to obtain the optimal operating points, we will show that the amount of fuel savings that can be achieved is substantial. Fuel mass is minimized, if one of the operating points is at the bsfc minimum and the other is at the low power end of the power range. The use of operating points above the bsfc minimum always results in bad fuel efficiency, if the average power corresponds to power that is below the bsfc minimum.

Keywords: operating points, series hybrid, bsfc curve, fuel mass consumption

1 Introduction

The question of optimally choosing operating points in series hybrid power generating equipment is a key to maximizing fuel efficiency [1]. Using a simple analytically tractable brake specific fuel consumption curve, one can investigate all possible choices of operating points that lead to optimal or close to optimal results. However, often what is needed is to find the optimum for bsfc curves that do not have a simple mathematical representation.

If energy storage capacity could be made available at no or low cost, one could run the ICE at an operating point that corresponds to the average required power, assumed this power is known a priori. In this case the storage device would handle the short term mismatch of power. The disadvantage of such a scheme is not only the required large storage capacity, but also the fact that this average power is likely to not correspond to the lowest achievable bsfc. Therefore the question of finding the optimal operating points for fuel consumption minimization arises. In our work we assume that cycling the engine between the optimal bsfc power and switching the engine off [3] is not a viable option as often is the case in large engines [1,2].

In this paper we therefore investigate the case of two and three different operating points for optimal overall fuel efficiency. The method employed uses the genetic algorithm to find the best set of operating points. This method can be applied even for bsfc curves that are analytically difficult to describe. Engine transients and their effect on fuel consumption are neglected and hence the provided study is applicable only for long term operation and a large storage capacity. Furthermore it is assumed that regardless of the choice of operating points, the series hybrid electric drive-train attached to the ICE-generator unit remains the same in all cases with efficiencies that do not depend on the operating points. Therefore this is not a comparison that addresses the problem of "if hybridization should be done", but it rather assumes that the decision of hybridization has been made. After that it is only a question of determining the correct operating point(s). This paper will not only show where the optimal two operating points are but also how much fuel can be saved.

2 Results

Tables 1 and 2 show the fuel consumption of a typical large hybrid drive system for the case of two and three operating points respectively. In the tables 1 and 2 all scenarios produce the same average power over the total run time, but yield totally different fuel consumption results as can be seen in the last entry of the tables. In both cases, the bsfc minimum occurs at 200KW, but in the two OP case the average power is 200KW while in the three OP case the average is 100KW, i.e. significantly below the optimal power point.

The analytical form for the bsfc curve used in tables 1 and 2 is given by:

$$Bsfc(P) = 190 + (0,01*(P-200)^2) \quad (1)$$

Table 1: Combinations of two operating points for an average power of 200 KW and the associated fuel mass consumption.

Power #1	128	277	259	158
Power #2	278,00	146,49	149,74	235,78
% time Power #1	0,52	0,41	0,46	0,46
% time Power #2	0,48	0,59	0,54	0,54
Average Power	200	200	200	200
Fuel Mass	49568,96	47208,19	44189,78	40911,83

Power #1	127	99	163	125
Power #2	219,41	212,48	208,12	203,95
% time Power #1	0,21	0,11	0,18	0,05
% time Power #2	0,79	0,89	0,82	0,95
Average Power	200	200	200	200
Fuel Mass	40073,93	39405,58	38514,24	38381,75

Power #1	227	249	204
Power #2	195,97	199,00	192,24
% time Power #1	0,13	0,02	0,66
% time Power #2	0,87	0,98	0,34
Average Power	200	200	200
Fuel Mass	38242,88	38121,52	38060,95

Table 2: Combinations of three operating points for an average power of 100 KW and the associated fuel mass consumption.

Power #1	188	132	157	64
Power #2	200,00	200,00	200,00	200,00
Power #3	91,99	95,00	94,99	90,97
% time Power #1	0,02	0,05	0,03	0,11
% time Power #2	0,03	0,03	0,03	0,11
% time Power #3	0,95	0,92	0,94	0,78
Average Power	100	100	100	100
Fuel Mass	28956,37	28941,03	28933,31	28736,84

Power #1	54	75	151	167
Power #2	200,00	200,00	200,00	200,00
Power #3	99,00	75,00	1,96	1,98
% time Power #1	0,09	0,2	0,02	0,03
% time Power #2	0,05	0,2	0,48	0,47
% time Power #3	0,86	0,6	0,5	0,5
Average Power	100	100	100	100
Fuel Mass	28721,09	28375,00	19456,86	19442,76

Power #1	220	210	195	188
Power #2	200,00	200,00	200,00	200,00
Power #3	1,96	1,96	2,00	1,92
% time Power #1	0,05	0,1	0,2	0,08
% time Power #2	0,44	0,39	0,3	0,42
% time Power #3	0,51	0,51	0,5	0,5
Average Power	100	100	100	100
Fuel Mass	19436,20	19413,20	19401,79	19398,32

Power #1	191	198	181
Power #2	200,00	200,00	200,00
Power #3	1,80	1,68	1,52
% time Power #1	0,1	0,42	0,04
% time Power #2	0,4	0,08	0,46
% time Power #3	0,5	0,5	0,5
Average Power	100	100	100
Fuel Mass	19369,02	19333,71	19325,53

What the above two tables indicate is that one pays a high penalty in normalized fuel consumption if one of the OP is far above the optimal associated power. Also, it can be seen that by choosing optimal OPs, fuel savings are typically around 30-35%. The assumed quadratic bsfc dependency is often a good approximation of the bsfc curve for a fairly large power interval around the bsfc minimum. Also note that the best results in fuel efficiency are obtained if at least one of the two OPs is near the bsfc minimum. In table 1 average power is twice as large as in table 2, and if one compares the best cases in both tables (rightmost columns) the fuel consumption in the 200KW case is a little less than twice the fuel consumption for the 100KW case. This is explained by the fact that the average and bsfc optimal power levels coincide in table 1, but not in table 2 for the 100KW case, where one is forced to operate the engine away from the optimal bsfc point.

Now, we use the actual bsfc curve of a 8.7liter V8 Cummins Diesel genset given in [5] and given in Figure 1 below. The data for power and bsfc is available only in the range between 80KW and 240KW. And therefore this is the range that we consider in our study. In this search for the optimal operating points the average power was chosen to be 140 KW. The results are similar as in the previous two tables: fuel consumption is minimized if one operating point is at the bsfc minimum, and the other is at the low power end, close to idle conditions. Of course this assumes that the average power is less than the power at the optimal bsfc point.

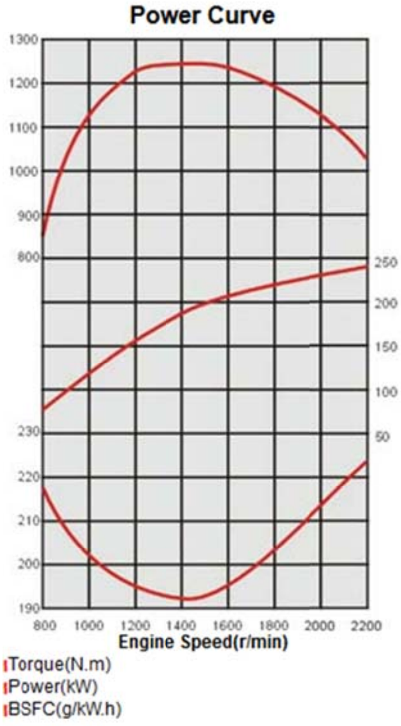

Figure1: Power curve for the Cummins 6L Series Diesel Engine model 6LTAA8.9-C325 [5]

In table 3, the genetic algorithm was used to determine fuel consumption and optimal operating points. In this case there is no clear winner, simply because the low power operating point could not be chosen arbitrarily small, simply because the engine data was available only between 80 KW and 240KW.

Table3: Combinations of two operating points for an average power of 140 KW and the associated fuel mass consumption.

Power #1	91	180	187	91
Power #2	187,08	101,57	94,84	172,67
% time Power #1	0,49	0,49	0,49	0,4
% time Power #2	0,51	0,51	0,51	0,6
Average Power	140	140	140	140
Fuel Mass	27977,068	27568,945	28137,271	27879,426

Power #1	100	94	93	220
Power #2	186,96	186,00	187,00	137,53
% time Power #1	0,54	0,5	0,5	0,03
% time Power #2	0,46	0,5	0,5	0,97
Average Power	140	140	140	140
Fuel Mass	27715,440	27892,500	28042,500	27623,050

3 Conclusions

This paper illustrates the amount of fuel savings in large series hybrids that are achievable using an optimal set of operating points. The method is based on the genetic algorithm to search for the optimal solution and is applicable regardless of the bsfc curve. An analytical analysis of this problem was very recently performed in [4]. In this work, mathematical conditions for fuel savings are provided, assuming the bsfc curves can be approximated or at least bounded by quadratic or linear relationships.

The amount of fuel savings relative to the case of non-ideal operating points or a fully modulated engine is shown to be significant. The optimum is achieved if one operating point is at the bsfc minimum and the other near idle conditions. If an operating point that corresponds to power larger than at the bsfc minimum, the fuel consumption is especially high. Even though in this paper all bsfc curves are quasi-quadratic, the proposed method can be used to find the optimal two OP for any bsfc curve (even without regard to differentiability or continuity of the bsfc curve). The proposed method can be implemented for Diesels as well as other engine types, such as natural gas.

Some of the future work therefore needs to address the case when the average power is higher than the power at the bsfc minimum. The question then is: "Should one still cycle the engine between two operating points or is it advantageous if the engine runs the entire time at average power?" Of course since instantaneous power and the power at the two operating points are very different, a large energy storage capacity is required. Therefore the utility of multiple operating points also should be addressed in order to reduce the instantaneous power mismatch and hence storage requirements.

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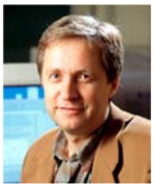

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