Performance Analysis of a Photovoltaic and Battery Powered Electric Vehicle with PMSM Motor Drive

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Abstract: In this paper, performance analysis for speed and torque tracking requirements of an electric vehicle (EV), being powered by a photovoltaic (PV) array and battery, for various driving modes is carried out. The designed four wheel electric vehicle is based on a Permanent Magnet Synchronous Motor (PMSM) drive train because of its various attractive features like its small size, light weight, small moment of inertia and high power density. The simulations have been carried out for effective speed trajectory tracking of the PMSM motor drive powered by a PV source under various speed trajectories and various loading conditions. Also, the simulation results for the complete electric vehicle with PV array and battery validate the adequate energy management between the two sources and also that the torque and speed tracking requirements of the vehicle is met during dynamical switching between the two sources. The proposed design scheme, thus, may be successfully used for the drive train of an Electric vehicle and may help to have an improved range as compared to a vehicle driven by battery alone.

Keywords: Photovoltaic; electric vehicle; PMSM; permanent magnet synchronous motor.

1. INTRODUCTION

In the last two decades, EVs and hybrid electric vehicles with PV sources have come up as a possible solution to reduce dependency on fossil fuel consumption and carbon dioxide emissions. Different AC or DC motors may be used in EVs. The PMSM comes at the top of AC motors in the medium range of power, as it has many good features [1] like its small size, light weight, small moment of inertia and high power density that make its use attractive for EVs, as the vehicles have limited space. Substantial work has been reported in the area of PV powered EVs, but almost none of the studies in this field have investigated the performance of PV-powered PMSM drives for an EV. Recently, a solar battery-powered electric auto rickshaw has been reported [2]. But, the details of motor used and comparison of different motor drives for the same have not been provided. Design, development and optimization of highly efficient solar cars have been reported [3]. They also make use of brushless DC motors. A solar-powered four-wheel drive using PMDC motors and a hybrid PV array-battery powered EV-PMDC drive scheme [4] have also been reported in the literature, but in both, the performance of the PMSM has not been investigated. In this paper, the performance of a PV and battery-powered EV based on a PMSM drive scheme has been investigated in detail for various driving modes of the vehicle. The proposed design may help batteries to run longer, thereby increasing the range of the EV.

2. SYSTEM DETAILS

The line diagram of the proposed PV-powered four-wheel EV drive scheme is as shown in Fig. 1. As shown, the PV-EV consists of three main subsystems, namely, the PV-EV electrical subsystem, the EV vehicle dynamics subsystem and the Energy Management Subsystem (EMS).

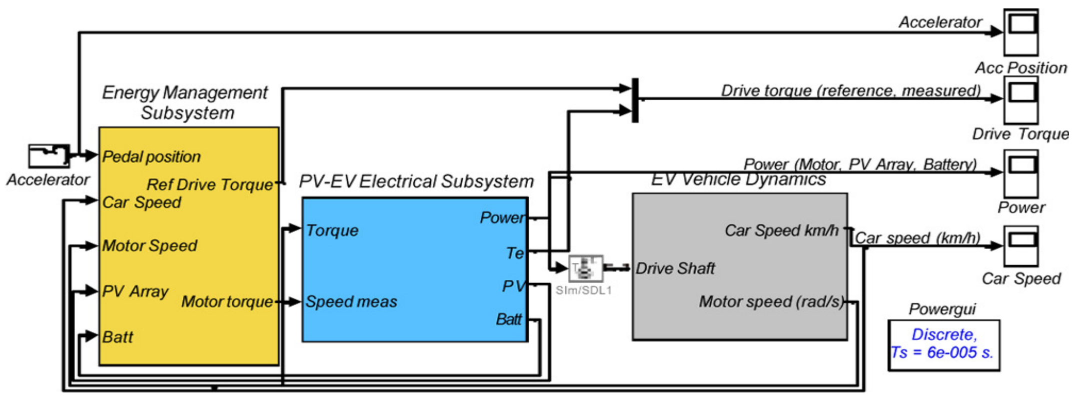

Fig. 1 PV and battery powered electric vehicle model

The electrical subsystem is composed of four parts, as shown in Fig. 2.

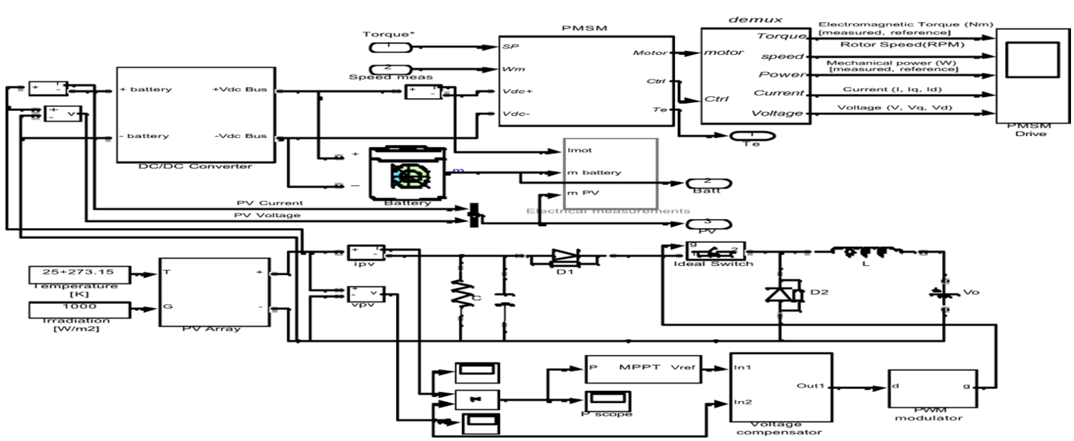

Fig. 2 Photovoltaic and battery powered PMSM drive scheme in MATLAB/Simulink

These are the electrical motor, the battery; the PV array and the DC/DC converter (boost type). The electrical motor is a 240 Vdc, 13 kW interior PMSM, with a maximum torque of 52 N-m. Vector control is used for the motor. Complete specifications for the motor are given in Table 1.

Table 1: Complete PMSM Parameters

Number of pole pairs	*P* 3
Armature resistance	*Ra* 0.0578 Ω
Flux linkage	*ψf* 0.1252 Wb
d-axis inductance	*Ld* 0.9 mH
q-axis inductance	*Lq* 1.5 mH
Rated speed	*ωr* 3000 rot/min
Maximum speed	*ω*max 5500 rot/min
Rated power	*PN* 7.5 kW
Maximum power, *PN* 13 kW	Nominal battery voltage 240 V
Maximum power, *PN* 13 kW	Nominal battery voltage 240 V

The battery is a 30.5 h, 240 V DC, 13 kW Lithium-Ion battery. The PV array consists of a series combination of three PV modules (KD_135SX), each having a maximum power of 135 W. A simple Perturb and Observe (P&O) based MPPT control has been used to extract maximum power from the PV array under Standard Test Conditions (STCs), i.e. irradiation G = 1,000 W/m^2 and temperature T = 25°C. Thus, the PV array provides the maximum power of 405 W under STC, thereby helping the batteries to run longer and hence, increasing the range of the EV. Also, a longer battery charge results in lesser grid charging, thereby indirectly aiding in lesser fossil fuel dependence and lesser emissions, as grid electricity generally involves these two. The DC/DC converter (boost type) is voltage-regulated. The EMS determines the reference signals for the electric motor drives, the PV array system and the DC/DC converter to distribute accurately the power from the two electrical sources. These signals are calculated using mainly the position of the accelerator, which is between +100% and -100%, and the measured EV speed. A negative accelerator position represents a positive brake position. It also controls the reference power of the electrical motor by splitting the power demand as a function of the available power of the battery and the PV array. This power is controlled by the DC/DC converter voltage. The modeling of PV array in MATLAB/Simulink is used in this research [5]. The solar array specifications used for this research are those for the KD135SX_UPU, manufactured by Kyocera. The EV data used is taken from the manufacturer's specifications for a compact car (Maruti Suzuki Swift). The parameters of the PMSM used are listed in Table 1. On the basis of the same, the maximum number of PV arrays to be connected in series is calculated based on feasibility of mounting it on vehicle's body and is found to be three.

3. RESULTS AND DISCUSSION

3.1 Simulation of PV-fed PMSM drive with vector control

In this part of the paper, the simulations for a PV-powered PMSM motor drive with speed control and load perturbation, which may be used in various drive trains of EVs along with the battery, is fully validated for effective speed trajectory tracking under different loading conditions. The full PV conversion scheme with PMSM drive is simulated using the MATLAB/SIMULINK software. The speed, rotor angle, current, and load torque responses of the PMSM drive for various speed modes and load torque are depicted in Fig. 3-4.

3.1.1 Speed, rotor angle, current and torque responses of PMSM motor for ramp changes in motor speed

The performance of the PV-powered PMSM drive for the case when the vehicle is continuously accelerating and decelerating is depicted in Fig. 3. The motor starts from standstill initially, linearly accelerates up to the speed of 320 rad/s in 0.04 s and then linearly decelerates to a standstill from 0.08 s to 0.12 s. Reference speed is shown with the green line, and actual speed of the motor is shown with the red line, and it is seen that with the PV source feeding the motor drive of the EV, the reference speed is effectively tracked by the motor. The rotor angle also varies in accordance with the motor speed. The motor currents obtained for the linear acceleration and deceleration of the motor also conform to the effective speed tracking, with the frequency linearly increasing, remaining constant and then linearly decreasing, according to the motor speed. The load torque to the motor is maintained constant at 52 Nm at 0.01 s, and is shown with the help of a step signal in Fig. 3. The motor develops corresponding electrical torque output of 52 Nm with few initial transients. The few transients at the starting in the speed, current and torque curves are owing to the reason that the motor takes high inrush of current while starting.

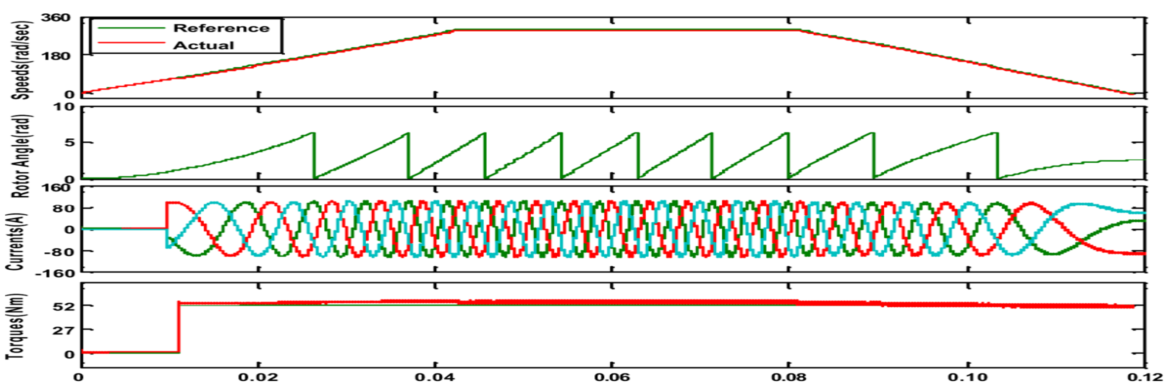

Fig. 3 Speed, rotor angle, current and torque responses of PMSM motor for ramp changes in motor speed

3.1.2 Speed, rotor angle, current and torque responses of PMSM for step changes in torque and speed

Finally, the PV-powered motor drive is subjected to various speeds ranging from low and medium to the maximum speed of the motor, i.e., 600 rad/s during time 0 s to time around 0.12 s, in Fig. 4. During this time, the motor is also subjected to three different load torques. Initially, the torque is maintained at 17 Nm from time 0 s to 0.02 s. At 0.02 s, the torque is changed to 34 Nm up to 0.07 s. From 0.07 s, the torque is kept at 51 Nm up to around 0.12 s. The reference speed and torque are represented with green lines and actual speed and torques are shown with red lines. The actual speed conforms to the reference speed trajectory. The electrical torque also conforms to the load torque, with a few transients before it settles to the steady value. As can be seen in Fig. 4, transients have higher peaks at lower speeds owing to the dominant effect of armature resistance at lower speeds. The motor currents also conform to the speed trajectory and reference load torque settings with the appropriate changes in frequency and amplitude of currents, as can be seen in Fig. 4.

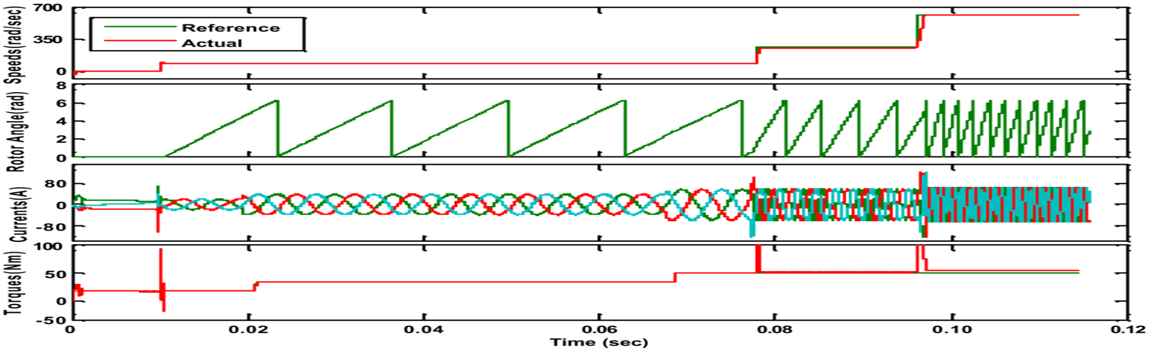

Fig. 4 Speed, rotor angle, current and torque responses of PMSM for step changes in torque and speed

3.2 Simulation of electric vehicle with battery and PV array at standard test condition (STC)

In this part of the paper, the simulation results for the complete vehicle along with the battery and PV array have been discussed. These results show the simulation of the EV based on SimPowerSystems and SimDriveline libraries in MATLAB/Simulink. The result shows four different operating modes of the EV over one complete cycle: accelerating, recharging the battery while decelerating, cruising and charging the battery during regenerative braking. The EV speed starts from 0 km/h to about 70 km/h at 12 s, and finally decreases to 55 /h at 16 s. This result is obtained by maintaining the accelerator pedal constant at 70% for the first 4 s, and at 25% for the next 4 s, when the pedal is released, then to 85% when the pedal is pushed again for 4 s, and finally sets to –70% (braking) until the end of the simulation. The accelerator pedal position, motor and car speed, drive torque, power, battery/PV current and voltage and battery SOC have been shown in Fig. 5 and 6.

3.2.1 Motor drive torque, power, current, rotor angle and car speed for the given accelerator pedal position input

The simulation results for motor drive torque, power, current, rotor angle and car speed for the given accelerator pedal position input have been shown in Figure 5. At *t* = 0 s, the EV is stopped and the accelerator pedal is pushed to 70%. The motor power requirement is shown with green line, the PV power by the red line and the battery power by the blue line. The PV array, which is simulated for STC, provides a constant power of 405 W at all times. The remaining power requirement of the motor is met by the battery. At t = 4 s, the accelerator pedal is released to 25%. Between *t* = 4 s and *t* = 6 s, the PV power is almost equal to the reference power. Hence, the battery is not much needed. Between *t* = 6 s and *t* = 8 s, it can be seen that the battery power requirement is considerably reduced, as a good part of motor power requirement is being met by PV array power. Between *t* = 8 s and *t* = 12 s, the accelerator pedal is pushed to 85%. The motor power requirement increases again, and is met by both PV array and the battery. Between *t* = 12 s and *t* = 16 s, the accelerator pedal is set to –70% (regenerative braking is simulated). The motor acts as a generator driven by the vehicle's wheels. The kinetic energy of the EV is transformed in electrical energy, which is stored in the battery. It can be observed that the battery power becomes negative, as it is receiving power from the PV array as well as motor. As the battery can receive up to 13 KW of energy, the required torque of around –37 m is being met.

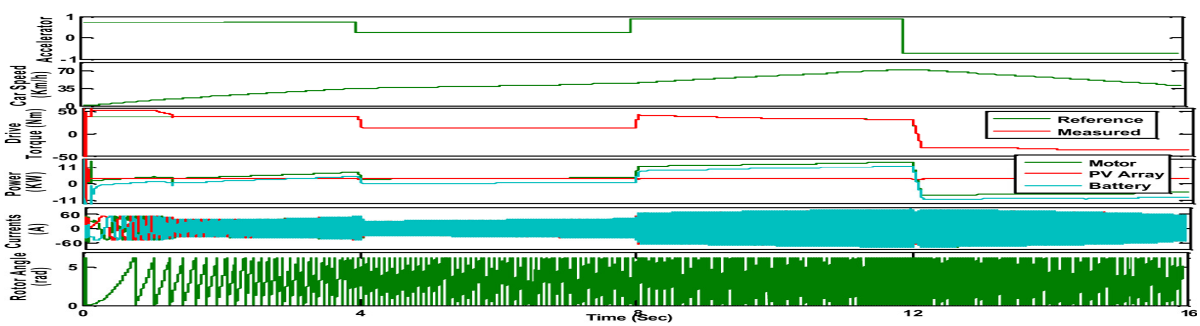

Fig. 5 Motor drive torque, power, current, rotor angle and car speed for the given accelerator input for EV with PV array and battery

3.2.2 Motor speed (rad/sec), PV and battery current and voltages and battery SOC for the given accelerator pedal position input as given in Fig. 5

The simulation results for motor speed (rad/sec), PV and battery current and voltages and battery SOC are shown in Fig. 6. The motor speed changes in accordance with the given accelerator pedal position in Fig. 5. The PV current remains constant, as it is operating at STC, but the battery current varies in accordance with the varying power requirements of the motor. The battery SOC is initially kept at 40.36%, which goes below to around 40.29% at t = 12 s, and then recovers because of charging during braking between t = 12 s and t = 16 s.

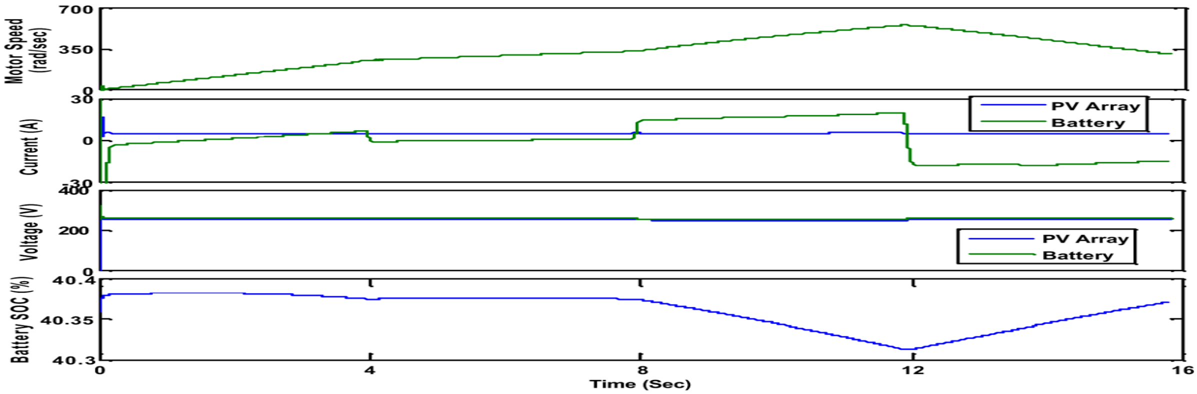

Fig. 6 Motor speed, PV/battery current/voltage and battery SOC for EV with PV array and battery

4. CONCLUSION

A PV-powered EV with PMSM motor drive is successfully implemented to be used in a four-wheel EV. The simulation results validate the effective speed trajectory tracking of the PMSM motor drive powered by a PV source under various speed trajectories and various loading conditions. Simulation results clearly validate the use of PV array in reducing battery power requirement and hence the proposed design.

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