I. COMPONENTS & SYSTEMS

I.A. 1000193.00 PHEV Advanced Series Gen-set Development/Demonstration Activity

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I.A.1. Abstract

Objective

- The objective of this project is to integrate ORNL advancements in vehicle technologies to properly design, size and simulate an advanced series hybrid (HEV/PHEV) gen-set. This project integrates two of the core strengths of ORNL – advanced combustion with emissions after-treatment technologies and advanced power electronics and electric machines. The goal is to design a “best effort” gen-set drawing on advanced, high risk technologies currently under development in each respective program activity at ORNL or by their partners.

Approach

- Perform a literature search of existing gen-set technologies
- Create a decision matrix to identify suitable technologies and application
- Down-select engine/fuel, generator motor and power electronics technologies
- Perform simulation study to evaluate benefits of various engine/fuel –traction motor combination

Major Accomplishments

- The literature searched was completed. It highlights the recent renewed interest in APUs for PHEV applications
- Relevant engine and electric machine technologies were listed and weighted in a decision matrix to down select which ones should be considered in the simulation study
- A simulation study was performed to quantify the efficiency of various APU combinations at the vehicle level. It points towards alternative fuel and advanced combustion for engine technologies and induction machines for generators.
- Engine and motor manufacturing partners were contacted regarding opportunities for simulation and hardware evaluation

Future Activities

- Pursue partners to proceed with hardware integration of both IC engine and electric machine
- Refine simulation based on actual data from potential partners
- Finalize component selection and sourcing based on technical merit and partnerships

I.A.2. Technical Discussion

Background

Series HEV and PHEVs present a unique configuration where a gen-set (engine-generator set, also referred to as Auxiliary Power Units (APU)) is used to recharge the Energy Storage System (ESS) and can be decoupled from the propulsion drivetrain, operating the gen-set for optimum energy efficiency. As such, gen-sets provide unique opportunities for component sizing and combustion operating regimes. Decoupling the IC engine from the variable load requirements of typical vehicle drive cycle, allows for the consideration/optimization of a wide range of technologies and key components: internal combustion engine, exhaust after-treatment, electric machine and power electronics.

Introduction

This project will draw from the extensive experience in power electronics and electric machinery from the Power Electronics and Electrical Power Systems Research Center as well as the broad knowledge in advanced combustion and emissions after-treatment through the Fuels, Engines, and Emissions Research Center, both centers being part of transportation section of ORNL. The emphasis will be placed on technologies currently under development in each respective center. It will attempt to focus on a modular gen-set that could have multiple applications outside of a vehicle, which would reduce cost based on high volume production.

This project will investigate several advanced technologies for each key component considering several aspects in its selection process such as efficiency, cost, strategic benefits (rare earth / non rare earth) and complementarity of the engine and motor technology.

Approach

A literature search will be performed to obtain the state of the art technology status for gen-sets aimed at PHEV applications.

A decision matrix will be developed to list various technology candidates and requirements both on the combustion engine side and the electric machinery side. Weighting factors will be applied to emphasize the key features for our PHEV application. The resulting scores will be used to down-select a limited number of technologies/ components to be evaluated via simulation.

Autonomie models for each gen-set component will be developed and evaluated at the vehicle level to quantify resulting gen-set combination efficiency. That will provide an additional selection criterion when recommending which technology to proceed with during the hardware demonstration phase of this project.

Results

Literature search

Gen-sets have seen a renewed interest recently, especially in the transportation sector and Electric Range Extended Vehicles (EREV) in particular. This is due to the high costs of Energy Storage Systems (ESS) and the “range anxiety” syndrome of Battery Electric Vehicles (BEV) owners who fear that their vehicle does not have enough energy stored in its ESS to complete some out-of-the-ordinary commutes. Yet adding battery capacity is not always a feasible option because of cost and weight. Therefore, using a small gen-set to recharge the battery offers a viable alternative to a larger, heavier and costly ESS, while potentially exceeding customer expectations with regards to vehicle range. Figure 1 shows a graphical representation which highlights the benefits of a gen-set architecture: reducing BEV ESS size from 100mile range to 40 mile range will reduce the vehicle cost dramatically. Some of those savings can be invested in an APU which can increase the EREV vehicle range past the original BEV 100mile range. This is particularly true for todays' ESS costs (red trace) but will remain true with 2020 target costs for batteries (blue trace).

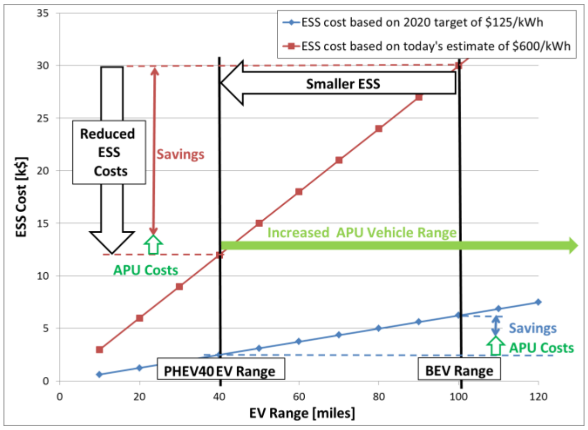

Figure 1. Trade-off between APU costs and ESS size depending on range and ESS cost

Most APUs identified during that search use a conventional gasoline 4-stroke small displacement (less than 1.2l) engine whose power output is less than 35kW. See Table 1 for results. There are some variations on the number of cylinders (from one to three) and configurations (V-twin and in-line) but the technology level remains low: all engines are port fuel injected. That choice of technology indicates that the emphasis has so far been placed on cost rather than efficiency, even though no paper proposes any cost figure for their APU to confirm the affordability of their product.

Table 1. Non-exhaustive list of APU

	Power	**Technology**	**Displacement**	**Cylinder**	**Generator**
Lotus	35kW	4 stroke, PFI	1200cc	3	Not specified
FEV-Pierburg	30kW	4 stroke, PFI	800cc	2	Permanent magnet
Mahle	30kW	4 stroke, PFI	900cc	2	Axial flux generator
Getrag	14kW	4 stroke, PFI	1000cc	3	Not specified
Polaris	22kW	4 stroke, PFI	325cc	1	Not specified
AVL	15kW	Wankel	254cc	1	Permanent magnet
FEV	18kW	Wankel	295cc	1	Not specified
AIXRO	15kW	Wankel	294cc	1	Permanent magnet

As shown in table 1, Wankel engines are being investigated too because of their high power density though emissions can be a concern.

Most engines run on gasoline (except for the Lotus APU which is said to be capable of ethanol and methanol). Fuels do not seem to have been investigated or optimized for those APUs.

There are some more advanced engine concepts that are advertised in the literature, such as Opposed Piston Opposed Cylinder (OPOC) engines, as well as turbines, but it is difficult to gauge their readiness because of the lack of tangible results.

It has to be noted that all of those APUs are concepts or technology demonstrators at best, but none have made it to production.

The generator technology is, most of the time, not specified in the papers. When it is, it is said to be permanent magnet machines, but no additional details are provided (such as interior magnet vs. exterior magnet design). The inverter technology and control methodology are never mentioned.

The main takeaways from that literature search are that there is a definite renewed interest for APUs for range extender applications but that the emphasis is on small displacement low technology (presumably low cost) engines. Engine efficiency and electric machine technology do not seem to be high priority factors.

Technology down-selection

For the purpose of this project, we want to emphasize technologies that ORNL's Fuel Engines and Emissions Research Center as well as Power electronics and Electric Machinery Research Centers have prior experience with. Therefore turbines, OPOC engines and Wankel engines will not be considered.

A matrix was created to prioritize engine technologies identified so far. Each engine type got assigned score with respect to four criteria: advanced technology, suitability of the technology for an APU application, alignment with prior and current engine research projects at ORNL, and cost (See table 2). The final overall score confirmed some of the down selection performed so far. Wankel engines and turbines can be ruled out. The study should focus on advanced combustion and alternative fuels.

Table 2. Engine selection matrix.

Criteria	Technology Prospect	Suitability for APU application	Alignment with ORNL Engine programs	Affordability	Total
Gasoline PFI	1	8	6	10	**25**
Gasoline GDI	5	8	8	5	**26**
Gasoline HCCI	9	10	10	4	**33**
Diesel	4	6	8	3	**21**
PCCI	7	10	10	3	**30**
RCCI	10	10	10	2	**32**
Ethanol PFI	4	8	8	10	**30**
Wankel	5	9	1	6	**21**
Turbine	8	5	1	1	**15**

The simulation study will focus its investigation on the following engine types:

- Gasoline Port Fuel Injected (PFI)
- Gasoline Stoichiometric Direct Injection (GDI)
- Ethanol Direct Injection (EDI)
- Gasoline Homogenous Charge Compression Ignition (HCCI)
- Diesel
- Reactivity Controlled Compression Ignition (RCCI)

No available dataset was complete enough to build reliable models for ethanol PFI and PCCI engine. PCCI technology characterization performed at ORNL focused on 5 modal test points that are not sufficient to build a look up table. Still that combustion work showed that PCCI efficiency is very close to conventional direct injection Diesel but can reduce NOx and PM emissions.

For electric machinery, fewer technologies are available, so a selection matrix was not necessary. The following four types will be simulated:

- Interior Permanent Magnet machine
- Field Wound machine
- Induction machine
- Switched reluctance machine

Simulation Study

If not already in existence, new Autonomie models were created for engines and electric machines identified in the previous phase of the project. Those models are based on steady state characterizations performed by FEERC and PEEMRC during previously completed DOE projects (see Figure 2 and 3 for examples of engine and e-machine efficiency tables).

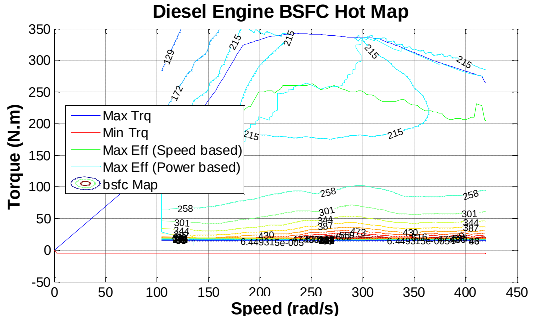

Figure 2. BSFC table for diesel engine.

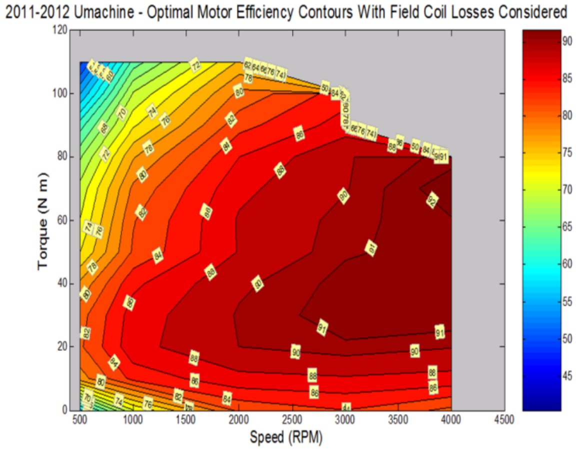

Figure 3. Efficiency characteristic of ORNL Novel Flux Coupling machine without Permanent Magnets.

The gen-set efficiency is evaluated in the context of a series PHEV the size of a Nissan Leaf over three different drive-cycles (UDDS, HWFET and US06). The gen-set is managed by the hybrid powertrain supervisory controller. It implements thermostatic control strategies: the engine can only be on or off based on the battery state of charge, and when activated, the engine operates at its peak efficiency conditions. All drive cycles are performed when the vehicle is in Charge

Sustaining mode so that the gen-set comes on and off regularly. By nature, thermostatic control is not charge balanced, so a correction factor is applied during post processing to compensate for state of charge discrepancies.

The size of electric machines and engines was standardized to equate 30kW, which reflects the average size of APUs identified in the literature search. Preliminary simulations were performed to confirm that this power level is suitable to sustain vehicle operation. Figure 2 shows how the ESS state of charge (green trace) can be maintained on a US06 cycle while in charge sustaining mode, with the engine generating 25kW of mechanical power, even though power demands for traction purposes might be as high as 60kW. Table 3 shows engine power levels for steady state speed operation and various road grades while in charge sustaining mode. A steady 30kW APU output is sufficient to maintain ESS energy levels while driving 70mph on a flat surface or 60mph on a 2% grade.

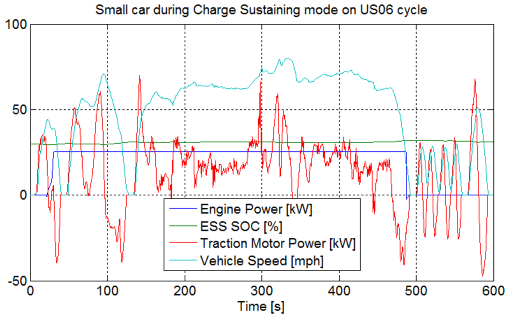

Figure 4. Series PHEV power requirements on US06 cycle while in charge sustaining mode

Table 3. Steady state engine power requirements in charge sustaining mode

Vehicle speed [mph]	Grade [%]	Engine Power [kW]
60	0	18.7
70	0	26.0
80	0	36.3
60	2	28.9
60	4	39.2
60	6	50.0

All gen-set combinations of the six engine technologies and 4 electric machine technologies were tested over the three drive cycles (UDDS, HWFET and US06). Fuel economy results were normalized by converting them to gasoline equivalent and charge balancing the ESS state of charge over each cycle in order to compare all fuels (gasoline, ethanol and diesel) without biasing results based on fuel energy content or hybrid operation.

For a given e-machine technology, HCCI proved to be the most efficient ahead of RCCI, Diesel, ethanol, PFI gasoline and GDI. It has to be noted that the PFI engine is an Atkinson cycle engine representative of the Prius engine, hence its high fuel economy. See Figure 5 for engine technology comparison when generator is an interior permanent magnet machine.

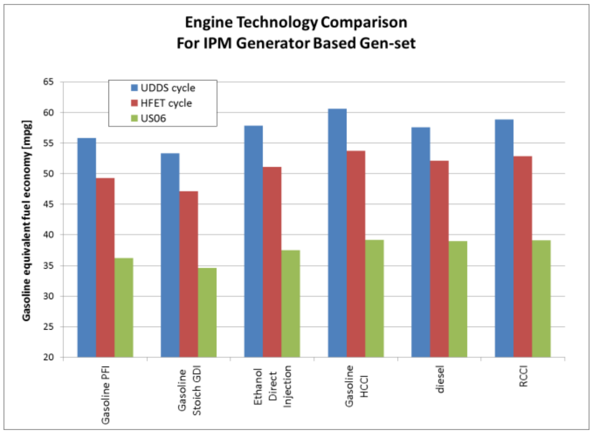

Figure 5. Comparison of engine technologies

For a given engine technology, interior permanent magnet generator demonstrated the most fuel economy ahead of induction machine and wound field and switched reluctance machines. See Figure 6 for generator technology comparison when engine is a PFI gasoline engine.

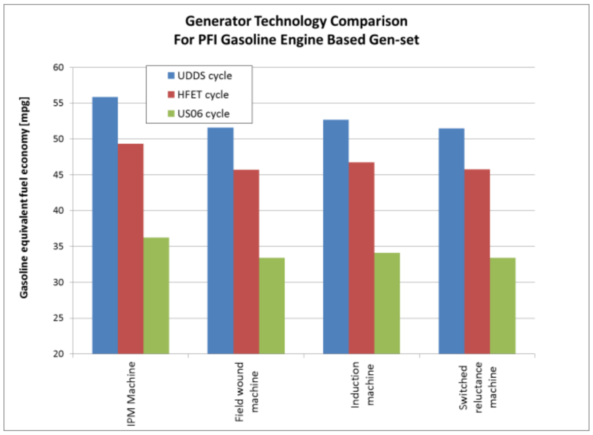

Figure 6. Comparison of electric machine technologies

Based on those results, the project should investigate alternative fuels such as ethanol and advanced combustion, such as HCCI for engine technology, and induction machines for generators. Other technologies demonstrated high efficiency such as Diesel and RCCI engines, or permanent magnet generators. Those technologies are not preferred for this application because of other criteria such as after-treatment requirements for diesel, dual fuel and associated complexity for RCCI, and use of rare earth materials for permanent magnet machines.

Conclusions

A literature search showed that there is a renewed interest for APUs for range extender applications. But cost seems to be more of a factor than efficiency when it comes to engine technology, selection since most engines are gasoline port fuel injected. Generator technology is not often described but permanent magnet machines are most often used. Engine and generator technologies were down selected to six engine types and four generator types to conduct a simulation study that yielded vehicle fuel economy for various engine-generator combinations. Out of those technologies, alternative fuels such as ethanol and advanced combustion such as HCCI are the most promising on the engine side, and induction type machines offer the best non-rare earth efficiency for generators. Therefore the project should focus on those technologies to proceed with a hardware phase.