An Efficient Fuel-Cell Battery Powered PMDC Motor Drive Scheme for Electric Vehicles

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Abstract—This paper presents a hybrid Battery-Fuel cell (Battery-FC) DC drive scheme for plug-in Battery-FC Hybrid Electric Vehicles (EV’s). The hybrid Battery-FC DC drive interface scheme is dynamically controlled using a modified tri-loop WM PID controller. The proposed efficient utilization scheme ensures efficient DC source energy utilization from the hybrid Battery-FC DC with minimal DC inrush current conditions by fully stabilized DC bus voltage. The multi-loop error driven battery-charging regulator allows for efficient DC energy utilization. The proposed hybrid green energy (Battery-FC) DC drive scheme is fully validated by using MATLAB/SIMULINK/Sim-power toolbox for cases without and with Free-wheeling energy recovery.

I. INTRODUCTION

The electrical vehicle (EV) and plug-in hybrid electrical vehicle (HEV) are emerging as a viable transportation option. Compared to conventional Internal Combustion Engine (ICE) vehicles, EV’s and HEV show higher fuel efficiencies and less gaseous emissions. Nowadays the development in Electric Vehicle (EV) technology is driven by the emerging climate changes due to carbon dioxide emissions, the need to reduce fossil fuel consumption, global energy rising demand, decrease dependence on fossil fuels and use of Internal Combustion Engine (ICE) vehicles. Accordingly, the more effective and convenient solution is a new generation of Green Electric Vehicles, which are charged by sustainable electric energy obtained from renewable energy sources. However, renewable green energy sources such as wind, solar, and fuel cell are intermittent in nature, and produce a fluctuating active power. Interconnecting these intermittent sources to the utility grid at a large scale may cause voltage/frequency problems of the grid, and lead to severe power quality issues [1].

The electric vehicle design requires charging electrical power sources including fuel cells, photovoltaic, batteries and future energy storage super capacitors. The challenge of emerging power system is that each power source component should be carefully designed, sized, tested and integrated optimally in the final system. If a component is not well matched, the entire test and validation cycle for the power system should be restarted and modified [2, 3, 4].

The main element of electric vehicles (EV’s) is the battery. This element stores a required amount of energy to be slowly released when needed. The battery also allows regenerative braking in an EV’s and can complement a slow dynamic energy source, such as the fuel cell. Benefits are drawn from these features in EV’s based on fuel cells such as the Honda FCX Clarity. The battery’s management system (BMS) must also ensure a fully efficient management battery’s state of charge (SOC). To accomplish this, the designer of the BMS must have a fully detailed simulation of the EV’s traction system including a detailed model of the battery [5].

Recently, Electric Vehicle technology is further enhanced and sustained by a need to reduce fossil fuel energy demand and concerns for climate changes due to carbon dioxide gaseous emissions, and decrease dependence to fossil fuels and combustion engine vehicles. Accordingly, the more effective and convenient solution is using the new generation of Green Electric Vehicles (EV’s), which are charged by electric energy obtained from renewable energy sources. All EV’s are supplied by efficient Lithium-ion batteries, which can be recharged through V2H/V2G Stations which can be supplied by green renewable energy sources such as Photovoltaic (PV) arrays, solar, and wind farms in commercial (V2G) power stations and Small scale Household PV-Powered (V2H) schemes [6, 7]. Several types of electric motors may be used for EV’s propulsion purposes. Earlier traction motors were exclusively dc motors, either series-excited or separately excited. Recently, more advanced ac motor drive systems have found application in EV’s propulsion using induction motors, permanent magnet synchronous motors, and permanent magnet brushless dc motors [8, 9, 10].

Unlike electric vehicles (EV’s), plug-in hybrid electric vehicles (PHEV) and hybrid EV’s are considered as more viable alternatives to reduce the current fleet of fossil-fuel-driven transportation vehicles and reduce the air pollution especially in densely populated metropolitan areas [11, 12, 13]. The PHEV is a hybrid vehicle with a storage system that can be recharged by connecting the vehicle plug to an external electric power source [14]. The increasing use of electric vehicles (EV’s) will certainly prompt the use of a large number of battery chargers to supply the DC voltage required to charge battery packs. Because of their limited energy capacity, EV batteries need frequent recharge, and it is usually desirable to do this as rapidly as possible. The ability to reduce the battery charging time depends on delivering as much tolerated current as possible during the charging period based on battery specifications [15, 16].

The objective of this paper is to design an efficient PMDC drive scheme for Electric Vehicles fed from a hybrid (Battery-FC) green energy sources, so that the FC can be used as an additional base energy source for the electric vehicles (EV’s) using the Lithium-Ion type Battery. The dynamic modeling and a novel coordinated control strategy for an integrated Electric Vehicle drive with a dynamic energy
recovery-freewheeling diode to recharge a Lithium-Ion Battery. The integrated PMDC Drive Scheme is fully stabilized using a Novel Switched Filter Compensator (SFC) scheme that ensures a fully stabilized Common DC-Bus voltage with limited inrush currents and damped voltage fluctuations in case of DC source and load Changes. The Lithium-ion Battery is fully utilized and efficiently recharged using the dynamic error driven multi loop multi-regulator control strategy. The switched Filter Compensator SFC Scheme is validated with the New Modified Tri-loop WMPID controller to control the DC-DC converter PWM-Switching and Switched Filter Compensator (SFC). The paper presents the validation of the electric vehicles (EV’s) PMDC motor drive Scheme with the multi loop Modified PID controller for the Electric Vehicles (EV’s) powered by the four-wheel PMDC motor drive. The time descaled and coordinated Tri-Loop dynamic error controller is used to regulate the motor speed, limit inrush currents, avoid motor overloading and reduce voltage excursions. 

II. SYSTEM DESCRIPTION

Figures (1, 2) show the proposed all-wheel electric vehicle drive system scheme powered with the hybrid Fuel cell FC-Lithium-Ion Battery. The proposed drive system consists of seven parts. There are DC voltage supply like a Lithium-Ion Battery, Switched Filter Compensator SFC, DC/DC Chopper, a controlled four PMDC motors for wheels, an extra Lithium-Ion Battery used as pickup source, a Freewheel Diode, and DC auxiliary loads (heating, lighting, DC motor for ventilation and air conditioning) are located at the common DC Bus (Vd). The DC renewable energy utilization scheme is regulated by a dynamic multi-loop regulation (A, B and C) control schemes, as shown in Figures (3, 4, 5), for energy recovery of hybrid battery and FC DC energy sources, common DC bus voltage stabilization and efficient flexible mode all-wheel electric vehicle drive system scheme. The proposed dynamic Tri-loop error-driven controller is a new fast dynamic regulation concept that operates as a dynamic type multi-regulator controller capable of handling any sudden changes in load and/or DC sources. Power quality issues include transient voltage variations (over-voltage, under-voltage and sustained Inrush currents). The DC compensator scheme is used to ensure stable, efficient, minimal inrush current operation of the hybrid multi source renewable energy scheme. The Modified Proportional Integral Derivate (MPID) multi regulators and coordinated controller are used for the following purposes:

1. Switched Filter Compensator SFC-PWM regulator for pulse width switching scheme to regulate the DC bus voltage and minimize inrush current transients and load excursions nonlinear Volt-Ampere characteristics. The HSFC device acts as a matching DC-DC interface device between the DC load dynamic characteristics.

2. The permanent Magnet DC motor drive with the speed regulator that ensure speed reference tracking with minimum inrush conditions and ensure reduced voltage transients and improved energy utilization.

III. SYSTEM DESCRIPTION

The global error is the summation of the three-loop individual errors including voltage stability, current limiting and synthesize dynamic power loops. Each multi-loop dynamic control scheme is used to reduce a global error based on a Tri-loop dynamic error summation signal and to mainly track a given voltage reference. The novel Modified Tri-loop error driven dynamic controller scheme was implemented to control both SFC and 4-Quadrant DC-DC Chopper. In the current regulation loop, the Weighted Modified WMPID controller is used to regulate the charging current and its output, so that the charging current ripple is reduced.

The dynamic error-driven absolute errors of all control-regulators (eA , etA , eB) is minimized dynamically to ensure effective tracking and minimal excursions. The Tri-loop error-driven dynamic controller is a novel coordinated dual action control used to modulate the switched filter compensator topology. The global error signal is an input to the Weighted Modified WMPID controller to regulate the modulating control signal to the PWM switching block. The Weighted Modified WMPID includes an error sequential activation supplementary loop to ensure fast dynamic response and effective damping of large excursion, in addition to conventional PID structure.

\[
e_m(k) = \left(1 - \frac{m(k)}{m_{base}}\right) \left(1 + \frac{1}{ST_{22}}\right)
\]

\[
e_m(k) = \left(\frac{i_m(k)}{i_{m,base}}\right) \left(1 + \frac{1}{ST_{24}}\right) \left(\frac{1}{1 + SD}\right)
\]
**Fig. 1** Basic PMDC EV Drive Scheme for (FC-Battery) powered Electric Vehicles using four PMDC motors without the new Switched Filter Compensation and Energy Recovery Scheme.

Moreover, the total or global error $e_B(k)$ for the DC motor scheme at a time instant:

$$
e_B(k) = e_m(k) + \sum_i e_{im}(k) + \sum_M e_{im}(k)$$ (4)

$$e_{im}(k) = \left( \frac{v_{im}(k)}{v_{im,base}} \right) \left( \frac{1}{1 + ST_{12}} \right) \left( \frac{1}{1 + SD} \right)$$ (5)

Moreover, the total or global error $e_A(k)$ at time instant:

$$e_A(k) = e_{vd}(k) + e_{id}(k) + e_{vd}(k) + e_{pd}(k)$$ (8)

$$e_{vd}(k) = \left( \frac{v_{vd}(k)}{v_{vd,base}} \right) \left( \frac{1}{1 + ST_{12}} \right) \left( \frac{1}{1 + SD} \right)$$ (6)

$$e_{id}(k) = \left( \frac{v_{id}(k)}{v_{id,base}} \right) \left( \frac{1}{1 + ST_{14}} \right) \left( \frac{1}{1 + SD} \right)$$ (7)
error by adjusting the process control inputs. Defining \( u(t) \) as the controller output, the final form of the MPID algorithm is:

\[
u(t) = K_P \times e(k) + K_I \int e(t) \, dt + K_D \frac{d}{dt} e(t) + (g_2 \times e^2(t)) + g_1 \times e(t) \left( \frac{1}{1 + SD} - 1 \right)
\]

(11)

Moreover, the total or global error \( e_{tA}(k) \) for the SFC scheme at time instant:

\[
etA(k) = eA(k) + K_A \cdot e_{PL}(k)
\]

(10)

In addition to tri-loop dynamic error driven controller, WM PID controller is modified by an error squared acceleration loop for fast dynamic response. Therefore, the output of the tri-loop controller (eA, etA, eB) is sent to a weighted modified PID (WMPID) controller.

A Modified proportional-integral-derivative controller (MPID controller) is a generic control loop feedback mechanism (controller) widely used in industrial control systems. A MPID controller calculates an "error" value as the difference between a measured process variable and a desired set point. The controller attempts to minimize the

**IV. FUEL CELL STACK**

A fuel cell is a chemical device that continuously changes the chemical energy of a fuel and an oxidant into electrical energy. A fuel cell can be compared to a battery, which can be recharged when you consume power from it. As a result, fuel cells can power different electrical applications such as computer notebooks, automobiles, home power generators, industrial size power generators, and other small electronics [17].

The Fuel Cell Stack block implements a generic model parameterized to represent most popular types of fuel cell stacks fed with hydrogen and air. The block represents two dynamic models.

- Simplified model.
- Detailed model.

You can switch between the two models by selecting the level in the mask under Model detail level in the block dialog box. The simplified model represents a particular fuel cell stack operating at nominal conditions of temperature and pressure. The parameters of the equivalent circuit can be modified based on the polarization curve obtained from the manufacturer data-sheet.
V. DIGITAL SIMULATION RESULTS

The hybrid Li-Ion Battery-Fuel cell (Battery-FC) renewable energy scheme for an efficient DC drive scheme for plug-in Battery-FC Hybrid Electric Vehicles (EV’s) has been validated. The weighted modified PID has been applied to the voltage and current-tracking control of the same EV battery charger scheme for performance comparison and for speed tracking for PMDC motor. MATLAB/Simulink software was used to design, test and validate the effectiveness of DC drive scheme for plug-in Battery-FC Hybrid Electric Vehicles (EV’s) with the SFC device. The digital dynamic simulation model using MATLAB/Simulink software environment allows for low-cost assessment and prototyping, system parameters selection and optimization of control settings. The use of MPID to minimize controller absolute value of total error. This is required before full-scale prototyping, which is both expensive and time-consuming. The effectiveness of dynamic simulators brings on detailed sub-models selections and tested sub-models MATLAB library of power system components already tested and validated.

The digital simulation results validated the effectiveness of WMPID controllers in providing efficient energy utilization, fast charging and stabilized DC chopper. The WMPID controllers are more effective and dynamically advantageous. The control system comprises the three dynamic multi-loop error-driven regulators.

The main tests included the efficiency of the hybrid (Battery-FC) renewable energy scheme for an efficient DC drive scheme for plug-in Battery-FC hybrid Electric Vehicles (EV’s). Four digital simulation case studies are studies, including typical excursions; disturbances, fault and variations in loads were studied.

A) Case 1: Normal Operation

In this case, digital simulation for the basic and modified EV-PMDC drive schemes shows the voltage, the current and the power for the system without SFC, with SFC and with Freewheel Diode. Figures (9, 10, 11) show the system dynamic voltage, current and power response at all Buses. In the same time, Figures (12, 13) show Voltage -vs- Current and Voltage -vs- Power characteristics at all Buses.

B) Case 2: Motor Speed Variations

The Scheme is subjected to power four PMDC motors torque disturbances. The dynamic motor torque is changed by changing the speed trajectory. The Figures (16, 17, 18) show the speed, error, Electrical torque, and Motor current for different trajectories. In the same time Figures (19, 20) show the Motor speed, Electrical torque, Error and Momentum vs Time.

C) Case 3: Static DC Load Isolation

Static DC load was removed from the DC bus system at different times from the beginning of digital simulation. Figures (21, 22) illustrate the system voltage and current with the SFC filter compensator. The effect of the SFC filter compensator is obvious at the time of reconnecting the DC static load to the DC bus system. The SFC filter improved the power quality at DC collection bus.

D) Case 4: PMDC Motor Mechanical Torque TL Changing

The motor torque and the speed under different load disturbances are studied by changing Mechanical Load Torque TL. Figures (23, 24) show the effect of changing TL.

E) Case 5: DC Bus Fault

An open circuit fault created at the DC bus for 100 ms at the time 1 Sec and a short circuit fault created at the DC bus for 200 ms at the time 1 Sec to test the stability of the system. Figures (25, 26, 27, 28) illustrate the system voltages and currents with the filter compensator. The effect of the filter at the time of fault clearance indicates few voltage and current overshooting with the filter less than that without the filter compensator.
Fig. 10 Digital simulation results without and with (SFC + Energy Recovery) for the current at all DC Buses under normal condition.

Fig. 11 Digital simulation results without and with (SFC + Energy Recovery) for the power at all DC Buses under normal condition.

Fig. 12 Voltage -vs- Current (V-I) Characteristic at all DC Buses.

Fig. 13 Voltage -vs- Current -vs- Power (V-I-P) Characteristic at all DC Buses.

Fig. 14 Total control errors $e_A$ & $e_B$ error and control signals $V_{CA}$, $V_B$.

Fig. 15 EV-PMDC Capacitor currents.
Fig. 16 Motor speed dynamic Reference tracking response, error, Motor electrical torque and Motor current.

Fig. 17 Motor speed dynamic Reference tracking response, error, Motor electrical torque and Motor current.

Fig. 18 Motor speed dynamic Reference tracking response, error, Motor electrical torque and Motor current.

Fig. 19 2nd Motor speed dynamic tracking response, Power, Electrical torque and Motor Current Characteristic.

Fig. 20 Motor speed dynamic Reference tracking response, Momentum, Motor electrical torque and Motor current.

Fig. 21 Digital simulation results without and with (SFC + Energy Recovery) for the voltage at all DC Buses with static DC Removal Disturbance.
Fig. 22 Digital simulation results without and with (SFC + Energy Recovery) for the current at all DC Buses with static DC Removal Disturbance.

Fig. 23 Digital simulation results without and with (SFC + Energy Recovery) for the voltage at all Buses under motor load torque changing condition.

Fig. 24 Digital simulation results without and with (SFC + Energy Recovery) for the current at all Buses under motor load torque changing condition.

Fig. 25 Digital simulation results without and with (SFC + Energy Recovery) for the voltage at all DC Buses under open circuit OC fault condition.

Fig. 26 Digital simulation results without and with (SFC + Energy Recovery) for the current at all DC Buses under open circuit OC fault condition.

Fig. 27 Digital simulation results without and with (SFC + Energy Recovery) for the voltage at all DC Buses under short circuit SC fault condition.
VI. CONCLUSION

The paper validated an extension a novel Green Plug Filter Compensation Scheme and Energy Recovery (SFC) using Freewheeling diode and hybrid Fuel cell-Battery power system feeding a PMDC drive for Electric Vehicles. The control strategy stabilizes the common DC bus and Retrieve Recycle Energy from the PMDC All-Wheel motor drives during deceleration and Speed reference changes. The control scheme is coordinated by a tri-regulation controller speed with multi-loop error-driven modified / weighted PID controller. The coordinated multi-regulator control scheme is validated for hybrid FC-Battery DC source and load excursions. Dynamic response is adjusted via weight and gain selections using the WMPID control scheme. The goal of the MPID tri-regulation control scheme is to minimize DC current inrush conditions and stabilize the common DC bus voltage, enhance energy DC utilization from the hybrid Battery-FC sources and maximize the real power recovery from DC drive motors. The proposed WMPID tri-regulators controller can also ensure energy recovery and stabilization of the common DC bus with efficient energy recovery during source and load excursions as well as deceleration and Electric Vehicle DC speed changes.

REFERENCES


AUTHOR BIOGRAPHY

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