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Agent-based power sharing scheme for active hybrid power sources

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Abstract

The active hybridization technique provides an effective approach to combining the best properties of a heterogeneous set of power sources to achieve higher energy density, power density and fuel efficiency. Active hybrid power sources can be used to power hybrid electric vehicles with selected combinations of internal combustion engines, fuel cells, batteries, and/or supercapacitors. They can be deployed in all-electric ships to build a distributed electric power system. They can also be used in a bulk power system to construct an autonomous distributed energy system. An important aspect in designing an active hybrid power source is to find a suitable control strategy that can manage the active power sharing and take advantage of the inherent scalability and robustness benefits of the hybrid system. This paper presents an agent-based power sharing scheme for active hybrid power sources. To demonstrate the effectiveness of the proposed agent-based power sharing scheme, simulation studies are performed for a hybrid power source that can be used in a solar car as the main propulsion power module. Simulation results clearly indicate that the agent-based control framework is effective to coordinate the various energy sources and manage the power/voltage profiles.

Keywords: Hybrid power sources; Agent technology; Active power sharing

1. Introduction

The active hybridization technique provides an effective approach to combining the best properties of a heterogeneous set of power sources to achieve higher energy density, power density and fuel efficiency. Active hybrid power sources can be used to power hybrid electric vehicles with selected combinations of internal combustion engines, fuel cells, batteries, and/or supercapacitors [1,2]. They can be deployed in all-electric ships to build a distributed shipboard electric power system [3,4]. They can also be used in a bulk power system to construct an autonomous distributed energy system. An important aspect in designing an active hybrid power source is to find a suitable control strategy that can manage the active power sharing and take advantage of the inherent scalability and robustness benefits of the hybrid system.

Many efforts have been taken to develop passive and active hybrid power source techniques [5–8]. However, the power management in those active hybrid power sources is performed by either a central controller or a supervisory controller, which requires collecting the measured information regarding the current, voltage, temperature, pressure, or even flow rate from each component using long wires. Due to the large number of wire connections, there exist severe electromagnetic interference (EMI) problems. In addition, the centralized control structure is susceptible to bottlenecking and single-point failure and presents difficulty in reconfiguration and rescaling of the hybrid power sources. As the number of individual sources in the hybrid systems increases largely, the control issue associated with the active power sharing becomes very complicated and even challenging. In this case, distributed control, with decision-making done locally within each source, can facilitate coordination of these sources that are competing for electric power that is shared by them and potentially create a scalable and robust power supply system. By having each individual power source or load in the active hybrid system follow a common communication scheme based upon a dedicated controller-area network (CAN), inserting additional sources in a hybrid system to meet the increasing load demand would be easier than the traditional way of incorporating new sources into a centralized

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control structure. In this context, the multiagent system technology is a suitable and effective approach for autonomous control of multiple components in the hybrid system [9–14].

The multiagent system technology has been applied in manufacturing, transportation, power systems, and many other fields [15–22]. This approach is successful in modeling and control of distributed systems. A limitation in control applications is that an advanced decision-making ability based on local information and limited communications may be required to achieve desirable performance. Although an increasing number of researchers have been discussing issues related to different aspects of multiagent technology since the last decade, there is still no strict definition about what an agent is. This research will employ the multiagent system technology to manage the active power sharing among multiple sources in a hybrid energy system. An agent can be either a physical entity that acts in the environment or a virtual one, i.e., with no physical existence. In the context of hybrid power sources, the physical entity is the agent that directly controls an individual power source while a virtual one may be a piece of software that makes negotiation with other agents or stores data in a database.

This paper presents a multiagent-based power sharing scheme for active hybrid power sources. In the following, the agent-based control framework for active power sharing in the hybrid power source is presented. To demonstrate the effectiveness of the proposed agent-based power sharing scheme, simulation studies are performed for a hybrid power source that can be used in a solar car as the main propulsion power module.

2. Agent-based power sharing scheme

In general, agents may have the following major characteristics. Agents have a certain level of autonomy, which means that they can make decisions without a central controller or commander. To achieve this, they can be driven by a set of tendencies. For instance, in a battery system, a tendency could be “to charge the batteries when the load demand is low and the state of charge is low, too”. Thus, the multiagent system decides when to start charging based on its own rules and goals and not by an external command. In addition, the autonomy of every agent is related to the resources that it possesses and uses. These resources could be the available fuel for an internal combustion engine or hydrogen for a fuel cell stack. Agents are capable of acting in their environment. Essentially, agents are able to perceive changes in the environment in which they are immersed and also respond to those changes with their actions whenever necessary. Agents have a proactive ability. Agents have their own goals and do not just act in response to changes that have occurred in their environments. They also initiate actions to try to achieve their goals. In multiagent systems, an agent has certain behaviors and tends to satisfy certain objectives using its resources, skills and services. Agents have a social ability, which means agents can communicate with one another via agent communication language (ACL). This could be regarded as part of their capability of acting in their environment. As an example, let’s consider a hybrid system consisting of a solar array and a battery: the battery uses power from the solar array to charge it or discharges itself in case of no sunlight. In order to achieve this operation optimally, the two agents have to exchange many messages. This is a type of action because by this communication the environment is altered in a different way than if the two agents were acting without any kind of coordination.

A multiagent system is a distributed and coupled network of intelligent hardware and software agents that are working together to achieve a global objective. In the hybrid power source under study, each individual source is represented as an autonomous agent that provides a common communication interface for all the different components in the system. The control strategy or active power sharing algorithm for each represented component is completely incorporated in the software port of the agent, so it is also called a “control agent”. The control agent can activate the power converter that is connected to the corresponding power source. With each control agent running on a separate micro-processor, the hybrid power source becomes distributed.

The issue of controlling the hybrid power source becomes designing an appropriate multiagent system that can interact with its environment. For this multiagent system, the environment would include the fuels supplied to the individual sources and the loads. The agent-based approach facilitates self-organization. Since each agent is independent, once it joins the multiagent system, the logic enables it to interface itself to the other existing agents. A common method for the interface is through a directory service which allows the agents to register themselves, publish their capabilities, and then self-organize their activities. Using an agent directory service, agents do not have to be aware of other agents. For example, a load agent will look for sources registered in the directory whenever it wants to secure a new supply contract. This allows for agents to be added or removed from the system at any time since the agents are included in contract net negotiations once they register themselves with the directory service. The ability for agents to be self-organized contributes to the scalability and robustness of the hybrid power source. Since the system is self-organizing, there could be no limit to how many agents can join the hybrid system at one time and no restrictions on when an agent can join. If an agent goes offline, other agents are able to cope with the loss of that agent and reorganize the system.

The proposed multiagent based power sharing scheme is shown in Fig. 1, where each energy source, energy storage unit and load is represented as an autonomous agent. The solid lines represent the power flow while the communication flow is represented by the dashed line, which connects each agent in the system. The following is a brief description of the system elements.

2.1. Energy source unit

The energy source unit provides electric power to the load. Generally, the combination of energy source units should meet the average demand of the loads. Examples of typical energy sources are fuel cells, microturbines, photovoltaic cells, or wind turbines.

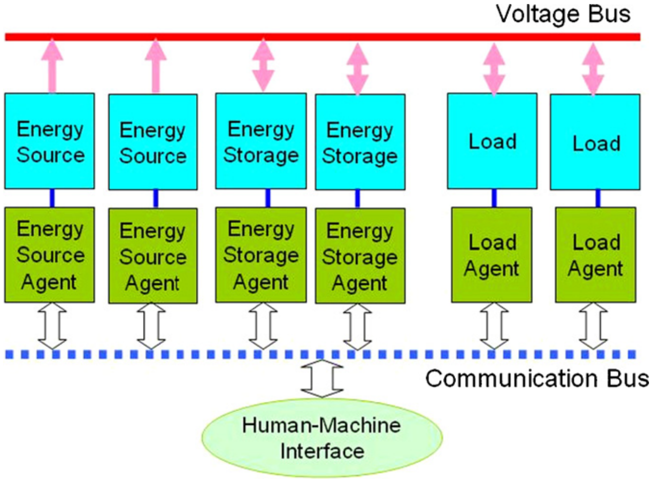


Fig. 1. Multiagent-based power sharing scheme for hybrid power sources.

2.2. *Energy storage unit*

The energy storage unit stores energy when the energy supply within the hybrid system is sufficient and supplies energy to the load when excess energy is demanded. Examples include batteries, supercapacitors, and flywheel energy storage systems.

2.3. *Load unit*

The load unit represents the sink of the power source at any specific moment. The hybrid power source may have multiple loads such as the drive motor, pumps, fans, air conditioner, and so on in a hybrid electric vehicle.

2.4. *Energy source agent*

The energy source agent manages the represented energy source based on the local measured information and the communications with other agents. The agent will determine how much energy will be supplied and direct the corresponding energy source to do so. The control strategies for different types of energy sources may be different than each other, depending upon the characteristics of the fuels.

2.5. *Energy storage agent*

The energy storage agent manages the represented energy storage unit based on the local measured information and the communications with other energy source agents and load agents. The energy storage agent will determine how much energy will be stored or supplied at a specific time.

2.6. *Load agent*

The load agent is to manage the corresponding load to make it a controllable energy resource. In an agent-based hybrid power source, the load also participates in the power sharing. For example, the motor will be used as a generator to charge the energy storage devices when the vehicle is braking.

2.7. *HMI*

The human machine interface (HMI) is for the users to monitor and observe the status of the power source.

Fig. 2 shows the architecture of a typical agent. The agent senses the environment through the *Perception* module and responds to the environment through the *Effecter* module. The *Decision-Making* module is the central part of the agent, acting like a brain for a human being. There are multiple control objectives and strategies in the agent and an appropriate strategy is chosen by the agent according to the sensed information. The intelligence of the agent is embodied by the proper selection of control strategies. The agents can communicate with each other through *Communicator* modules.

An important design decision in the multiagent system is how to choose a strategy for each unit to coordinate among one another in order to satisfy the energy demand of the loads and accomplish distributed control of the hybrid system. The agent coordination strategy defines a common communication framework for all the interactions between agents. A contract net

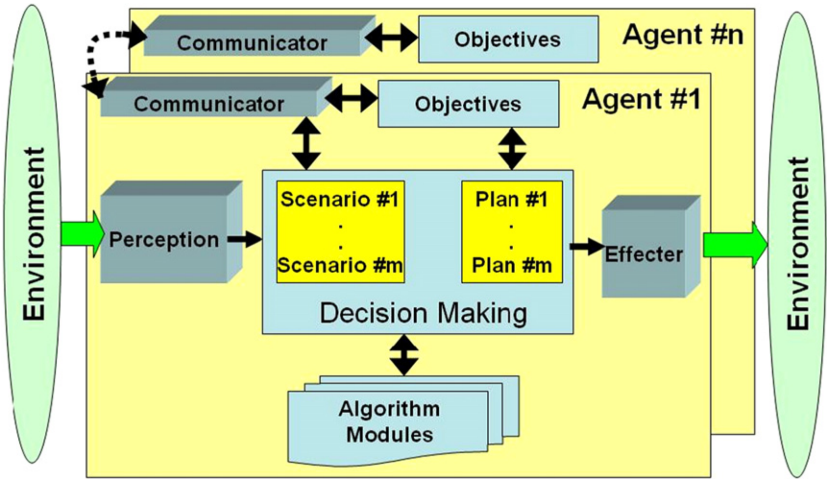


Fig. 2. Architecture of a typical agent.

protocol is one of the simplest coordination strategies [20]. All of the discussions between agents are started simply by a requesting agent asking the other agents for a proposed contract to supply some certain amount of energy, and then awarding contracts from the returned proposals in a fashion that minimizes the cost or fulfils some other goals. The disadvantage of the contract net protocol is that there is only simple negotiation without allowing for counter proposals. Effectively, the initiating agent has to pick from the presented contracts and cannot negotiate the amount of energy supplied. An advantage of the contract net protocol is that it distributes computing, allowing the specific agent which started a contract net process to be responsible for evaluating bids and deciding based on its own rules which contracts to accept.

Another aspect in developing a multiagent system is the use of a directory service. A directory service allows the agents to register themselves and publish their capabilities. Using a directory service, agents do not have to be aware of the other agents. For example, a load agent will look for power sources registered in the directory whenever it wants to secure a new supply contract. This allows for agents to be added or removed from the system at any time since the agents are included in contract net negotiations once they register themselves with the directory service.

3. A multiagent-based hybrid power source

The hybrid power source under study comprises a photovoltaic (PV) panel, a proton exchange membrane (PEM) fuel cell stack, and a lithium-ion battery, all of which are connected to a dc voltage bus through appropriate dc–dc power converters, as illustrated in Fig. 3. Each source is represented by a control agent, which is used to manage the corresponding power converter or measure and communicate the local information. The currents and voltages of the PV panel and fuel cell stack are measured, filtered appropriately, and then fed into the local control agents. The battery agent is responsible for sensing the local information and communicating this to the other agents. The power conditioning system (including power converters and the associated control agents) controls the power flowing from each source of energy, and allocates the available power to recharge the battery if possible.

Since the solar insolation varies with time and the PV cell has a nonlinear voltage–current characteristic [23], the PV system has to track the maximum power point (MPP) by controlling a dc/dc converter interposed between the PV panel and the voltage bus to ensure efficient operation. The power used to recharge the battery may come from the PV panel or the fuel cell stack. When designing the PV power subsystem, it is desirable to consider the safety limitations of the battery. The battery voltage (i.e., the bus voltage) should be maintained within the safe range, which means that the voltage cannot exceed the safety limit. This is a concern when the battery is full and the load is light. So the control agent for the PV subsystem has two operation modes: maximum power point tracking (MPPT) mode and bus (battery) voltage limit (BVL) mode. Fig. 4 shows the state machine representation of the control strategy. The circles represent the regulation modes (states) of the system. The arrows indicate changes from one regulation mode to another (events). Each event happens under a condition that is unique to the current regulation mode (state). Initially, it always works at MPPT mode. Whenever the battery voltage reaches the voltage limit, BVL mode will apply. Under any of these two modes, the load will be disconnected (DISC) if the battery discharging current exceeds the safe operating limit (for instance, four times the rated charging current).

Since the fuel cell is supplied with fuel and air through pumps, compressors, valves, etc., it has a relatively large time con-

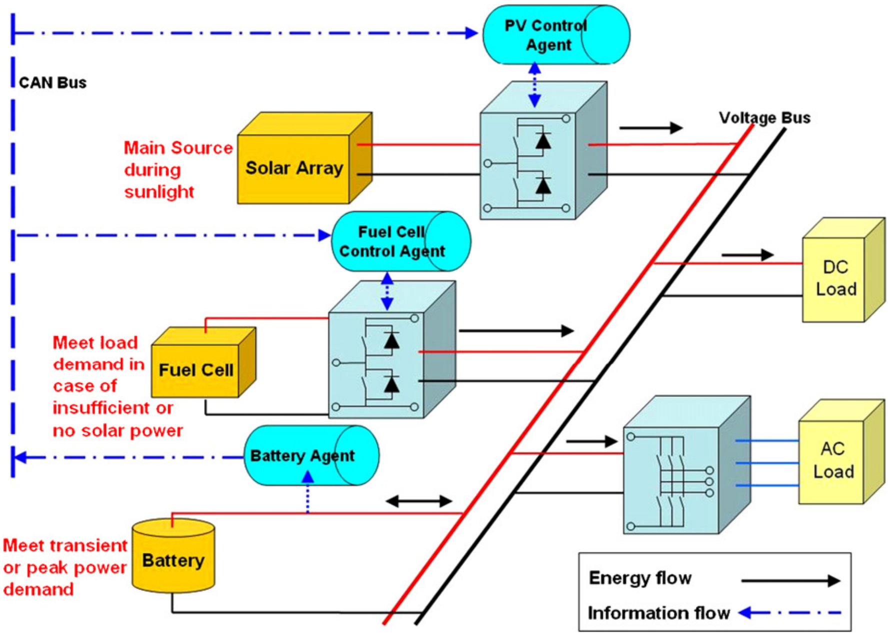
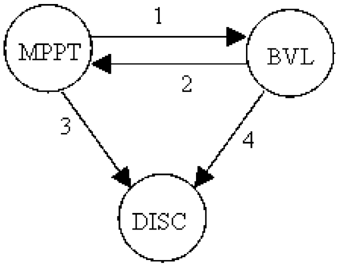


Fig. 3. Structure of the hybrid power source under study.



States:
MPPT: Maximum Power Point Tracking mode
BVL: Bus (battery) Voltage Limit mode
DISC: Disconnecting the Load
Conditions of Events:
1: $V_b > V_{ref}$
2: $V_b < V_{ref}$
3, 4: $|I_b| > I_{disc}$ (for instance, $I_{disc} = 4 \text{ x } I_{ref}$.)

Fig. 4. State machine representation of the control strategy for the PV control agent.

stant (at the order of seconds), compared with the electrical time constant (at the order of milliseconds). As a result, the fuel cell system cannot accurately respond to the rapid increase or decrease in the load power demand, and may be damaged by repetitive stepped power loads. For this reason, the fuel cell in the hybrid power system is normally operating under nearly steady state conditions, while the battery is responsible for transient energy delivery or recovery by supplying or absorbing instantaneous peak power.

Taking the above concerns into account, the fuel cell is to compensate for the rest of the average power requirement (the power that the PV system is insufficient to meet) and recharge the battery bank, while the battery supplies the peak power when the demanded current is in excess of what the PV panel and fuel cell stack can handle. Therefore, the fuel cell control agent should be responsible for managing the fuel cell output current and regulating the bus voltage (i.e., limiting the voltage of the battery). The battery control agent is to follow the bus voltage such that the battery serves as a source of energy when the load demands excess energy. To this end, the fuel cell boost converter is controlled to maintain the battery to a given state of charge (voltage). To achieve a fast dynamic response, the boost converter is primarily controlled by an inner current regulation loop. As show in Fig. 5, a classic PID compensator associated with a PWM generator is selected for fuel cell current control. This inner current regulation loop is supplied by the reference signal, ifc_ref, which is generated by the outer voltage loop, as shown in Fig. 6. The battery voltage loop, producing the reference fuel cell current, consists of a P controller limited in both magnitude and slope. With this algorithm, the fuel cell current increases when the battery voltage becomes low, while the fuel cell current starts to decay when the battery reaches full charge. This strategy, as well as PV power control system, regulates the battery voltage. It is interesting to note that the fuel cell is turned off when the battery is fully charged. In this case, only the PV and the battery supply the load. This strategy has an advantage of saving fuel.

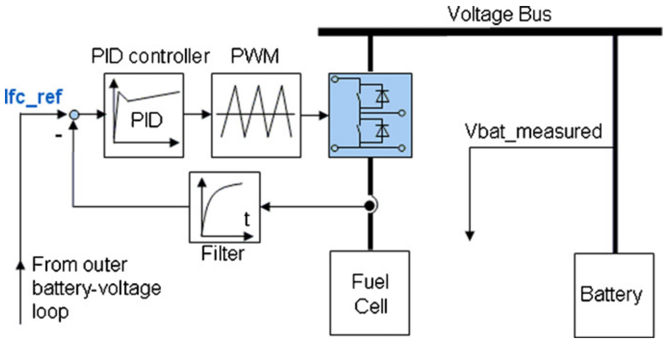


Fig. 5. Inner current regulation loop for the fuel cell control agent.

4. Results and discussion

To demonstrate the effectiveness of the multiagent-based power sharing scheme, simulation studies were conducted in the virtual test bed (VTB) environment [24] for a hybrid power source that can be slightly adapted for use in a solar car as a propulsion power module or in an electric ship as a service power unit. In this study, the time delay in the communication network is ignored since the main objective here is to verify the feasibility of the agent-based control platform for hybrid power sources. In the future work, a hardware platform will be built and the communication delay will be considered.

Fig. 7 shows the schematic view of a 2 kW hybrid power system under study. The power system was assumed to be located at the latitude 34°N and longitude 82°W. The system was operated from 8:00 a.m. to 11:00 p.m., 12 May 2007. The sky was assumed to be clear and the ambient temperature was assumed to be constant at 27 °C during the operation. Fig. 8 shows the solar insolation that the PV panel received which increased from about 500 W m^{-2} at 8:00AM and reached the maximum at 12:36 p.m. The solar insolation decreased to zero at around 5:30 p.m. The PV panel was configured as an array of cells, each cell having an active area of 2×3.5 cm^2, and a responsivity of 0.305 A W^{-1}. The second power source was a 40-cell PEM fuel cell stack. The active area of each cell was 292 cm^2. The battery was configured as an array of 12×25 cells. The capacity of each cell was 1.5 Ah. The initial state-of-charge of the battery was 0.3. The load consisted of a constant-power ac load, a constant-power dc load and a pulsed-power dc load. The load drew about 1.5 kW of peak power and about 1 kW of average power. The power converters were represented by switching-average models. Details of VTB models for fuel cells, solar cells and lithium-ion batteries are described in [25–27].

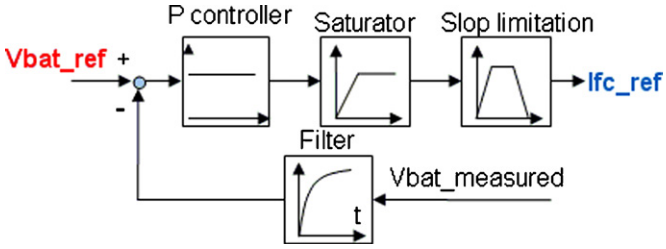


Fig. 6. Outer voltage regulation loop for the fuel cell control agent.

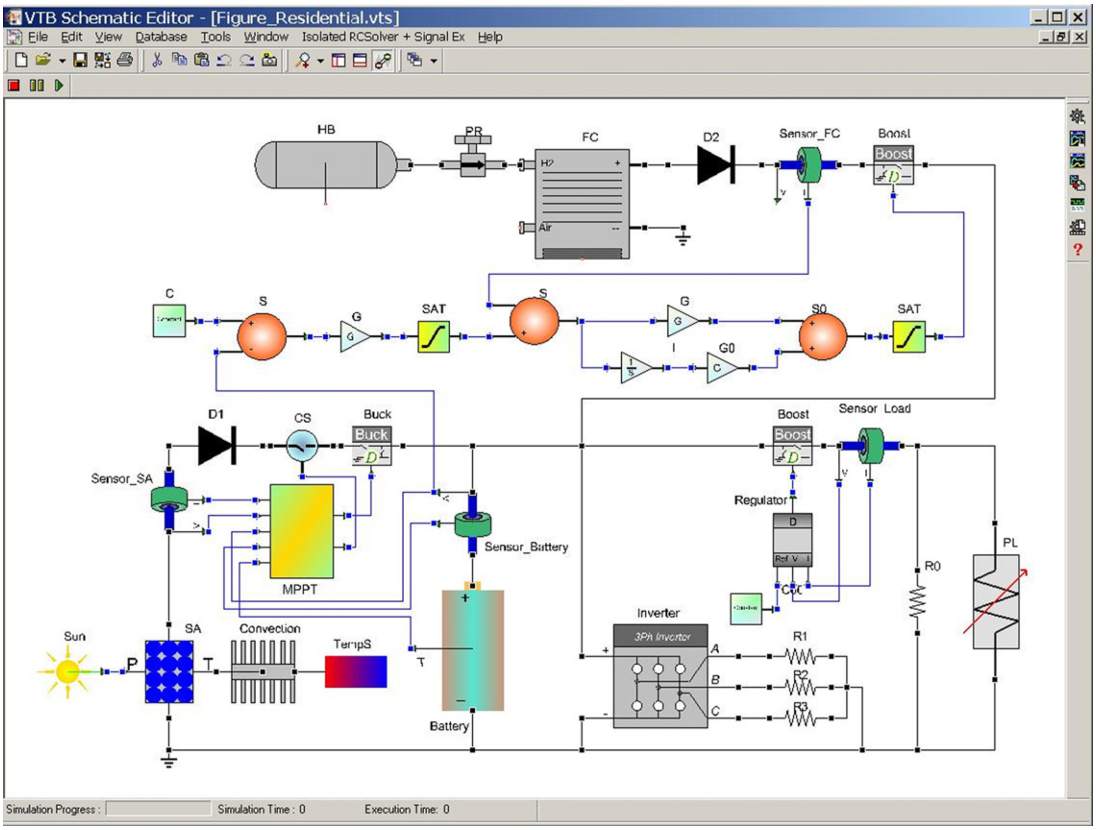


Fig. 7. Schematic view of the hybrid power system under study.

The measured currents and voltages are locally fed to the fuel cell control agent, PV control agent and battery agent, whose principles of operation are described in Section 3. The battery agent sends its own local information to the fuel cell control agent and the PV control agent. These agents then calculate the control outputs and send control commands to the corresponding components based on local information and limited communications. According to the safe operating conditions, the voltage of the battery was limited to 50.4 V. The limit of the fuel cell current was set at 30 A. The preset value of the battery voltage reference for the fuel cell current regulation was 50 V. The simulation results are shown in Figs. 9 through 12. Fig. 9 shows the currents from the PV panel, the fuel cell stack, and the battery. Fig. 10 shows the voltages of the PV panel, the fuel cell stack and the battery. Note that the bus voltage is equal to the voltage at the battery terminal. The power output from each source of energy is plotted in Fig. 11. The calculated state-of-charge of the battery is plotted in Fig. 12.

Initially, the fuel cell output a maximum current (30 A) due to the low state of charge (voltage) of the battery. Both the PV panel and the fuel cell supplied power to the load. The PV controller

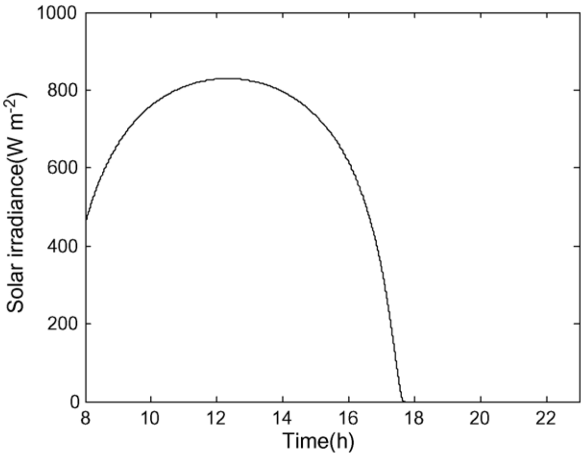


Fig. 8. Solar insolation received by the PV panel.

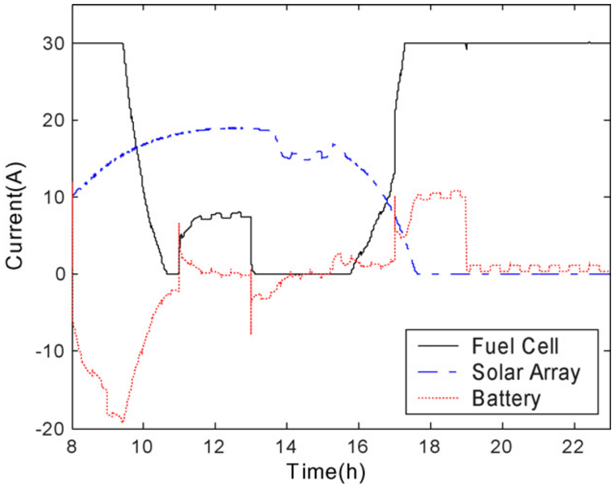


Fig. 9. Currents from the PV panel, the fuel cell stack, and the battery.

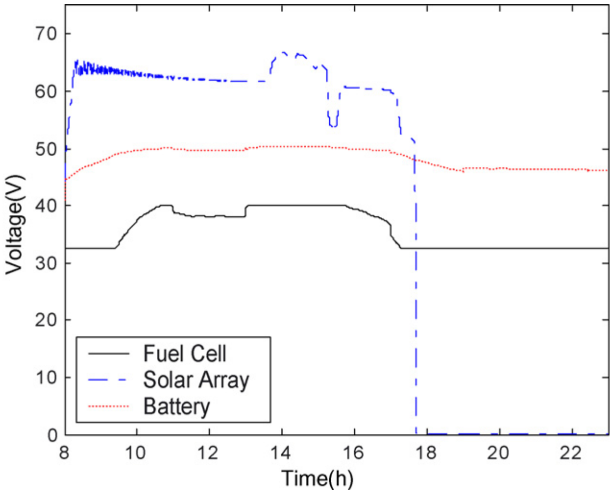


Fig. 10. Voltages of the PV panel, the fuel cell stack, and the battery.

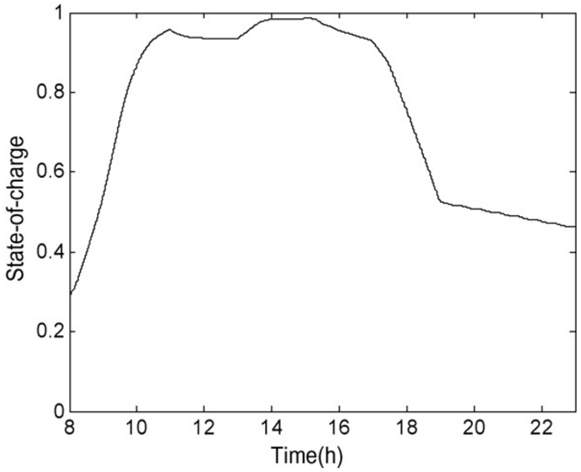


Fig. 12. Calculated battery state of charge.

was working at MPPT mode, tracking the maximum power point of the PV panel. The output power of the PV panel increased with the solar insolation. The battery was charged because the load demanded low power. The state-of-charge of the battery, as shown in Fig. 12, increased rapidly. When the battery voltage reached a preset value (50 V), the fuel cell began to decrease, as shown in Fig. 9, while the PV panel output as much power as possible. The fuel cell voltage then increased slightly. The fuel cell was shut down at about 10:30 a.m. because at this time the battery was almost full. Between 11:00 a.m. and 1:00 p.m., the load drew peak power of 1.5 kW. The battery began to discharge to support the peak power, and the fuel cell current increased to about 10 A due to the decrease of the battery voltage. After the 2-h operation of peak power, the battery was charged again and the fuel cell was shut down because of the low load demand.

At about 2:00 p.m., the battery voltage reached the limit, BVL mode applied and the bus (battery) voltage was regulated at 50.4 V. Less current flowed into the battery and thus the output current of the PV panel declined, resulting in an increase in the PV panel output voltage. It is interesting to note that whenever the PV controller is working at BVL mode, the fuel cell is always shutdown to save fuel because at this time the battery voltage exceeds the setpoint for the fuel cell current regulation. At 4:00 p.m., the solar insolation was insufficient to power the load, the fuel cell restarted to supply additional power and the PV system worked at the MPPT mode. After the sunset, the fuel cell and the battery powered the load.

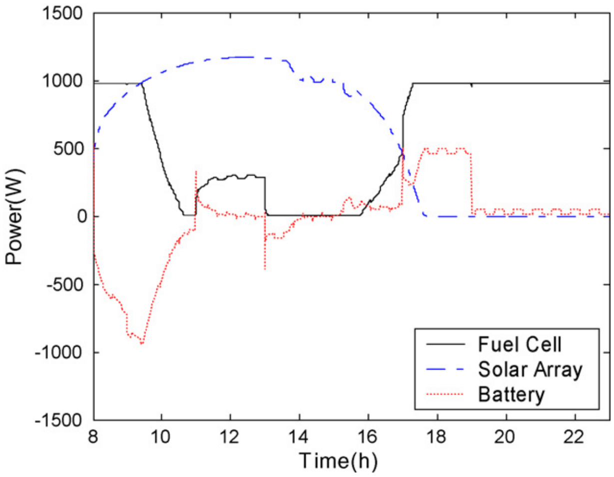


Fig. 11. Power from three sources of energy.

5. Conclusion

A multiagent based power sharing scheme was proposed for active hybrid power sources. The features of agent technology were first reviewed. The agent-based control scheme for the power sharing in the hybrid system was then presented. To demonstrate the effectiveness of the proposed agent-based power sharing scheme, simulation studies were performed for a hybrid power source that could be used in a solar car as the main propulsion power module. Simulation results clearly indicated that the multiagent scheme was effective to coordinate the power sharing among a variety of power sources and manage the power and voltage profiles.

The multiagent scheme allows for distributed control of hybrid power sources, with decision-making done locally within each source, and can potentially create a scalable, robust power supply system. The multiagent control scheme mitigates the EMI issues and eliminates the single-point failure problem. By having each individual power source or load in the active hybrid system follow a common communication scheme based upon a dedicated controller-area network (CAN), inserting additional sources in a hybrid system to meet the increasing load demand is easier than the traditional way of incorporating new sources into a centralized control structure.

Acknowledgment

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