Robust Control Architecture for a Reformer Based PEM APU System

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ABSTRACT

Battelle has built multiple auxiliary power generators using liquid logistic fuels that tightly couple fuel cell and fuel processing systems, providing new control challenges. Acting as an auxiliary power supply places difficult requirements for load following and transients. Additional challenges arise from the differing time constraints of the fuel processor and fuel cell systems and the need to maintain water balance. A novel method of controlling the system has been formulated and applied, providing pushbutton start capabilities. The control system has proven to be robust and easily adaptable to system design and operating parameter changes. In addition to control concerns, the requirements for vehicle integration and desulphurization have been investigated.

INTRODUCTION

The Battelle Advanced Power Generator (APG) uses logistic liquid fuels and generates electrical power from these fuels through the use of a fuel processor and fuel cell. Five systems have been built and demonstrated operating on synthetic JP-8 (S-8) and desulphurized JP-8, producing net output power in the range of 2 to 5 kilowatts. Two systems using sulfur bearing JP-8 are being concurrently designed and built for integration later in 2009.

Fuel processing from logistic fuel to hydrogen is accomplished with steam reforming and for JP-8, hydrodesulfurization. The core reforming process is accomplished in micro-channel reactors. The use of micro-channel technology enables the fuel processor to be much smaller and lighter than similarly sized systems and to respond more quickly to load changes. Micro-channel response is rapid; but, compared to the speed at which transients can occur on the electrical load, the fuel processor is still slow. The control system developed for the APG decouples the thermal transients from the load transients, providing fast, stable response to load changes. A provisional patent has been filed on the novel aspects of the load following control system.

System Design

A system block diagram is provided in Figure 1. Air, fuel, and water are input into the reformer. The water is vaporized into steam and then fuel is added to the steam. The fuel and steam mixture passes through the reforming reactor panels and is converted to reformate consisting primarily of H_2, H_2O, CH_4, CO_2, and CO. A palladium alloy membrane separator extracts most of the hydrogen for use with the fuel cell. The remaining hydrogen and other gases are directed to the combustor of the reformer to provide the heat for the endothermic reforming reaction. Maintaining the proper amount of returned hydrogen is critical to the thermodynamic stability of the system. Too much hydrogen returned causes combustion temperatures to exceed material limits. Too little hydrogen returned to the combustor causes the reformation reaction to be retarded. The portion of hydrogen that permeates to the fuel cell combines with oxygen from air, generating an electric current. Fuel cell voltage is unregulated and varies by a factor of approximately two from zero load to maximum load. Battelle's APG systems include a current-mode, custom designed power management module (PMM) to couple the fuel cell to a battery or other energy storage device that delivers electricity to the load.

The system is divided up into subsystems called line replaceable units (LRU). Each LRU provides a specific function (e.g. fuel delivery) and includes the necessary hardware, sensors and controls to manage and provide the specific function. The system is divided into seven LRUs each managing different parts of the system: air, cooling, fuel, fuel cell, fuel processor, power management and water. Because each LRU is largely self-contained, the system can be distributed throughout a vehicle when used as an auxiliary power generator or packaged together in a single device. Communication among LRUs is via controller area network (CAN) with the fuel processor LRU having the lead role.

Water management is an important aspect of making a steam reforming system viable for clients unable to supply water for the operation of the generators. The Battelle APG has been shown to have positive water balance (net producer of water). This accomplishment is primarily a function of system design through its water recovery subsystem, and is accomplished by the control of the fuel processing and cooling subsystems.

Control Hardware Design

Battelle's early APG systems were based on a central control assembly. Experience has shown that independent control for each LRU offers a number of benefits. Each LRU contains its own electronic control unit (ECU) that communicates with the other ECUs via CAN. Although distributed control increases the number of circuit card assemblies required, each ECU is simpler reducing the total integration time while increasing reliability. Distributed control also allows incremental improvements to be made to the design of each LRU, which are transparent to all but the ECU and LRU being modified. Each ECU addresses only a few inputs and outputs, allowing faster scan times with low cost microcontrollers.

Control Software Design

The software for the control system includes a multilevel state based structure and a control algorithm associated with the primary run state that allows for a robust, load following implementation. The state system will be presented first, with the load following second.

In the multilevel state table, system operation is defined by the value of a major and minor state variable. Each state pair has an entry and exit condition along with an exit state. The state cannot be entered unless the entrance conditions are satisfied, and a state will continue to execute until a set of exit conditions is met. Once the exit conditions are met the state changes to that of the exit state. Depending upon decisions made during the state's execution, the exit state may change, and thus the state table does not need to be executed sequentially. The major states describe overall operating status, such as pre-heat, reformer start, hot idle, fuel cell start, load following, and shutdown. The minor state represents a subset of the operating status. For example, the fuel cell start major state includes a minor state – "ramp fuel flow" to achieve hydrogen production. The entrance conditions for the ramp fuel flow minor state would be the verification of proper combustion ignition. During execution of the state the fuel flow set-point would be raised. The exit condition would then be verification that fuel flow has reached the set-point. The multilevel state table enables a simple description of the flow of the system to and from various operating conditions. The state transitions are critical to protecting the system from improper and unsafe operation. When both entrance and exit conditions are used, the system is protected from single code errors and momentary excursions in sensor readings. Table 1 lists the major states and includes example minor states to illustrate state progression.

PEM Fuel cells typically have a minimum operating load to maintain proper humidification and generally prefer to operate at 25% capacity or above. The hot-idle state addresses this issue. Instead of exactly matching the requested electrical load, for small loads, or no load situations, the system will enter the hot idle state. In this state the batteries supply the energy to the load. The fuel consumption is reduced to a minimum value to maintain the reformer at temperature: the fuel cell is shut off completely. Once the batteries have been depleted to a predefined level, the hydrogen production will ramp up and the fuel cell will be run at an appropriate level to recharge the batteries.

The primary operating state is load following. This state is achieved when the load on the APG exceeds the minimum recommended operating load for the fuel cell. Within this state, a specific control algorithm was created to respond quickly to load changes, while still maintaining the thermodynamic balance of the system. The load transients are fast: a compressor powered by the APG could instantly draw several kilowatts of power. Any fuel cell system will need reserve energy to slow the transients applied to the fuel cell and reformer to a rate that is manageable. The quicker the APG, fuel processor, and fuel cell can ramp their output, the smaller amount of reserve energy required, reducing system size and cost.

The Hydrogenics HyPM8 PEM fuel cell used in the most recent APG can ramp over its entire power range from 0 to 8.5KW in less than 12 seconds if adequate hydrogen is available. However, changes in hydrogen flow require changes in fuel, water, and air flows to the reformer. To assure safe and reliable operation, these changes must be synchronized with water flow leading fuel flow increases and lagging fuel flow decreases. Considering the lags in pump and flow meter response, we have found that a ramp rate of approximately 35 watts per second is reasonable. The result is a 1KW ramp in approximately 30 seconds. The rate is less than ideal, but manageable with a pair of standard automotive batteries as energy storage. In an effort to avoid slowing response even more, the control system must not introduce any additional lags or rate limits to the system operation.

The fuel processing system is highly non-linear in response and operation. To optimize control, other authors have typically developed a dynamic model of the system and built linearizing observers using state feedback [1,2]. Such systems often attempt to estimate the composition of the reformate species to properly observe and control the reaction. These systems are complex to develop requiring great effort to derive a system model and control system, in addition to the time for testing and verification. The Battelle developed control system for the APG uses a classical control approach, which does not require a system model, can be easily transferred to other systems and is straightforward to tune. The control system is also designed to work towards goals on several of the process variables, effectively optimizing efficiency at each operating point without the need for a complex efficiency map.

The load following control algorithm works using two proportional, integral, derivative (PID), algorithms and a feed forward algorithm as shown in Figure 2. The outermost algorithm takes a load estimate and multiplies it by a variable feed forward gain to set the amount of fuel flow. The coupling of the fuel flow directly to the load value allows the control system to respond to transients without any lag. Due to the nonlinear nature of fuel flow to power, a constant feed forward gain does not provide acceptable results. The implemented control system effectively linearizes about a point, and responds to transients according to the linearized value. The result is a fuel flow set close to the actually required value, but with measureable deviation. To obtain the necessary value, the feed forward gain is adjusted to match the system output to the load.

The functionality of this algorithm has been further adjusted using a state of charge algorithm that works to properly maintain the energy storage device. For the present systems, lead acid batteries are used, but in the future more exotic battery chemistries or ultra capacitors could be considered. Therefore, energy storage charging and discharging needs to be monitored and controlled. The control algorithm achieves this by using a state of charge estimate to adjust the feed forward gain used for the fuel flow setting. By increasing the gain, more fuel and thus more energy will be put into the batteries (or less will be taken). Thus, the battery charging profile can be controlled by adjusting the gain of the feed forward algorithm. The present system using lead acid batteries float-charges them to 26.3 volts while previous systems have used 24.5 volts.

When the fuel flow is adjusted by the feed forward control algorithm, the permeate pressure is the first affected variable on the fuel processor. A rise in fuel flow will increase the hydrogen partial pressure raising the permeate pressure. The permeate pressure can then be lowered by increasing the hydrogen consumption of the fuel cell. Thus, a process variable can be obtained for estimating the percent of hydrogen consumed by the fuel cell and that which is returned to the combustor. To maintain a proper combustion temperature the ratio of the hydrogen combusted to that which is sent to the fuel cell must be controlled. This control is achieved by adjusting the fuel cell current to maintain a permeate pressure according to a set-point. Therefore, if the permeate pressure is increasing, signifying a net excess of hydrogen being returned to the combustor, the fuel cell current will increase, raising the hydrogen flow going to the fuel cell and reducing the permeate pressure. The control algorithm is executed by a PID algorithm shown in Figure 2 as PID^2.

Due to the system non-linearity with respect to efficiency, the permeate pressure maintained will need to be different for various operating points. In addition, the time variant nature of system performance with respect to catalyst activity, fuel cell lifetime, and other factors, requires that the control system be adaptable to these changes without changing the code base. To accommodate these requirements, the permeate pressure set-point is controlled by a cascaded PID algorithm whose process variable is the combustion temperature. This PID algorithm is represented as PID^1 in Figure 2. The arrangement forms a cascaded control algorithm in which the set-point of one control algorithm (permeate pressure) is controlled by the output of the second control algorithm (combustion temperature). The set-point for the combustion temperature control algorithm is held constant. The complete operation of the control algorithm is that an increase in fuel flow will cause the permeate pressure to rise, forcing the fuel cell to increase its current draw, lowering the permeate pressure back to the set-point. The reformer would then be put into a new operating state, dictating a different proportion of returned hydrogen to the combustor. If the operating state requires more hydrogen to be combusted, the combustion temperature will fall. The decrease in temperature will cause the permeate pressure set-point to be raised, the fuel cell will draw less current, and more hydrogen will be returned. The returned hydrogen will then increase the combustion temperature to the constant set-point.

The use of a cascaded control algorithm allows for the separation of time constraints between the permeate pressure and system temperature which is critical to obtaining satisfactory transient response times. The permeate pressure control algorithm, which dictates the current production, can be tuned to operate as fast as hydrogen is produced. The combustion temperature control algorithm, which has long time constraints several times greater than the permeate pressure can be tuned to respond slowly, so as to not generate great temperature swings and be immune to electrical noise on the thermocouple measurement. Since the relationship between the process variable and output is observable under manual operation, the tuning of such control algorithms can be performed using the actual hardware, simplifying implementation across systems.

The control algorithm in its entirety is capable of responding to transients as fast as the mechanical devices allow, which presently is rate limited by liquid flow measurement. The slow and fast dynamics are separated through the use of cascaded controls, and by using a feed forward control algorithm the fuel input is tied directly to the load requirement. Through this arrangement, the system can increase fuel as soon as the load is detected, draw hydrogen when it is available, and correct for system non-linearity as the combustion temperature changes. The result is a system that is easily transferred between hardware implementation and robust with system state while still providing excellent performance. Results of a system run are included as Figure 3 and Figure 4. In Figure 3, a long duration run powering a refrigerator and several other loads is shown. A more detailed view of a portion of that run is shown in Figure 4.

Vehicle Integration

The APG has been designed to integrate with the electrical systems on vehicles or operate in a stand-alone fashion. The APG can be turned on and off via a single switch, initiating startup and shutdown. If more information is necessary or tighter integration with the vehicle systems is required, the system can receive commands and transmit data through a CAN interface.

For the stand-alone APG systems, the electrical power distribution is brought to NATO style connectors, which supply inverters for demonstration purposes. For an on vehicle system, the generator would need to interface with the alternator or other electrical power generation equipment. The APG would use the onboard vehicle batteries for energy storage and act as a battery maintainer. With the vehicle engine off and the APG operating in a hot idle mode, eventually electrical load will drag the battery voltage down to a level where charging is necessary. When the state of charge of the batteries has been determined by the APG to be below the acceptable level via a low battery bus voltage, the system will exit hot idle and begin producing power. While producing power, the APG will both supply the external load and recharge the batteries. When the batteries are fully charged, depending upon the amount of load present, the APG will stay on either supplying the load, or return to the hot idle condition. This functionality has been demonstrated on standalone systems. When the vehicle engine is on and the alternator is supplying power, the APG will default to the hot idle mode due to high battery bus voltage, unless the alternator cannot supply the necessary current and allows the bus voltage to drop. When this occurs, the APG will detect the decrease in voltage and exit hot idle, supplying power to the vehicle power bus. Through being cognizant of the current from the battery and the load current, the system will run until the load is no longer exceeding the capabilities of the alternator and then return to hot idle.

Desulphurization Integration

The full JP-8 APG system under development uses a hydrodesulphurization (HDS) system to remove sulfur from the feedstock prior to reformation. The addition adds intermediate steps to the control system, the most interesting of which is the requirement to deliver reformate to the HDS reactor at a specified pressure. The effect is to reduce the turn down ratio of the system while HDS is operating. To provide a more suitable turn down, the HDS reactor will not be operated at all times reformation is taking place. A cleaned diesel storage tank will be provided, and excess fuel will be desulphurized when the system state permits. When the clean fuel tank is low, the system will be brought into a state where desulfurization takes place. Additional control hardware for HDS will be necessary, and provided through the inclusion of a second fuel ECU identical to the first, and an additional ECU serving new hardware required for desulfurization. The rest of the control system will remain the same. By reducing the electronics and software changes required to implement the HDS through building onto what is already completed, costs and schedule can be reduced. Such a system is being designed and fabricated later in 2009.

Conclusion

A robust control system has been developed that provides push button start functionality and fast transient response while managing the components of the system. The combination of hardware and software to implement control algorithms has provided a cost and time effective solution that is easily transferred to new system designs. The novel load following architecture reduces control complexity simplifying implementation, allowing resources to be focused on other design improvements.

Nomenclature

APG	Advanced Power Generator
CAN	Controller Area Network
ECU	Electronic Control Unit
HDS	Hydrodesulphurization
LRU	Line Replaceable Unit
PEM	Polymer Electrolyte Membrane
PERMEATE	Gas separated by membrane separator
PID	Proportional Integral Derivative
PMM	Power Management Module
REFORMATE	Gas that has passed through reformer
RETENTATE	Gas retained by membrane separator

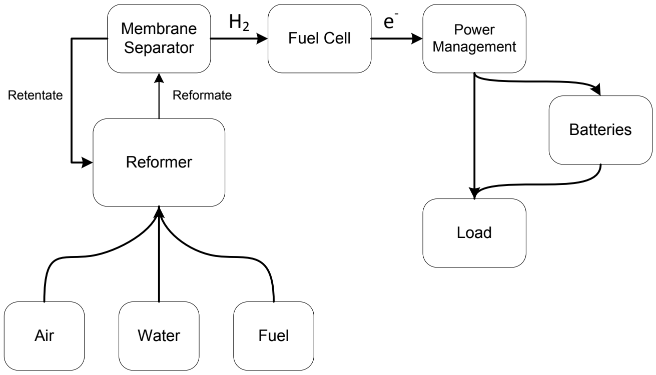

Figure 1. Air, Fuel, and, Water are input into the reformer.

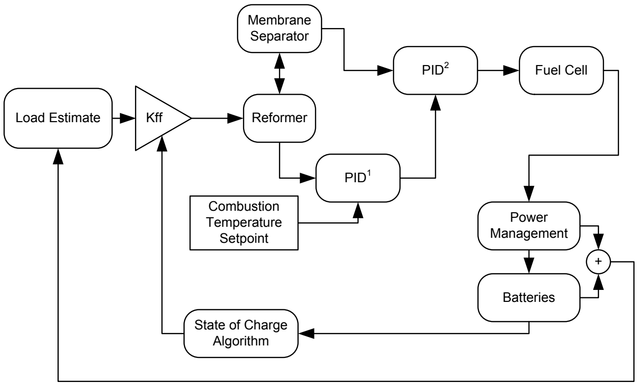

Figure 2. PID and feed forward algorithms.

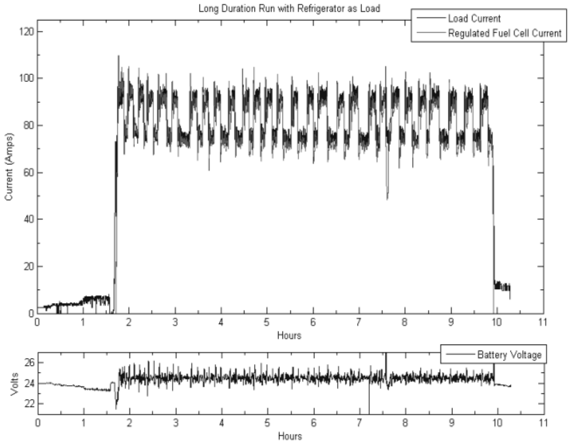

Figure 3. Long duration run powering a refrigerator and several other loads

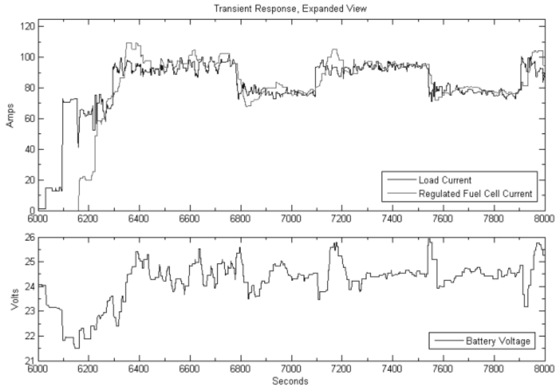

Figure 4. Detailed view Long duration run powering a refrigerator and several other loads

State Number (Major–Minor)	Description
1	Pre-Heat
2	Reformer Start
2-1	Verify Temperatures
2-2	Start Fuel
2-3	Verify Combustion
2-4	Prepare for Hot Idle
3	Hot Idle
4	Fuel Cell Start
5	Load Following
6	Shutdown

Table 1. Listing of the major states, including some minor states used to illustrate state progression.

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