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Drive Line for Plug-in Electric Vehicle with PMSM Motor and Hydrogen Fuel Cell

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Abstract

In the era of transportation, the best effort will be to replace conventional fossil fuels. Instead, the usage of fossil fuels will give way to renewable energy sources and other clean energies. Many institutions promote the developments and research in the area of hydrogen fuel cell development. This paper passes through the hydrogen fuel cell area as the primary source considered here is a hydrogen fuel cell. Since electric motors are the main stem of an electric vehicle (EV), in this paper the selection of the motor and its design is also discussed. This paper deals with the study of energy transfer over stages used in electric vehicles. Energy generated from the hydrogen fuel cell is converted into electricity which is used to drive the permanent magnet synchronous motor (PMSM) and hence the vehicle at the desired speed with the least effort in all real phase circumstances. The proposed paper analyses in detail the outcomes of an electric vehicle with all the constraints. For the smooth operation of an electric vehicle, a control strategy is being developed. The proposed system is simulated in MATLAB and a real case electric vehicle is designed with the help of MATLAB.

Keywords: Hydrogen fuel cell, boost converter, DC-voltage controller, torque controller, PMSM drive, Vehicle dynamics

INTRODUCTION

Trends in the development of electric vehicles and fuel cells have created a curious interest among researchers in the usage of plug-in electric vehicles. The plug-in electric vehicle is the best option for the replacement of traditional transportation technologies and reducing fossil fuel consumption. When fossil fuels are used to generate electricity, sulfur, nitrogen, and carbon oxides are released, causing a slew of environmental problems. The production of alternative energy sources has been prompted by the depletion of fossil fuel reserves and climate change caused by the pollutants. Wind, solar, and geothermal energy are some of the other energy sources. The inconsistency of wind and solar energy necessitates the use of alternative energy sources that can provide energy continuously. When analyzing energy sources the cleaner and consistent fuel could be hydrogen and hydrogen-containing compounds due to the high fuel value compared to other energy sources. Hydrogen fuel cells for electric vehicle applications are be- coming increasingly popular as a result of major advancements in fuel cell production. Fuel cells that use hydrogen as a fuel, to replace conventional battery sources [1] are new and technically advanced. Considering other traditional carbon- based fuel combustion, the hydrogen fuel cell can be used to produce electrochemically with no emissions of pollutants while also increasing energy efficiency. Fuel cells and batteries are electrochemical energy devices that convert chemical energy into electrical energy. The storage of chemical reactants in batteries differs from that of fuel cells, and they are consumed even when they are not in use. Fuel cells, on the other hand, use fuel only when it is needed which minimizes fuel wastage. The fuel cell is highly

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efficient for distributed power generation, transportation applications, and portable power sources because it has no moving parts, produces no noise, and is modular. The energy source of the proposed electric vehicle is a hydrogen fuel cell that uses liquid hydrogen and liquid oxygen to generate electrical energy. Energy generated in the fuel cell is converted into mechanical energy needed for the vehicle with the help of a converster and a traction motor. In this proposed framework, a growing trend is tested with the aid of a hydrogen fuel cell. For the process of voltage amplification of generated voltage by the source, boost converters are used [2]. Boost converters are widely used due to the property of voltage magnitude amplification and less complexity [3]. The boost converter has many issues like EMI issues, harmonics, etc. Hence a modified boost converter is used which has fewer drawbacks [4, 5]. The traction motor is driven by the energy through a converter at which the intermediate DC-link voltage acts as the source for the motor hence it should be constant and ripple-free [6]. It can be achieved by considering a new technique for the DC-link voltage control. It is important to run the traction motor at optimum efficiency points during the drive cycle for better EV performance [7, 8]. When comparing the output of various motor types, permanent magnet synchronous motors come out on top. In the field of variable-speed AC drives, permanent magnet synchronous motors are highly efficient over induction machines, especially in plug-in EVs and hybrid EVs. Its advantages are high power, torque to current ratio, efficiency, and ease of control [9, 10]. Torque-based Control of PMSM is implemented using dynamic models.

This proposed paper is organized as Section II discusses the proposed converter topology- the electric drive-line. Section III operating principles of the proposed drive-line. Section IV design of proposed drive-line. Section V control scheme of the proposed drive-line. Section VI results and discussion.

PROPOSED CONVERTER TOPOLOGY- THE ELECTRIC DRIVE LINE

The proposed system uses a hydrogen fuel cell to power an electric vehicle [15]. Because of the rising cost of gasoline and oil, the operating costs of diesel or petrol-powered vehicles have risen in recent years. This vehicle's byproducts, such as smoke and other toxic gases, would also pollute the atmosphere. The introduction of electric vehicles would help to alleviate this situation. This electric vehicle relies on batteries, which are more expensive due to their higher performance and longer life cycle. Using a hydrogen fuel cell it will lower the cost and extend the life of an electric vehicle. Hydrogen fuel cell, like electricity, is a source capable of delivering uninterruptible energy. In developing fuel cell vehicles, storage of fuel is a vital consideration. In this study, a recent development in hydrogen fuel cells and the control strategy of drive line is scrutinized, and check the feasibility of using hydrogen as a major fuel in transportation systems. The fuel cell produces electricity by splitting the cation and anion in the reactant using anodes and electrolytes [14]. Fuel cells use environmentally friendly reactants that contain water as a byproduct of the chemical reaction. The fuel cell will generate direct current (DC) power to power the electric car since hydrogen is one of the most powerful energy carriers. The generated DC power is fed to the motor through an AC drive control [11, 13]. By controlling the PMSM motor the torque developed in the motor is controlled and hence the vehicle [12].

OPERATING PRINCIPLES OF PROPOSED DRIVE LINE

The proposed drive-line is used for the transfer of electrical energy to mechanical energy through various steps. The hydro- gen fuel cell is used as the energy source. The generated voltage is then amplified to the desired level with the help of a boost converter. The dc-link voltage should be constant throughout the operation because it is the driving force for the drive-line, Hence a PI control is used for the boost converter. The DC voltage is then converted into AC voltage. The switching pulses for the operation are generated by considering the speed and current of the PMSM. In this proposed system the torque is controlled by controlling the current and speed.

DESIGN OF PROPOSED DRIVE LINE

A hydrogen fuel cell, a boost converter, a PMSM driver, a torque controller, and vehicle dynamics are all included in the proposed hydrogen fuel-driven electric vehicle [17].

Table 1. Parameters of fuel cell.

Fuel cell Nominal Parameters	
Stack Power, Nominal Maximum	3195 W 3481.352 W
Fuel Cell Resistance	0.36404 ohms
Nerst Voltage of One Cell [En]	1.0669 V
Nominal Utilization, Hydrogen Oxidant	72.82% 29.82%
Nominal Consumption, Fuel Air	49.73 slpm 59.21slpm
Exchange Current [io]	0.1824 A
Exchange Coefficient [alpha]	0.95493
FUEL CELL SIGNAL VARIATION PARAMETERS	
Fuel Composition [X_H2]	50%
Oxidant Composition [Y_O2]]	21%
Fuel Flow Rate [Fuelfr] At Nominal Hydrogen Utilization, Nominal Maximum	161.81 lpm 179 lpm
Air Flow Rate [Airfr] At Nominal Oxidant Utilization, Nominal Maximum	635 lpm 702.7 lpm
System Temperature [T]	873 Kelvin
Fuel Supply Pressure [Pfuel]	1.35 bar
Air Supply Pressure [Pair]	1 bar

DC Link Voltage Converter

The hydrogen fuel cell is the energy source for the vehicle. In this proposed system a 165v fuel cell is designed. Table 1 shows the parameters of the fuel cell.

The required voltage level for the smooth operation of the drive line is 600 V. It is achieved by a boost converter. Without a boost converter, the electric vehicle requires nearly 417 cells to power the motor. However, an electric vehicle uses only 68 cells and boosts the battery voltage from 165 V to 500 V. In this proposed system, during steady-state, The average DC voltage across the inductor must be zero.

The average value of Vs can be found by,

$$V_{cell} = (1 - D)V_{dclink} \tag{1}$$

$$V_0/V_{cell} = 1/(1 - Duty\ cycle) \tag{2}$$

$$Duty\ cycle = (V_{cell} - V_{dclink})/V_{cell} \tag{3}$$

Vo=500v, Vs=165v

$$\text{Duty cycle, } D = .67 \tag{4}$$

Inductor ripple current

$$\nabla I_l = V\,sDT/L \tag{5}$$

Consider 3% current ripple of maximum current

$$\nabla I_l = .03 \times P_{in}/p_{out} \tag{6}$$

$$\nabla I_l = .5809A \tag{7}$$

Inductance value

$$L = V_sDT/\nabla I_l \tag{8}$$

$$L = 95\mu H \quad (9)$$

Output capacitance designs based on voltage ripple 30%

$$C_d \geq I/2pif\,\nabla V_o \quad (10)$$

$$C_d \geq 254\mu F \quad (11)$$

For smooth operation consider capacitance value as

$$C_d = 1000\mu F \quad (12)$$

The dc-link voltage controller is designed under discontin- uous mode. The inductor should be zero before the end of a whole commutation cycle. The switching frequency is selected as 20 kHz.

PMSM Drive

The PMSM is a revolving electric machine with a classic three-phase stator, similar to an induction motor, and permanent magnets fixed on the motor's surface. The rotor magnetic field is constant since the air gap magnetic field is generated by a permanent magnet. In the design of modern motion control systems, PM synchronous motors have a range of advantages. The use of permanent magnets instead of field coils generates substantial air gap magnetic flux which leads to the design of highly efficient PMSM motors. Figure 1 shows the Torque Current controller.

The air-gap magnetic flux is generated in a PMSM by replac- ing the rotor's DC field winding with a permanent magnet. With permanent magnets on the rotor, losses from the field winding are minimized, and it increases the thermal characteristics and performance of the PM machines. The absence of mechanical components makes the motor lighter hence a high power-to- weight ratio for which a higher efficiency and reliability is achieved. Advancements in permanent magnet materials and power electronic devices which leads to the Permanent Magnet Synchronous Motor (PMSM) is a better option for motor applications, providing a high torque-to-weight ratio, a large speed range, and strong dynamic torque control. As a result, researchers are focusing more on PMSM motors because of their high performance, low rotor loss, lack of brush and slip- ring/commutator, good control over a large speed range, and high power density. PMSMs are now designed to be more efficient, with less mass and a lower moment of inertia. Because of its advantages, PMSM is now the best choice for speed and position control drives on machine tools and robotics. As a result, the invention of PMSM has not only eliminated the disadvantages of induction and synchronous motors but has also opened a new door for researchers in the field of EVs.

Table 2 gives the parameters of the PMSM motor.

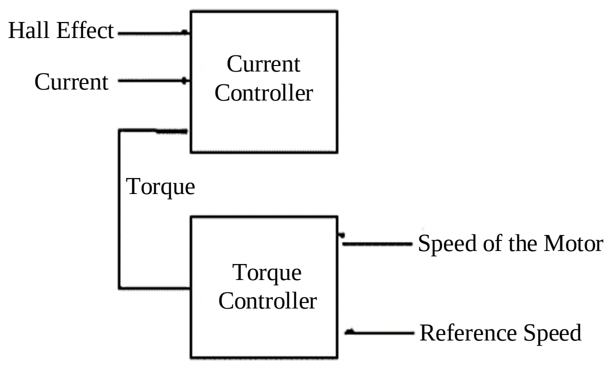

Figure 1. Torque current controller.

Table 2. Motor in MATLAB.

S.N.	Parameters	Value
1.	Nominal power	2.7 *KW*
2.	Voltage	415 *V*
3.	Frequency	50 *Hz*
4.	Synchronous speed	1500 *rpm*
5.	power factor	.9
6.	magnetic flux density	.5 Wb/mA^2
7.	pole	2
8.	winding factor	.955

Vehicle Dynamics

The vehicle dynamics model only considers the vehicle's longitudinal dynamics. The motor driving torque is the input and the velocity of the vehicle is the output. Constraints used for the validation of the proposed system are the inclination, throttle, and wind resistance.

The driving force of the vehicle,

$$F = (T_t q)/r \tag{13}$$

Ttq: motor torque
r: effective rolling radius.

For smooth operation of the electric vehicle, The driving force and resistance force should be in equilibrium. For smooth operation of the electric vehicle, The driving force and resistance force should be in equilibrium.

$$F_t = F_r \tag{14}$$

With the help of Vehicle Dynamics, it will help to get references for the application of real-time models, that can simulate the driving environment platform as in the real case. The parameters customize the model by using data. It includes a library of modeling propulsion, steering, suspension, vehicle bodies, brakes, and tire components.

Vehicle Dynamics provides a standard model architecture that can be used for testing purposes. Table 2 shows the parameters used for the vehicle dynamics.

CONTROL SCHEME OF THE PROPOSED DRIVE LINE

DC Link Control

DC link voltage control is an essential part where ever the requirement of constant DC voltage like industrial motor drives, automotive on-board chargers, and inverters, medical equipment power supplies, etc. The factors considered when using a DC control are possessed cost, harsh environment, and stringent reliability constraints. DC-Link capacitors can improve system energy density and reduce ripples caused by rapid switching which is inherent to switching power conversions. The DC link Voltage Control is implemented with the help of proportional- integral (PI) control and feed-forward control. The generation of the pulse is done by optimizing the transient response in reference to current control signal. The block can use anti- windup gain if any saturation takes place.

The DC link Voltage Controller,

Gate pulse = (Kp+Ki (T_s Z)/(Z-1))(vref-v)+FF

here:

K_p : proportional gain of PI controller.

Table 3. Vehicle parameters.

S.N.	Parameters	Value
1.	Mass of Car(W)	1500 Kg
2.	Max Speed (v)	100 Km/hr
3.	Rolling resistance (Wr)	120 Kg
4.	Aerodynamic or Wind resistance (W_A)	81.31 Kg
5.	Gradient resistance(Wg)	704.20 Kg
6.	Total weight (W_T)	2405.54 Kg
7.	Acceleration (a)	.462 m/s^2
8.	Propulsion force (F)	1111.35 Nm
9.	Power required (P)	2 KW

K_i : integral gain of PI controller.
T_s : sample time of PI controller.
v_ref : required voltage.
v : out put voltage voltage.
FF : feed forward input.

PMSM Control

PMSM control is the stage preceding to dc link [18]. The smooth operation of the vehicle requires a minimum amount of torque and the torque should be measured and controlled throughout the operation. Figure 2 shows the torque current switching control. Figure 3 shows the proposed PMSM controller. The speed of the rotor and the stator current is measured. The speed error signal is generated with the help of a PI controller. The error signal generated by the PI controller is converted into a dq0/ABC frame in order to control the current signal. In our proposed system the torque is controlled by measuring the speed of the rotor and the current supplied to the stator current. Figure 4 gives the idea about the proposed torque reference control.

In the proposed control the speed of the rotor and current is measured using sensors. The speed controller converts the speed into torque reference which is done by using a PI speed regulator model. Where N* is the reference speed. The equivalent torque reference is generated by PI controller. In the current controller hysteresis current controller is used for the generation of switching pulses. T* and I give the input to the controller which is then analyzed and the hysteresis controller generates the switching pulses for controlling the three-phase inverter.

Vehicle Dynamics

Vehicle dynamics is the validation test for the vehicle parameters with actual cases. Figure 5 shows the control diagram of the vehicle dynamics. The vehicle dynamics are designed in such a way that the torque is considered as the input variable and constraints are the conditions and results in the velocity of the vehicle. The constraints for the vehicle dynamics are the throttle, inclination, and air resistance. Vehicle dynamics would help to create a real case environment for the test of the proposed system with real-life values like vehicle mass, length, capacity, motor, etc. Figure 6 shows the torque distribution over the tire using differential gear. The torque output from the PMSM motor is fed to the differential gear in the front and rear. From the differential gears, the torque is distributed over front and rear tires.

The block represents a 2 axle four-tire vehicle body. The axle is driven by a mechanical gear that is connected to the shaft of the PMSM, which is controlled by the dc-link voltage and hence the fuel cell.

RESULTS AND DISCUSSION

A 2 kw drive-line is developed and verified using MATLAB. The hydrogen fuel cell of 165 V is used as a source. The dc-link voltage controller is implemented using a closed-loop con- troller. The torque controller of the PMSM motor is designed with the torque-current controller. The PWM frequency selected for the dc-link controller is 10 kHz and that of the PMSM controller is 20 kHz.

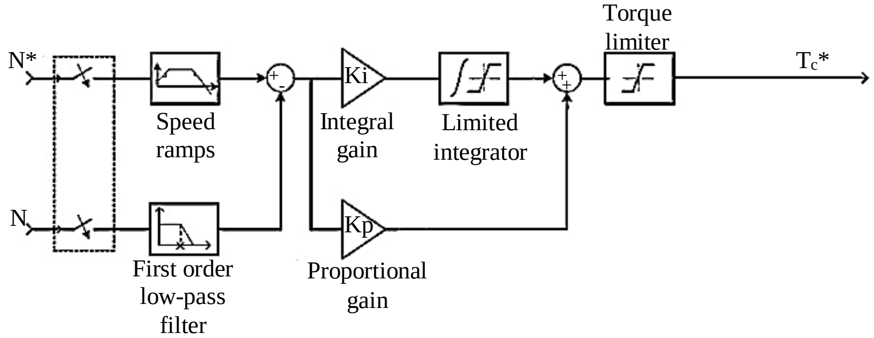

Figure 2. Speed-Torque converter control.

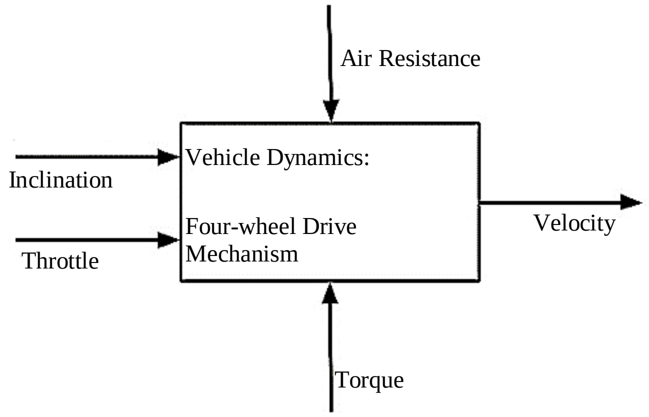

Figure 3. Control block of vehicle dynamics.

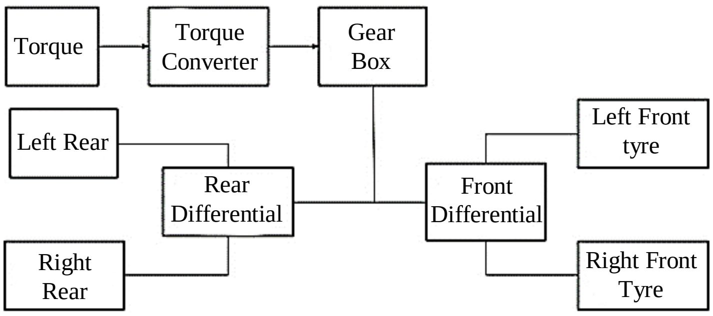

Figure 4. Mechanical parts of vehicle dynamics.

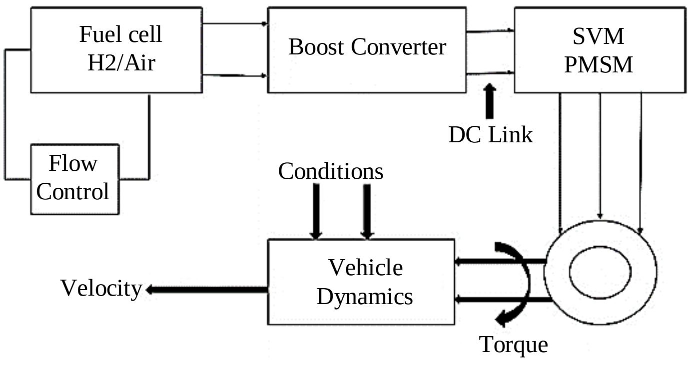

Figure 5. Vehicle dynamics.

Steady State Performance

The input voltage (cell voltage) is 165 V. Figure 6 shows the V-I curve of the hydrogen fuel cell. From the performance, it is clear that The fuel cell voltage is amplified and maintained at a level of 600 v. The inductor current is in continuous conduction mode. Figure 7 shows the steady-state wave forms of vs,is,vdc,idc the vehicle.

Figure 8 shows the control pulse for dc-link voltage. The dc- link voltage reference is 600 V and it is achieved by the closed- loop control. The control pulse is generated in such a way that the output voltage converges to reference voltage. Figure 9 shows the wave forms of the steady state performance of the three phase inverter. The dc voltage is inverted to three phase ac voltage for driving the PMSM motor. The stator current of the PMSM motor is controlled in such a way that the output torque of the PMSM motor is in rated value. Figure 10 shows the torque current performance of the PMSM motor under steady- state operation. The torque developed is a constant value under load conditions. The pulse generated will be in such a way that the current reference changes with torque requirements.

Dynamic Performance

The performance of the driveline is investigated under load variation. Figure 10 shows the dynamic response of the EV. During the operation the rotor speed of the PMSM is varied but the dc link voltage and torque are kept constant at desired level through out the operation. This is because the current controller varies the input current thus the power input and hence the torque.

Vehicle Dynamics

The proposed data and designed values can be verified using vehicle dynamics. Figure 11 shows the vehicle dynamics properties under constant throttle condition. In these constraints, wind, inclination, the throttle is kept constant. The velocity of the vehicle increases and reaches the maximum value in the least time. Figure 12 shows the vehicle under variable constraints. In the real case the throttle can be vary with road conditions. Hence performance analysis is carried with variable throttle conditions. The constraints may change with environmental conditions like wind change, the inclination of the road, and throttle change. Figure 13 shows the vehicle dynamics under various conditions. As the wind power varies which affects the velocity of the vehicle it can be overcome by increasing the throttle. The results in Figure 14 show that the vehicle is capable of overlaying any type of real environmental issues.

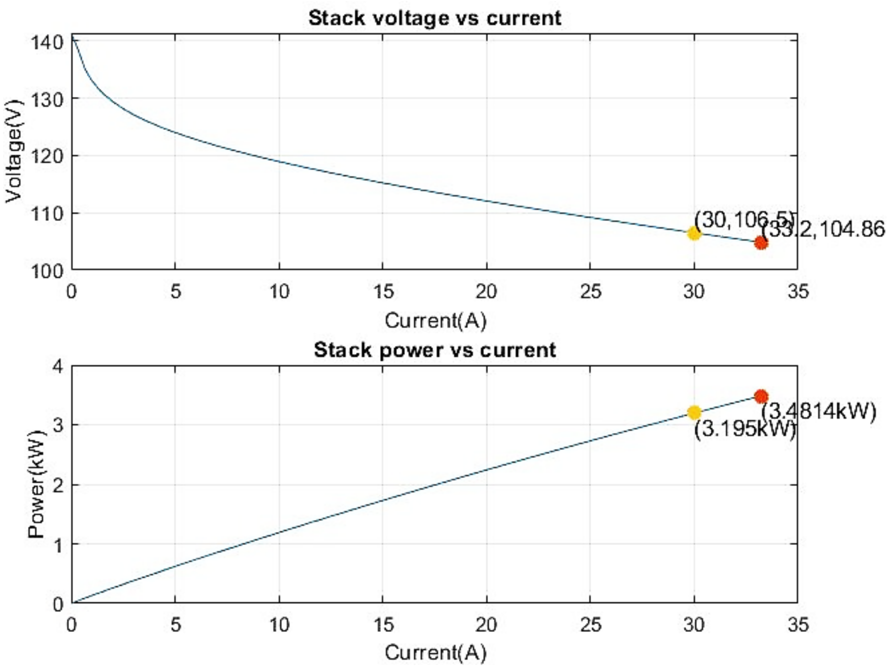

Figure 6. Fuel cell V-I curve.

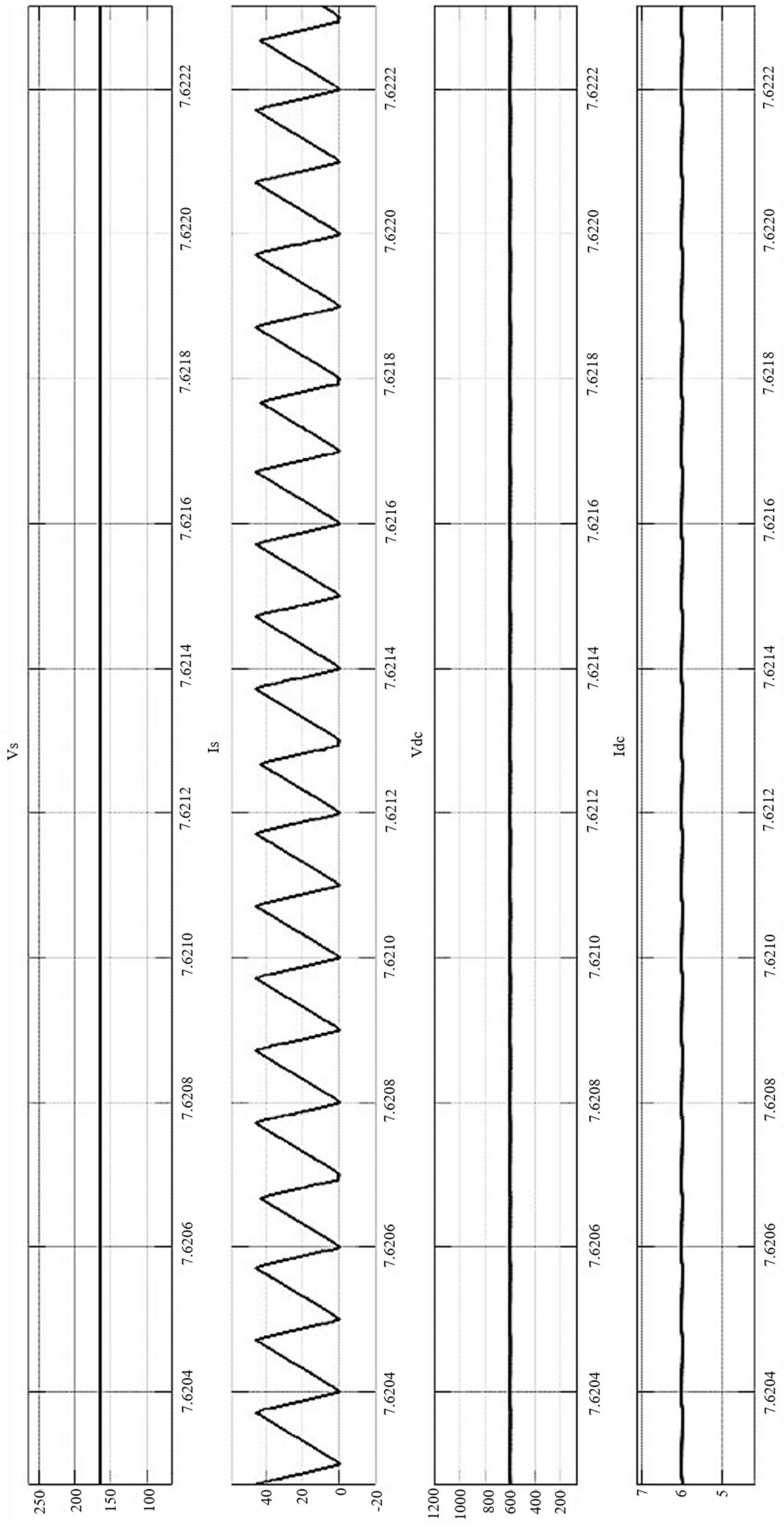

Figure 7. Steady state performance.

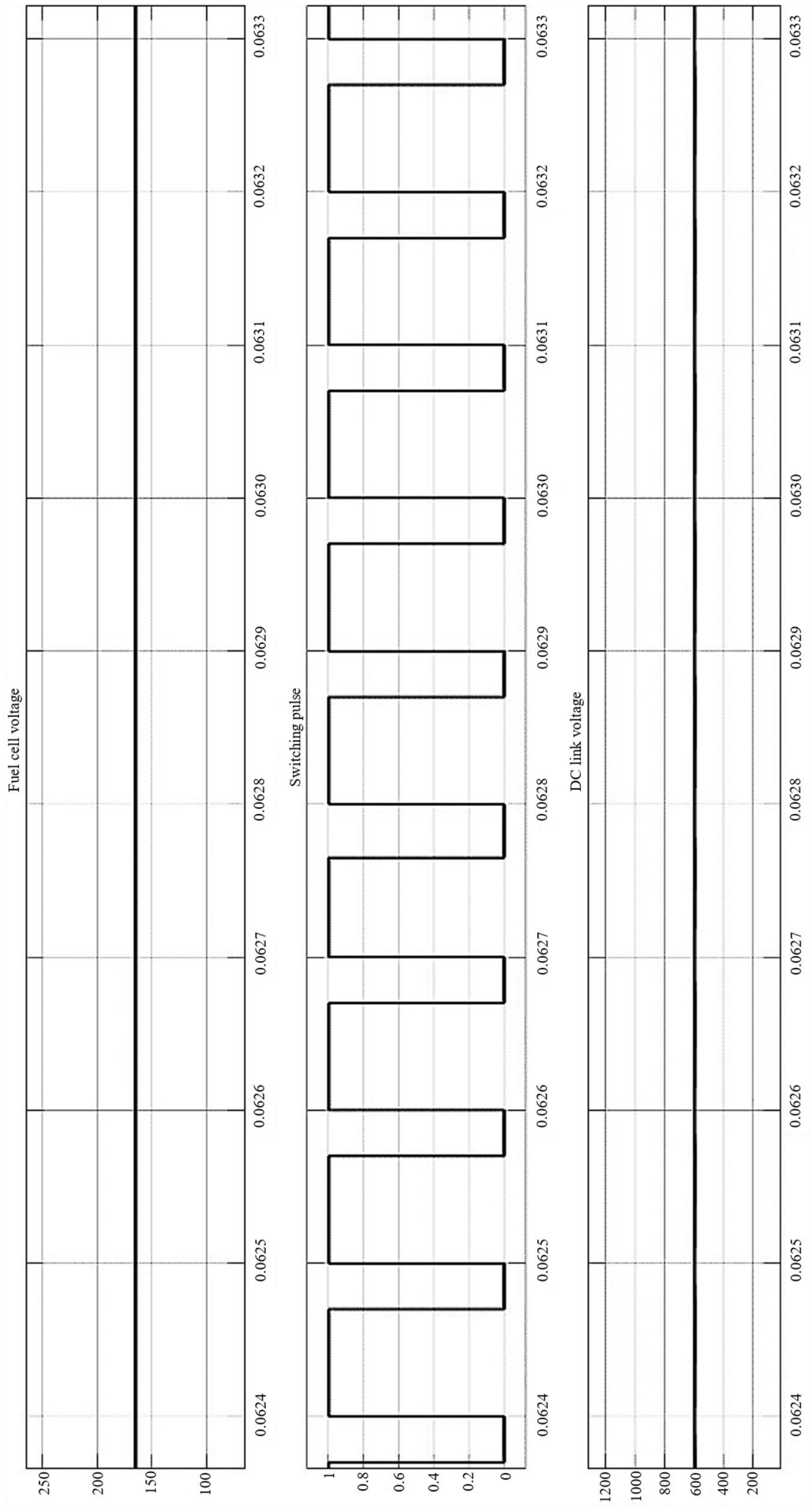

Figure 8. DC link control.

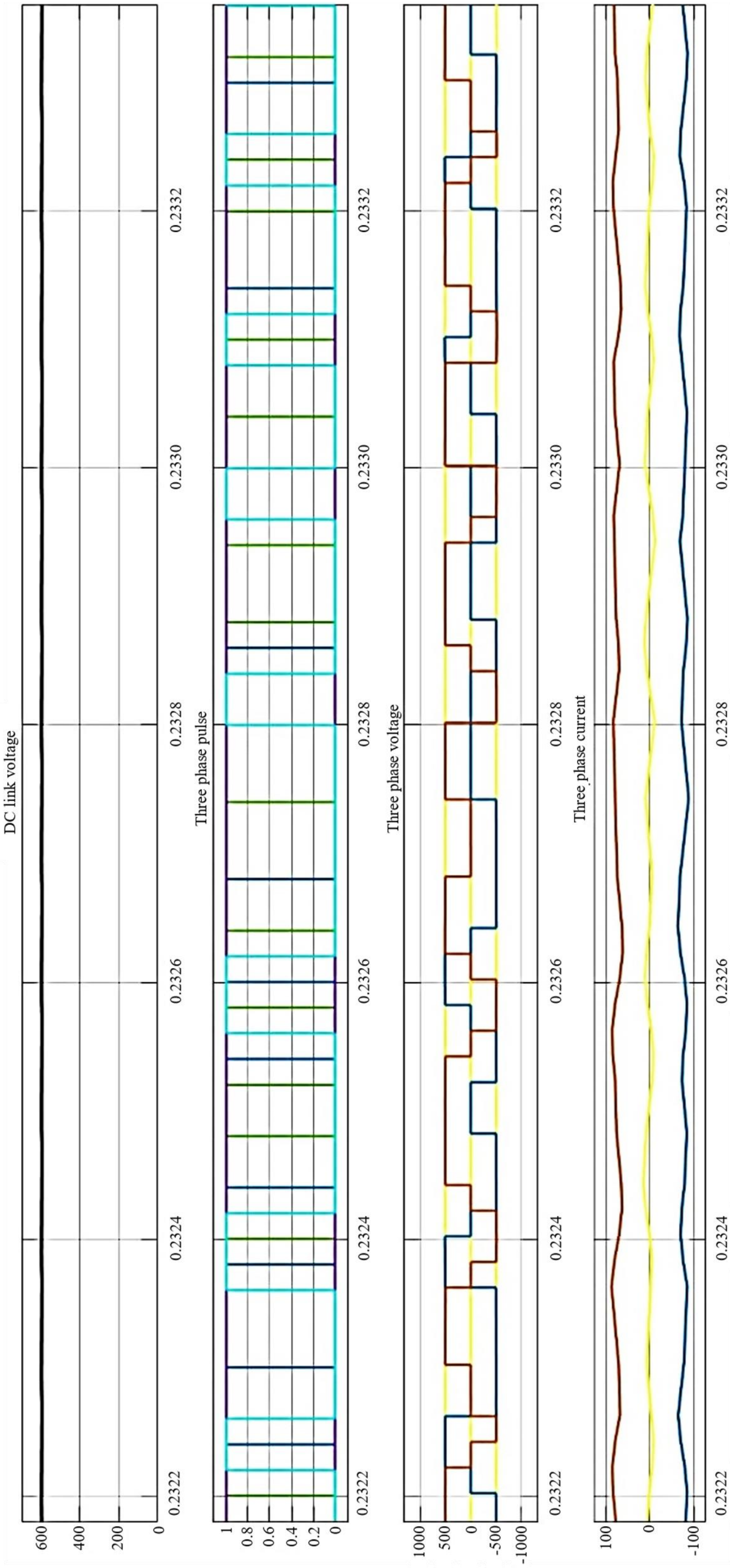

Figure 9. Steady state performance of three phase motor.

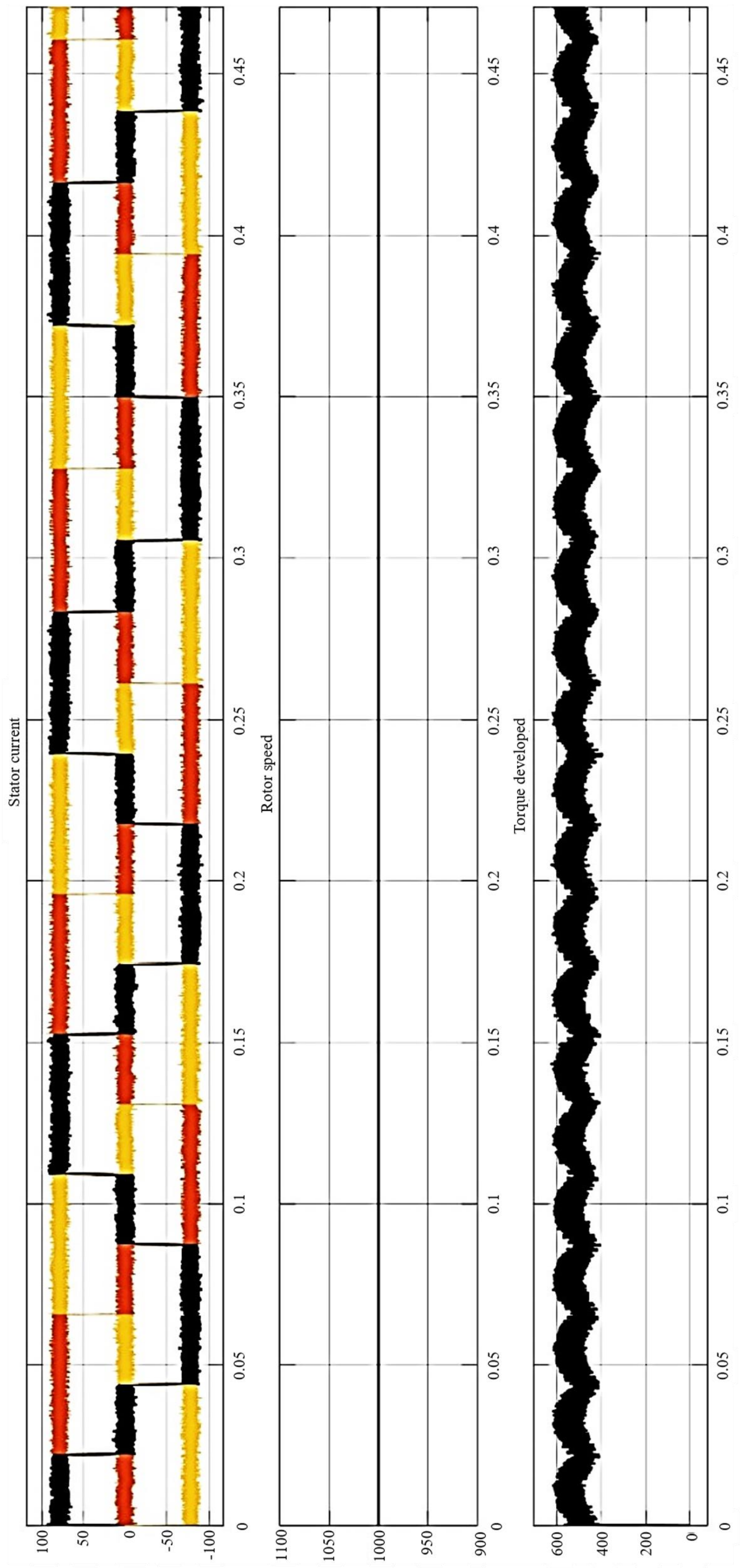

Figure 10. Torque-current performance of three phase motor.

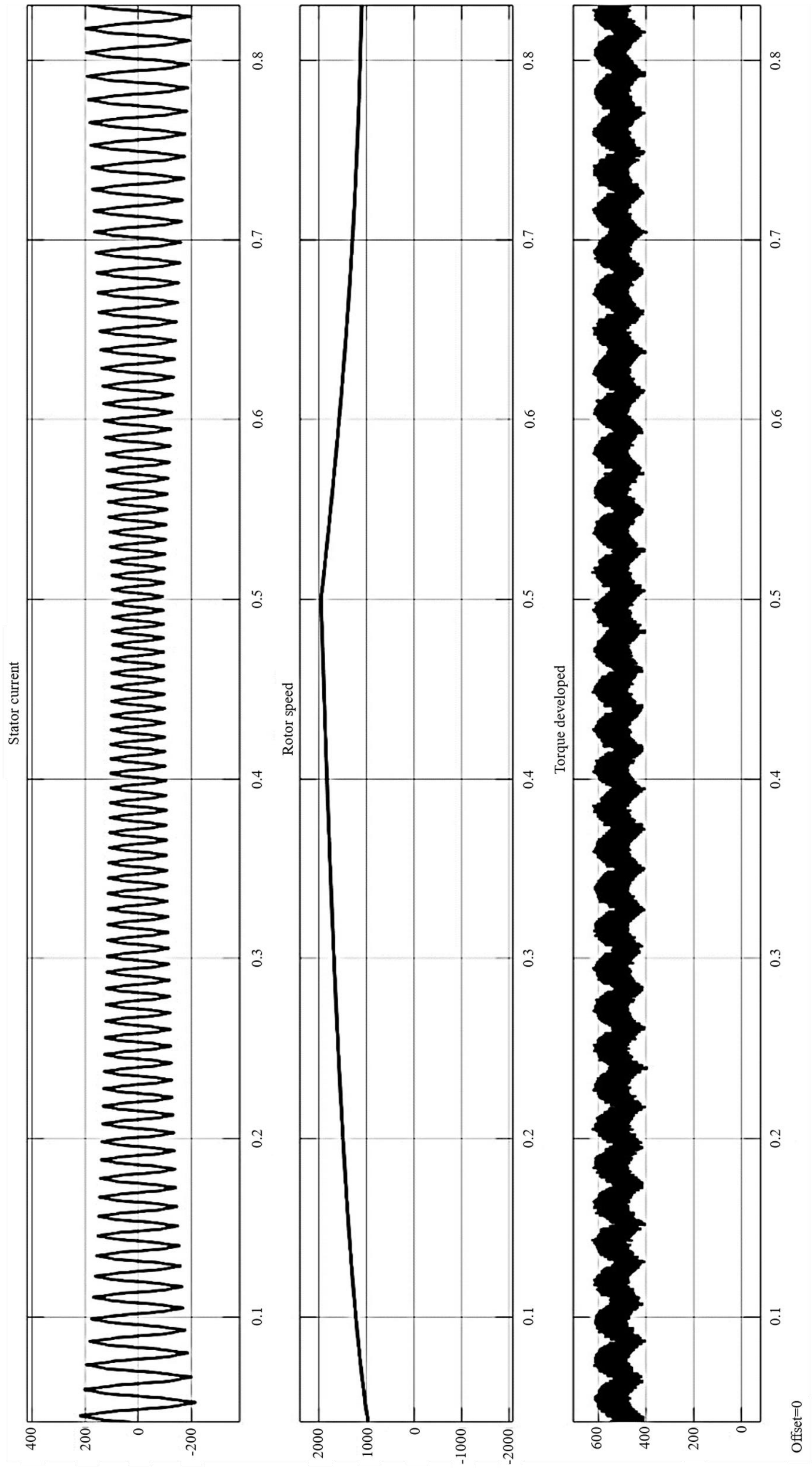

Figure 11. Dynamic performance of three-phase motor.

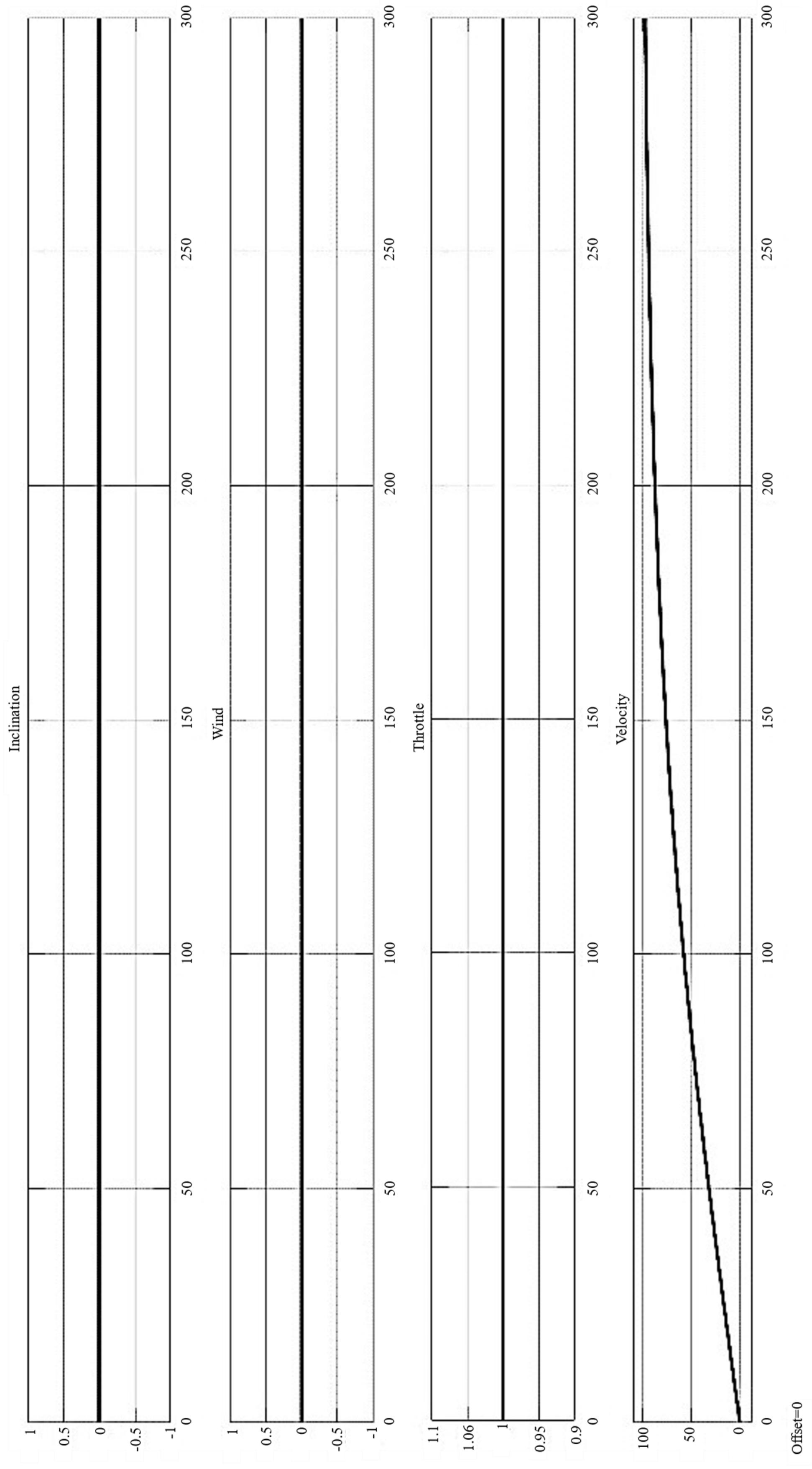

Figure 12. Vehicle dynamics.

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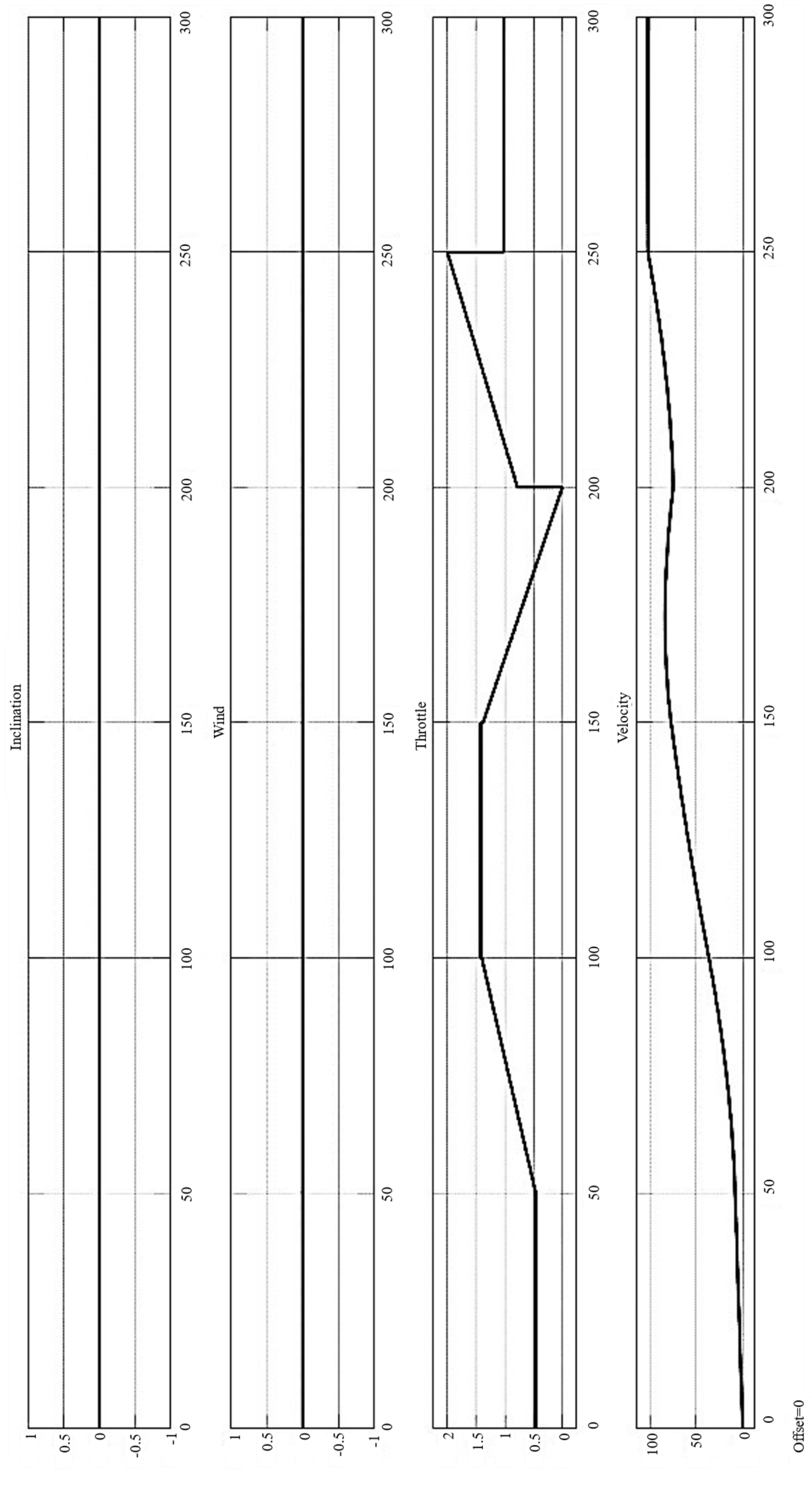

Figure 13. Vehicle dynamics under various throttle condition.

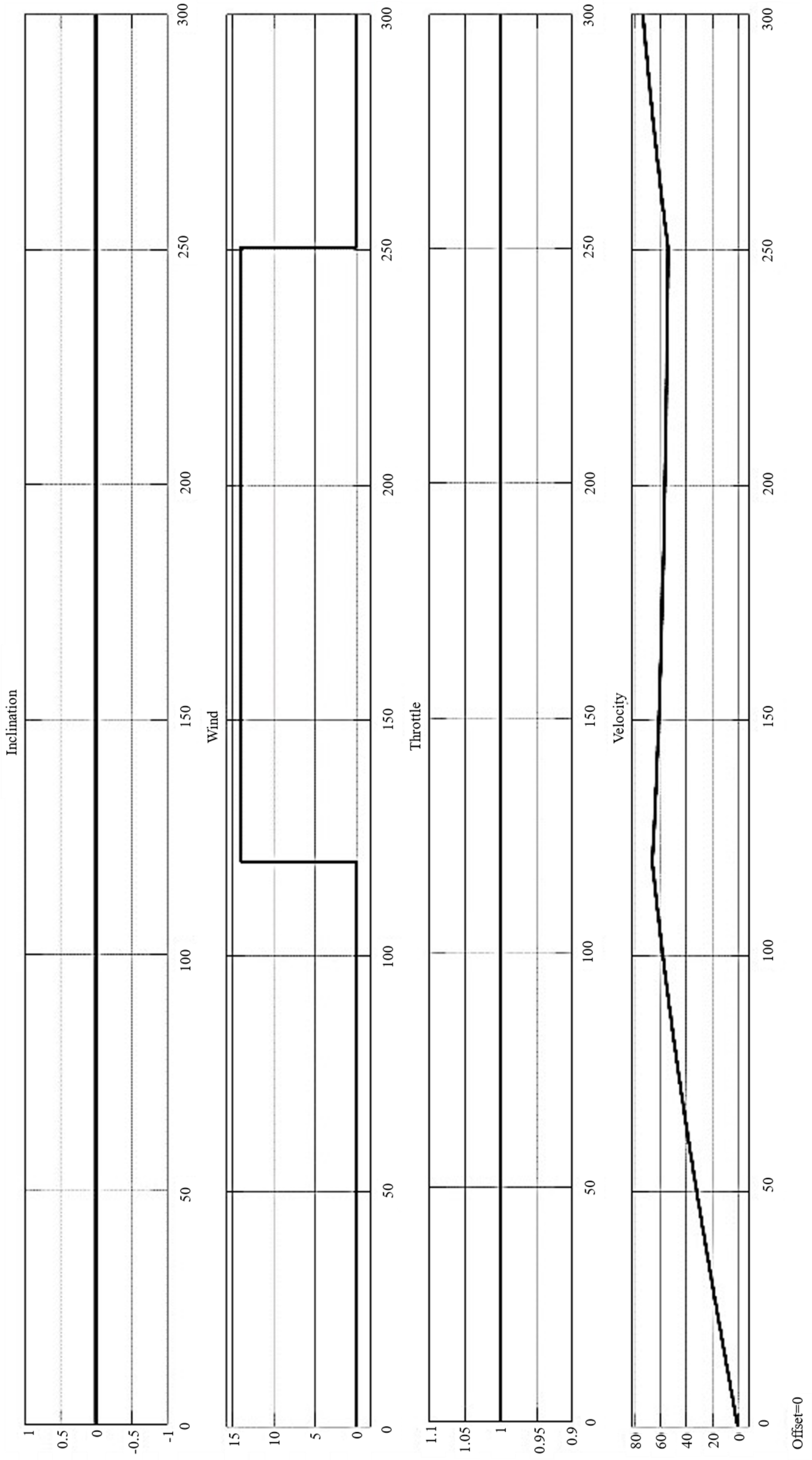

Figure 14. Vehicle dynamics under various condition.

SUMMARY

In this proposed paper, the steps for the design, implemen- tation, and verification of a fuel cell electric vehicle have been clearly discussed. For stea the DC link voltage constant. The simulation results validate the proposed design. For future work, the proposed design is implemented with the real case environment and constraints of the vehicle. The study of the power requirement of electric vehicles is done by considering the environmental conditions. The assumed data are standard values obtained from the real- life electric vehicle. The paper gives an alternative solution to conventional motors used. A permanent magnet synchronous motor (PMSM)has an advantage over conventional methods. The design and validation of PMSM are done in the proposed paper. The results lead to the conclusion that by controlling the speed of the motor or varying the torque developed we can con- trol the speed of the electric vehicle. The results are being tested using a four-wheel drive mechanism in MATLAB/SIMULINK.dy-state and dynamic performance at different throttle conditions are successfully done By keeping the DC link voltage constant . The simulation results validate the proposed design. For future work, the proposed design is implemented with the real case environment and constraints of the vehicle. The study of the power requirement of electric vehicles is done by considering the environmental conditions. The assumed data are standard values obtained from the real-life electric vehicle. The paper gives an alternative solution to conventional motors used. A permanent magnet synchronous motor (PMSM)has an advantage over conventional methods. The design and validation of PMSM are done in the proposed paper. The results lead to the conclusion that by controlling the speed of the motor or varying the torque developed we can con- trol the speed of the electric vehicle. The results are being tested using a four-wheel drive mechanism in MATLAB/SIMULINK.

CONCLUSIÓN

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