Ant Colony Optimization Applied to Optimal Energy Management of Fuel Cell Hybrid Electric Vehicle

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Abstract—This paper investigates the applicability of the Ant colony based algorithms to solve dynamic optimization problems and specially focused on optimal control problems. The algorithm was implemented to solve optimal control of energy management in fuel cell hybrid vehicle (FCHV) as a case study. The main components of this vehicle are battery and fuel cell. The objective is to reach the best performance, fuel economy, and acceptable operation of this hybrid structure. Ant Colony algorithms are used to solve combinatorial problems in recent years, especially in engineering problems. Ant Colony algorithm belongs to a class of search algorithms derived from the process of ant-searching food. An object oriented programming (OOP) tool is developed for simulation of this hybrid structure. The simulation results demonstrate the validity and the convenience of ACO approach for dynamic optimization problem and encourage more research towards another application. It prepares a good environment for benchmark of different supervisory control of FCHV.

Keywords: Energy Management, Fuel Cell Hybrid Vehicle, Ant Colony Optimization, Optimal Control

I. INTRODUCTION

Fuel cell powered vehicles are the only best long-term solution to the rising concerns about oil resources depletion and environmental pollution. The hybridization of a fuel cell powered vehicle is a good option for mitigating the stress on the fuel cell via load leveling and to cope with challenging operating conditions such as frequent start-up, cold-start response. Another reason for hybridization is the opportunity for energy efficiency improvement. Actually, the additional energy storage device permits the capture of regenerative braking energy, which will benefit vehicle fuel economy and can potentially permit downsizing the fuel cell system. In addition an extra degree of freedom in the power flow offers energy management optimization opportunity. How the power split is to be made during vehicle operation comprises a new control task, which is referred to as the supervisory controller or energy management problem. Based on [5] and [6], different approaches to solve this problem are divided into two categories: heuristic and optimal.

Heuristic methods are used for real time applications and offer reasonable fuel consumption [7]. These methods do not involve explicit minimization or optimization; instead, the energy management is implemented with rules and algorithms based on engineering intuition [8].

On the other hand optimal methods assume the knowledge of the entire driving cycle and find the global optimal control numerically; dynamic programming (DP) [10] and numerical search methods such as genetic algorithms [9] belong to this category. These methods give the optimal solution over the prescribed driving cycle but are not implementable due to the necessity of knowing the driving cycle a priori [8].

It is proved that the Ant Colony Optimization (ACO) is a powerful optimization method for solving Combinatorial Optimization Problems (COPs). It works well when applied to various NP-complete problems, i.e. traveling salesman problem [11].

Latterly a number of algorithms inspired by the foraging behavior of ant colonies have been applied to solution of difficult discrete optimization problems and recently, have been used in optimal control problems [2], [11].

Jelmer van Ast converted optimal control problem into a stochastic COP. It requires that a continuous time-state model of the system, together with a finite action set, become formulated as a discrete, nondeterministic automaton [11], [12]. Borzabadi converted discretized form of the optimal control problem to a quasi-quadratic assignment problem in the time-control space and applied the ACO to solve the problem [2].

This paper introduces a novel method for applying ACO algorithm to the solution of optimal control problem in energy management of FCHV.

II. ANT COLONY OPTIMIZATION

Ant Colony Optimization (ACO), in swarm intelligence methods, is a pattern for designing metaheuristic algorithms for combinatorial optimization problems [12]. Marco Dorigo...
pioneered the research in this area in 1992 in his PhD thesis [1]. The first algorithm was aiming to search for an optimal path in a graph, based on the behavior of ants seeking a path between their nest and a source of food. The original idea has since diversified to solve a wider class of numerical problems. The original idea comes from observing the behavior of ants seeking the shortest path between the nest (home) and food. It is worth noting that individual ants are not much smart but utilizing collective mechanism, complex tasks are accomplished.

Ants use the environment as a tool for communication. They exchange information indirectly by depositing pheromones. This information platform has a local scope, namely only an ant located where the pheromones were left has knowledge of them. This system is called “Stigmergy”.

The functioning of an ACO algorithm can be explained as follows. In the beginning of optimization process, i.e., first iteration, all the possible transition trajectories through the states of the problem are supplied with an equal amount of pheromone. A set of computational agents (a colony of ants) moves through states of the problem by applying a stochastic local decision policy based on pheromones level. By moving and completing a tour, each ant incrementally builds a solution candidate to the problem. Once the path is completed, the ant evaluates the solution and modifies the pheromones value on the components used in its solution. This pheromone information will attracts future ants toward better solutions by increasing their probability distribution; In fact this system is based on positive feedback. Furthermore, an ACO algorithm includes evaporation mechanism which decreases all pheromone level over time, in order to prevent the system from getting stuck in local optima.

III. ACO FOR OPTIMAL CONTROL

In this paper, ACO method is used to construct optimal control profile for an optimal control problem concerning energy management of a fuel cell hybrid vehicle. To implement this method, initially the state-time space is discretized (instead of control-time space). This choice enables us to examine different state profiles to find out optimal one while assigning constant controls to corresponding subinterval and automatically satisfies condition on state-time boundary.

In order to find optimal solution we must examine performance index in the set of all possible pairs of state-time space. These admissible pairs should satisfy system dynamic (Battery Pack Dynamic) and other constraints (i.e. maximum variation of the state). Once optimal states found, optimal control function can be calculated using inverse system dynamic.

Here we introduced a state discretization based method where the time interval is divided to n subinterval and state to m nodes.

Now a trivial way to find optimal solution is to calculate all possible patterns, and compare the corresponding trades off. Such a trivial approach will result in a huge computational cost and it is worth to examine special patterns guiding us to optimal one. In fact in trivial method evaluated performance index of the current patterns doesn’t have a role in construction of the next pattern. Utilizing ACO method, patterns are constructed based on the performance index of previous iterations leading to a method with less computational cost. Pheromone deposition in ACO method plays this valuable role. Also pheromone evaporation is another mechanism which favors the exploration of different patterns during the search process. This favors the elimination of poor choices made in pattern selection.

Ant’s tour

Initially all patterns are supplied with equivalent pheromone trail level.

\[
\tau_0 = \tau_0
\] (1)
Ants choose their path using probability function. The probability function $p_{ij}^k$ with which an ant at time $k$ located at node $i$ choose the node $j$ to move and is given by the following probabilistic decision rule:

$$p_{ij}^k = \frac{\tau_{ij}^k}{\sum_{j \in S_{i,k}} \tau_{ij}^k} \quad (2)$$

After all the ants completed their tour, the pheromone information is updated according to relation

$$\tau_{ij}^k = (1 - \rho)\tau_{ij}^k + \sum_{n=1}^{N} \Delta \tau_{ij}^k \quad (3)$$

Where $\rho \in (0, 1)$, is the evaporation rate and $\Delta \tau_{ij}^k$ is amount of pheromone deposited on route $ij$. In fact pheromone update acts as a guiding rule for construction of next iteration pattern near the optimal solution of the current iteration.

Amount of pheromone that should be deposited is calculated via performance index.

$$\Delta \tau_{ij}^k = \frac{1}{I_{ij}^k} \quad (4)$$

Where $I_{ij}^k$ is cost of the system for going from node $i$ to node $j$ at time $k$. Iteration is a complete cycle involving ant’s movement, pheromone evaporation and pheromone deposit. Iterations will be continued until logical convergence to optimal solution is made.

### IV. PLANT MODEL

The plant consist of a fuel cell hybrid vehicle and its components model are described as follow:

#### A. Fuel Cell System

Fuel cells are promising technology for hybrid vehicles. A fuel cell device convert chemical energy into electrical energy by means of the oxidation of a fuel (hydrogen). Nowadays, they have been considered as alternative power converters in transportation especially in hybrid vehicle [14].

In a pure fuel cell vehicle, the stack has to track the demand power, but in a hybrid structure, the fuel cell remains the component to provide the net energy and energy storage (battery) allows flexibility in choosing of fuel cell operating point to reach the best fuel economy.

In this paper, the represented fuel cell system has been simulated using a lookup table data [4]. The dependence of output variable of fuel cell on operational parameters of stack such as partial pressure, temperature and humidity is neglected. In this regard, Figure 3 shows the net efficiency and hydrogen consumption versus stack net current.

As mentioned, the main goal of presented control strategy is fuel economy. The stack net fuel consumption depends on the internal electrochemical reaction. Thus, the consumed mass flow of hydrogen is a nonlinear map of stack variables. For simplicity, it was assumed to be linearly related to the current drawn at the stack level as shown in Figure 3:

$$\dot{m}_j(t) = K_n j_i(t) \quad (5)$$

The fuel cell model is described by simple algebraic relationship, which relates the output power to consumption rate of stack. The stack power as a function of fuel cell current obtained from voltage polarization curve as follow:

$$\begin{cases}
I_p = A_p j_i \\
U_p = N_p u_{p, i} \Rightarrow P_f = \eta A_p N_p u_{p, i} j_i
\end{cases} \quad (6)$$

Where $i_e$ is current density and $u_{p, i}$ is single cell voltage. Based on strategy of this paper, the fuel cell model has requested power as input and fuel consumption rate as output. The polarization curve only characterizes the stack behavior and once the power calculated from this curve, the net efficiency could be applied [15].

#### B. Battery Pack Dynamics

The storage system has an important role in hybrid vehicles. The prime mover supplies the main fraction of power demand, but these sources are normally slow, and cannot adapt themselves to transient behavior of load. The task of storage system is to compensate the fluctuation of load, so the charge and discharge property of storage device is very important. With respect to a simple lumped parameter model of battery (with voltage source and internal resistance as constant parameters) shown in Figure 4 and using Kirchhoff law, model equation is as follow:

$$E_b - i_e R_s - u_b = 0 \Rightarrow P_v = P_b + i_e^2 R_s \quad (7)$$

Note that motoric references used for sign convention, which positive terminal power charges the battery. From above equation, the battery current obtained in term of input power.

$$P_s = P_v(i_e) = E_b - R_s i_e^2 \Rightarrow i_e = \frac{E \pm \sqrt{E^2 - 4R_s P_s}}{2R_s} \quad (8)$$
The battery loss appeared as square term, which represents the same amount of dissipation regardless of charging or discharging mod.

The battery state of charge is the only state variable, so the dynamic behavior of battery expressed as a simple integrator of current or power [4].

$$Q \dot{S} = i_b \Rightarrow S = \frac{1}{Q} \int E \pm \sqrt{E^2 - 4RP} dt$$

(9)

The charge sustaining is a constraint on battery, which is useful in benchmarking and comparative studies, especially in energy management improvement potential. Based on charge sustenance, the changes of battery charge along a cycle must be zero.

$$\Delta S = \int \dot{S} dt = S(t_f) - S(t_i) = 0 \Rightarrow S(t_f) = S(t_i)$$

(10)

$$Q \dot{S} = i_b \Rightarrow S = \frac{1}{Q} \int E \pm \sqrt{E^2 - 4RP} dt$$

(9)

D. Vehicle Driving Cycle & Power Demand

Driving Cycle: The driving cycle simulate vehicle motion on urban or highway road [17]. Each cycle is used for special application, and this work uses the NEDC cycle for case study of an urban passenger car shown in Figure 6 [18].

In simulating a vehicle along a driving cycle, it must be noted that the vehicle speed (and maybe more information about motion condition) is dictated through driving cycle. Therefore, vehicle longitudinal dynamics treated as a map between power component of road and request from propulsion system.

$$\begin{align*}
\text{Road Side} & \begin{bmatrix} F_r \end{bmatrix} \\
\text{Vehicle Dynamics} & \begin{bmatrix} T \end{bmatrix} \\
\text{Propulsion Side} & \begin{bmatrix} P \end{bmatrix}
\end{align*}$$

(12)

For purpose of current analysis, the vehicle is driven along a standard driving cycle (so the vehicle speed and acceleration are priori known), then the power needed to produce this motion can be calculated. By passing this power through drive line system, the power demand from powertrain is determined.

Starting with Newton 2nd law, the longitudinal vehicle dynamics described as:

$$\sum F_i(v, a) = \sum F_T(v, a) - \sum F_R(v) - F_i(a) = 0$$

(13)

Therefore, vehicle driving power that must be adapted to driving cycle requirement is:

$$P_v = F_v v = \left[ F_v(u) + m\dot{u} \right] u$$

$$P_i = 0.5 \rho_a C_s A_v u^3 + mg\left[ \mu \cos(\phi) + \sin(\phi) + \dot{u} / g \right] u$$

(14)

As seen in above equation, the power demand has two components, overcoming road load and accelerating vehicle.

Correction of power demand: since an inverse dynamic model is used to predict power demand to powertrain, it must be corrected as shown in Figure 7 based on components potential during traction and braking, i.e. rate of battery charge and discharge and fuel cell power delivery capacity.
\[ P_d = \begin{cases} \dot{u} < 0 & \text{max}(P_\text{d}, -\text{max}(P_i)) \quad \text{Braking} \\ \dot{u} > 0 & \text{min}(P_\text{d}, \text{max}(P_i + P_f)) \quad \text{Traction} \end{cases} \] \tag{15}

Figure 7 The Corrected Vehicle Power Demand based on Plant Capacity

E. Final Assembled Model

The final model consists of two sections, calculation of power demand and feeding it to powertrain components as shown in Figure 8.

By integrating equations of vehicle dynamics and capacity of components, the power demand calculated and corrected.

\[ P_d = P_d \ u, \dot{u} \] \tag{16}

The energy balance between road load and powertrain are as follow:

\[ P_d = P_b + P_f \] \tag{17}

Above equation has one degree of freedom. By assigning power split between battery and fuel cell, each component share is determined. Now feeding each component power to its model, the objective and constraint are determined. The power of fuel cell tends to fuel consumption and the power of battery tends to constraint on rate of charge and discharge. The charge sustaining is satisfied always, since the profile of battery state of charge is came from optimization routine.

\[ H = \sum \omega_i H_i \quad \text{Objective} \]
\[ x_{t + \Delta t} = x_t \quad \text{Constraints} \] \tag{18}

The objective function is the resultant of problem criteria on a temporal window of N samples. As shown before, this structure can be modeled as dynamic optimization problem, which system dynamics must be treated as constraint and satisfied by control profile.

For optimum energy management between power sources, the following criteria are considered in goal function:

A. Fuel Cell Stack

The high variation of fuel cell set points must be avoided and also it must work in high efficiency zone. Also hydrogen consumption in stack considered as an important term in objective function.

\[ H_{\text{Fuel Consumption}} = \int \dot{m}_i dt = \sum_{i=0}^{n} \dot{m}_i I_i T_i \Delta t \] \tag{19}

\[ H_{\text{Current Variation}} = \int \left| \frac{\partial I_i}{\partial t} \right| dt = \sum_{i=0}^{n} \left| \frac{I_{i+1} - I_i}{\Delta t} \right| \] \tag{20}

\[ H_{\text{Efficiency}} = \int |I_f - I_{\text{MedEff}}| dt = \sum_{i=0}^{n} |I_i - I_{\text{MedEff}}| \Delta t \] \tag{21}

B. Battery

As a main constraint, battery SOC at initial & final of driving cycle must have the same value which represents charge sustaining. This term provide a suitable condition to compare control strategies. Also the rate of change in battery SOC must be minimized.

\[ H_{\text{SOC Conservation}} = S(t_f) - S(t_i) \] \tag{22}

\[ H_{\text{SOC Variation}} = \int \left| \frac{\partial S_i}{\partial t} \right| dt = \sum_{i=0}^{n} \left| \frac{S_i - S_{i+1}}{\Delta t} \right| \] \tag{23}

VI. SIMULATION RESULTS

Simulation was carried out with corrected power demand based on standard driving pattern for vehicle speed. The considered vehicle data has been selected based on Iran national car (SAMAND). In this regard, by using the presented optimization method, the proposed algorithm was implemented with OOP methodology of MATLAB 2011 on an Intel Core2Quad PC.
Table I  Vehicle Subsystem Parameters

<table>
<thead>
<tr>
<th>Battery</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Nickel Metal Hydrid</td>
</tr>
<tr>
<td>Max Power</td>
<td>42 (kW)</td>
</tr>
<tr>
<td>Specified Power</td>
<td>500 (W/kg)</td>
</tr>
<tr>
<td>Energy Density</td>
<td>50 (Wh/kg)</td>
</tr>
<tr>
<td>Nominal Capacity</td>
<td>38 (A/h)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Electric Motor</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>AC Induction</td>
</tr>
<tr>
<td>Max Power</td>
<td>126 (kW)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Vehicle</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Mass</td>
<td>1.162 (kg)</td>
</tr>
<tr>
<td>Tire Rolling Resistance</td>
<td>0.013</td>
</tr>
<tr>
<td>Aero Dynamic Drag Co-efficiency</td>
<td>0.29</td>
</tr>
<tr>
<td>Effective Frontal Area</td>
<td>2.2 (m2)</td>
</tr>
<tr>
<td>Density Of Air</td>
<td>1.202 (kg/m3)</td>
</tr>
<tr>
<td>Gear Ratio</td>
<td>0.71</td>
</tr>
<tr>
<td>Wheel Radius</td>
<td>0.306 (m)</td>
</tr>
<tr>
<td>Gravitational Acc.</td>
<td>9.81 (m/sec2)</td>
</tr>
</tbody>
</table>

The major goal of simulation program is to calculate the power split between two sources, the accumulator and fuel cell stack. The simulation results under the global optimal control law have been shown in Figure 9, including powertrain variables. The results represent improvement of more than 9.7% with this approach in comparison with a conventional rule based method [13]. As shown in this figure, the optimal control strategy causes that the set point of fuel cell has a semi flat profile and its variations gets minimum changing. Table II compares overall fuel consumption in driving cycle between different control strategies.

Table II  Simulation Results

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Consumption [gr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Battery Used Strategy</td>
<td>802</td>
</tr>
<tr>
<td>Conventional Strategy</td>
<td>800</td>
</tr>
<tr>
<td>NG Based Optimum Strategy</td>
<td>797</td>
</tr>
</tbody>
</table>

VII. CONCLUSION

Automotive is responsible for pollutants & economical impacts. Hybrid vehicles are an attractive opportunity which uses new energy sources for decreasing fuel consumption, pollution and better performance. The fuel cell power plants have been reached cheaper energy to satisfy the economical and environmental problem particularly in urban areas.

In this paper, a fuel cell hybrid vehicle has been used as dual sources for providing necessary demand power. To reach an instantaneous energy management, this structure has been modeled as a dynamic optimization problem, which minimizes the gas consumption and satisfies plant dynamics. Ant colony as a combinatorial optimization approach has good results in solving optimal control applications, and in this research, it is a suitable strategy. With respect to the structure of this problem, a GUI was developed in MATLAB based on OOP approach. The advantage of OOP implementation is summarized as reusability (inheritance), reconfigurable code (different optimizer, different working space & different driving cycle) and extensibility (addition of more components). The results show better fuel economy. Also it shows that the presented approach is a powerful method for solving offline optimal control of energy management problems.

REFERENCES


Figure 9 Optimum Plant Simulation


