Technical Sciences, 2023, 26, 5–15

Yearbook peer-reviewed scientific journal
ISSN 1505-4675
e-ISSN 2083-4527
TECHNICAL SCIENCES
Homepage: https://czasopisma.uwm.edu.pl/index.php/ts/

UNIWERSYTET WARMIŃSKO-MAZURSKI W OLSZTYNIE

DOI: https://doi.org/10.31648/ts.8257

AN OPTOELECTRONIC SYSTEM FOR CONTROLLING A DIRECT CURRENT MOTOR. PART 1: ELECTRICAL AND ELECTRONIC DESIGN

Zenon Syroka

ORCID: 0000-0003-3318-8495
Faculty of Technical Sciences
University of Warmia and Mazury in Olsztyn

Received 2 October 2022; accepted 18 December 2022; available online 19 December 2022.

K e y w o r d s: digital control, motor controller, electric and hybrid vehicles, microcontroller.

A b s t r a c t

An optoelectronic system for controlling a direct current (DC) motor is presented in Part 1 of the article. The software for the designed motor is described in Part 2. A system for processing data from an infrared transmitter was built. The project was upgraded in successive stages of development, and it ultimately evolved into a small computer with a motor controller. The designed system automatically adjusts the motor's rotation and speed. The user is tasked only with conveying operational commands. The entire system is based on a single microcontroller.

The designed optoelectronic system receives user commands (the program can be modified to support free-space optical communication networks conforming to all communication standards). The system activates the motor, counts the number of rotations and adjusts the motor's position.

The designed system operates on the following principle: the user sends commands to the motor via a remote control with an infrared diode. The keys on the remote control have been programmed with different commands. The transmitted data are processed by the system which activates the motor and sets the desired motor speed. The task is completed, and the system is ready to process the next command. If the number of rotations differs from the preset value, the motor's position is adjusted. If the physical position of the rotor axis is altered, the system corrects the offset to the last programmed position. The designed system can be easily adapted to various types of motors and IR controllers.

Correspondence: Zenon Syroka, Katedra Elektrotechniki, Energetyki, Elektroniki i Automatyki, Wydział Nauk Technicznych, Uniwersytet Warmińsko-Mazurski w Olsztynie, ul. Oczapowskiego 11, 10-719 Olsztyn, e-mail: zenon.syroka@uwm.edu.pl, syrokaz@onet.eu.

Introduction

Wireless infrared devices for controlling direct current (DC) motors use free-space optical communication networks. Free-space optical data links rely on electromagnetic radiation in the visible or the infrared spectrum which is sent by the transmitter to the receiver, where electric charge – the control signal – is generated by a stream of photons. The signal is then amplified, demodulated and processed. In this solution, the signal is carried by the free space between the transmitter and the receiver. Various sources of electromagnetic interference with a wavelength similar to the wavelength at which the transmitter and the receiver operate can limit the applicability of the above solution. In indoor premises, electromagnetic interference is generated by heat sources, lamps and sunlight, and the number of potential disruptors is likely to increase over longer communication distances. Despite the above, numerous devices can be implemented in free-space optical communication systems, including distance sensors, slotted optical switches with aperture width of several millimeters to more than 10 centimeters, remote controls for household equipment with a range of several meters, data transmission systems used by telecommunications companies, such as VLC and FSO with data transmission speeds of up to 10 GB/s and a range of more than 10 kilometers, as well Lunar Laser Communication Demonstration (LLCD) which relies on laser light to communicate with a receiver station across a distance of several hundred kilometers (385 km).

The aim of this study was to develop an optoelectronic system for controlling a DC motor. A system that processes data from an infrared transmitter and handles tasks broken into data frames was built. The project was upgraded in successive stages, and it ultimately evolved into a small computer with a motor controller. The designed system automatically adjusts the motor's revolution and speed. The user is tasked only with conveying operational commands.

The device receives user commands (the program can be modified to support free-space optical communication networks conforming to all communication standards). The system activates the motor, counts the number of rotations and adjusts the motor's position. The system features optoelectronic components, a DC motor and devices for controlling the motor.

The user sends commands to the motor via a remote control with an infrared diode. The keys on the remote control have been programmed with different commands. The transmitted data are processed by the system which activates the motor and sets the desired motor speed. The task is completed, and the system is ready to process the next command. If the number of revolutions differs from the preset value, the motor's position is adjusted. If the physical position of the rotor axis is altered, the system corrects the offset to the last programmed position. The designed system can be easily adapted to various types of motors and IR controllers.

A patent application for the developed system has been submitted to the patent office.

Main assumptions

The aim of this study was to develop and optoelectronic system for controlling a DC motor. The physical position of the shaft axis was monitored by two position sensors. The motor was controlled by a system which smoothly adjusts the motor's speed and direction of rotation.

– the system for controlling a DC motor should fulfill the following requirements:

– the system should be powered from a DC source with the option of using batteries for controlling mobile devices;

– the motor's rotational speed should be controlled within a wide range of values;

– motor load during start-up should be minimized;

– constant torque should be maintained on the shaft during start-up;

– the control system accessible to the user should be galvanically isolated from high-voltage circuits in the drive system;

– the user should be able to program the motor's rotational speed and monitor the motor's and the system's performance;

– system development costs should be minimal.

The following tasks were performed to meet the above requirements:

– suitable components for building the system were selected;

– software for controlling the device was developed;

– algorithms for operating the device were developed;

– the system was built on a prototype breadboard;

– the developed system was tested.

The system was designed to meet the following technical requirements:

– data should be transmitted and received via infrared wireless communication;

– the system should be easy to adapt for use in a different DC motor;

– the applicability of selected optoelectronic components for controlling a DC motor should be verified;

– the rotation of a DC motor should be controlled with similar precision to a stepper motor;

– the motor's performance should be controlled with an IR remote control;

– the designed system should be transparent, and the user should be able to modify system parameters without affecting the system's overall performance;

– the system should feature cheap and easily available components;
– the designed system should be highly reliable;
– the user should be able to monitor control parameters via a computer connected to the microcontroller;
– programming tools should be developed to calibrate the entire system;
– the impact of the external environment on the system's operation should be minimized;
– the motor's rotational speed should be controlled by pulse-width modulation;
– data transmission errors caused by noise should be eliminated.

The designed system should also meet the following functional requirements:
– minimal human control should be required to operate the system;
– the motor should be controlled and its position should be adjusted automatically;
– the system should be reliable;
– calibration data should be transparent.

Block diagram of the control system

A block diagram should present the control algorithm in a simple and transparent manner without a detailed analysis of the functional dependencies in the designed system. An optoelectronic system for controlling a DC motor is presented in a block diagram in Figure 1. The diagram was divided into seven functional blocks which illustrate the functional dependencies between system components.

The most important block is the microcontroller (*2*) which processes data and is connected to other system components. The role of each block is described below:
– (*1*) the data processing system monitors input ports and controls output ports based on the received parameters and the developed algorithm;
– (*2*) the motor controller processes the signal from the microcontroller which determines the motor's rotational speed and direction of rotation;
– (*3*) motor – a rotating DC motor;
– (*4*) the power adapter supplies the device with electricity;
– (*5*) the system for monitoring the motor's position and changes in state provides information about the position and rotation of a DC motor;
– (*6*) the system for displaying information about the motor's position presents the number of steps communicated by the microcontroller;
– (*7*) the data receiver receives commands (data frames) via an infrared link.

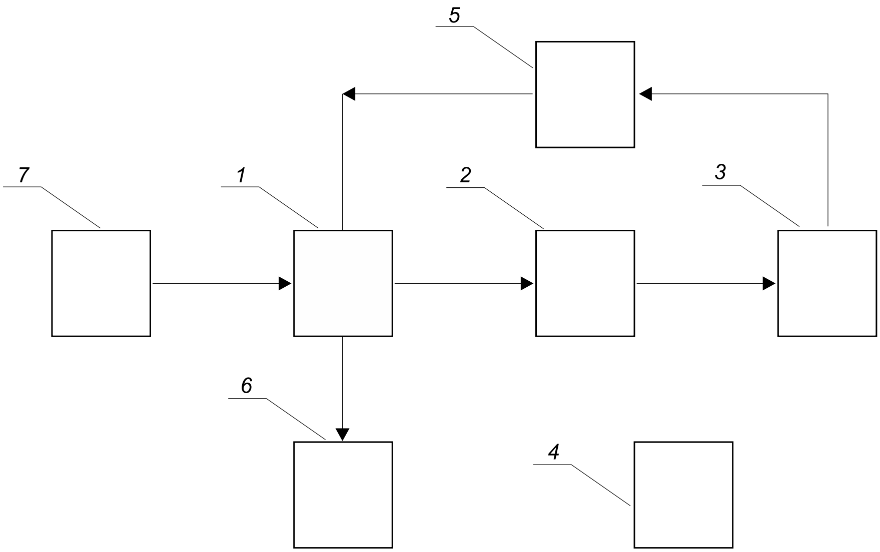

Fig. 1. Block diagram of an optoelectronic system for controlling a DC motor; *1* – data processing system; *2* – motor controller; *3* – motor; *4* – power adapter; *5* – system for monitoring the motor's position and changes in state; *6* – system for displaying information about the motor's position; *7* – data receiver

Functional diagram

The functional diagram in Figure 2 presents the functional blocks shown in the block diagram and provides detailed information about the connections between system components, including pin headers.

The diagram of the entire system, subassemblies and the connections between different components is presented in Figure 2. The main components are the data processing system (block *1*) and the system that displays information about the motor's position (block *6*). The system's operations are governed by the ATmega328p microcontroller which receives information from the optical encoder (block *5*) and TSOP32236 IR receiver (block *7*). Block 1 sends commands to the motor controller (block *2*).

The signal sent by the IR remote control is received by the TSOP32236 miniaturized IR receiver module. The module has been designed for use in remote control systems that rely on infrared light. A PIN diode and a preamplifier are assembled on a lead frame in an epoxy package that acts as an IR filter. The IR filter improves reception by blocking ambient light in the near-infrared spectrum. A demodulated input signal can be directly transmitted to the microcontroller and decoded. The supply voltage is 2.5 V to 5 V. The supply current is very low

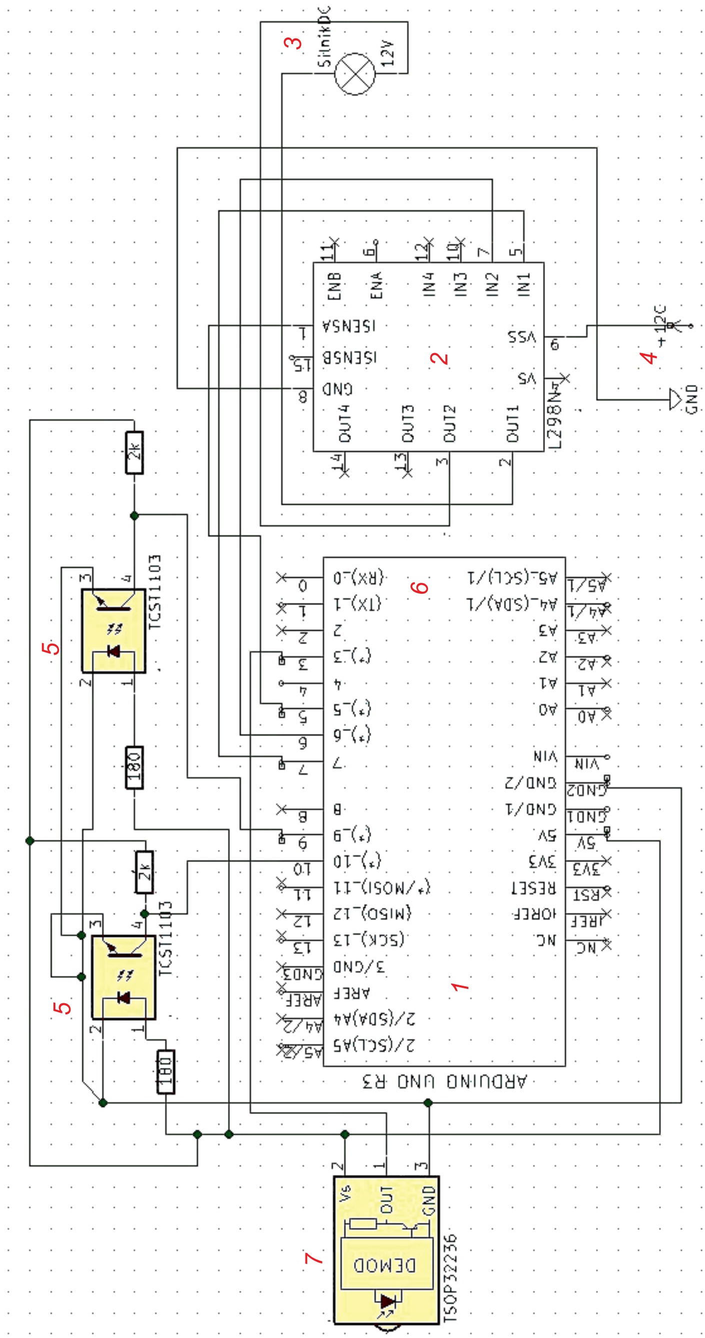

Fig. 2. Functional diagram of an optoelectronic device for controlling a DC motor. *1* – data processing system; *2* – motor controller; *3* – motor; *4* – power adapter; *5* – system for monitoring the motor's position and changes in state; *6* – system for displaying information about the motor's position; *7* – optical receiver

at 3 mA, and the output current is 5 mA. The connections of the IR receiver are shown in Figure 2.

– OUT – output pin connected to the microcontroller;
– Vs – power supply pin;
– GND – ground pin.

All IR receivers contain photodetectors that sense light. A PIN photodiode was applied in the designed system. Photodetectors are semiconductors that operate on the same principle as photoemitters, but in a reversed order. When a stream of photons hits a connection, electron-hole pairs are created and electric current is generated. Cheap photodetectors are made of silicon and receive light in the range of 780–950 nm. PIN diodes, avalanche diodes and phototransistors can be applied as photodetectors. Photodetectors, in particular Darlington photodetectors, are highly sensitive, but they are characterized by relatively slow response times and sensitivity to temperature. Phototransistors are used in presence detection sensors, speed sensors and position sensors. They can be also applied for data transmissions, but with low speed. A photodiode is more resistant to saturation and has a faster response time.

Encoders measure position and changes in state that influence the rotational speed and direction of DC motors. A shielded rotary encoder was installed between two slotted TCST1103 optocouplers. The encoder tracks the rotation of the motor shaft and counts pulses, which enables precise motor control.

The TCST1103 transmission sensor contains an IR emitter (LED diode) and a phototransistor, positioned on opposite sides. The maximum supply voltage is 70 V, and the maximum current is 60 mA for the emitter and 100 mA for the detector. The optocoupler also contains a filter that blocks visible light to eliminate interference. The LED diode emits IR light with 950 nm wavelength. The sensor is encased and features 4 labeled pins for easy connection.

A phototransistor is activated by light with a specific wavelength. Bipolar phototransistors are most popular. Bipolar transistors have transparent casing, and the base-collector junction features a PIN photodiode. When photons hit the photodiode, electron-hole pairs are created, and the generated electric current controls the base-emitter junction. The greatest advantage of a phototransistor is that unlike a photodiode and an integrated IR receiver, a phototransistor possesses internal gain that does not have to generated outside the system. However, a photodiode has to generate sufficient current to control a junction, and response times are slow. Photodiodes applied in transistors have to generate relatively high current, they are highly sensitive and produce more noise. A phototransistor is a hybrid between a transistor and photodiode; therefore, it has the same characteristic parameters, but the values of these parameters differ.

Block *7* receives information from the remote control, and the received data are processed by the microcontroller. The motor (*2*) is driven by the L298N controller which receives information from the data receiver and controls the motor's rotational speed and direction. The power adapter (*4*) is connected to the controller.

The L298N controller features pins that control the operation of a DC motor, and it can be additionally supplied by a 12 V 1 A power adapter. The adapter enables motor operation at maximum voltage and maximum current intensity, and it eliminates voltage drops that could disrupt the operation of the microcontroller.

The L298N driver unit controls the direction and rotational speed of a DC motor. The L298N STMicroelectronics controller is an integrated monolithic circuit in a 15-lead Multiwatt package with 12 V supply voltage. The maximum output current is 2 A per channel. Maximum logic voltage is 5 V. The unit features a built-in 5 V voltage regulator for supplying logic systems which can be disconnected by installing a jumper. The input pins of the logic part are available on 2.54 mm ARK screw connectors, and the system can be connected to the breadboard without soldering. ARK screw connectors have been introduced as motor outputs and power inputs. A radiator is mounted to the rear wall of the L298N controller for improved heat transfer. The L298N is a dual H-bridge controller that can simultaneously drive two DC motors or one stepper motor. An H-bridge is an electronic circuit that switches the polarity of the voltage applied to a load, and can be applied to change the direction of a DC motor. The simplest H-bridge features four connecting elements. When two terminal wires are connected, the motor is polarized to rotate in a given direction. When the remaining two wires are connected, polarization is reversed, and the motor rotates in the opposite direction. The circuit features four NPN transistors. High voltage drops are a disadvantage of this solution. When the motor is supplied with 5 V voltage, the voltage in the motor is much lower (3-4 V) due to a drop in the collector-emitter saturation voltage of two active transistors. The entire system should be provided with an overvoltage-protect circuit featuring diodes. However, when the system is switched, the current flowing through supply transistors could be too high, and the transistors could be damaged. This problem can be resolved by reducing current with a resistor, but the more powerful the motor, the greater the increase in current, which could damage the system. Voltage drops can be minimized with MOSFET transistors. Due to gate polarization, MOSFET transistors should be replaced by two P-type and two N-type transistors. In a MOSFET transistor, the gate should be polarized relative to the source, which is why the gate for P-type transistors is polarized relative to power supply, and the gate for N-type transistors is polarized relative to the ground. Voltage drops are caused only by RDS-ON resistors with very low resistance. Control systems featuring MOSFET transistors are influenced by the polarity of the input signal, and the same potential cannot be used to control different types of transistors. By contrast, regular transitions are connected in pairs to produce high current gain.

Fully integrated H-bridges have been designed for a wide range of automotive applications. They have overtemperature protection and better parameters than the designed system. Integrated H-bridges have TTL logic design (0-5 V), and they can be controlled with microcontrollers.

Ready-made modules speed up the selection of system components, and they can be easily replaced when the results are unsatisfactory or when the initial design assumptions are modified. Ready-made modules have features and components that facilitate system operation.

The controlled device was a worm gear DC motor (3). A rotary encoder was installed on the rotor shaft. The encoder is connected to optocouplers to monitor the motor's rotation. The worm gear simulates the motor's operation under load and features a self-locking mechanism which facilitates control and enables the user to predict the motor's behavior during operation. The components of the designed control system have the following characteristics:

– DC motor without worm gear – brushed DC electric motor with input voltage of 9-15 V; idle speed – around 7500 rpm; rated voltage – 12 V; idle current – 0.06 A; average power consumption – 0.22 W;

– worm gear: 1:150 reduction ratio; rotational speed – 50 rpm; materials – plastic and metal. The worm gear features a self-locking mechanism;

– rotary encoder: external diameter – 35 mm, opening diameter – 4 mm; distance between openings – 13 mm.

An optoelectronic rotary encoder measures rotational speed based on the photoelectric effect. It is composed of a disc with transparent and opaque segments. Infrared light transmitters are mounted on one side, and IR sensors are attached on the other side of the disc. When the disc rotates, the emitted light pulse reaches IR sensors, which leads to changes in voltage. Pulses are counted to determine angular displacement. Measurement accuracy is determined by the number of slits in the disc.

Conclusions

An optoelectronic system for controlling a DC motor was designed. The developed system processes data from the IR transmitter and handles tasks broken into data frames. The system receives user commands (the program can be modified to support free-space optical communication networks conforming to all communication standards), activates the motor, counts the number of rotations and adjusts the motor's position.

The designed system was built around an Arduino microcontroller which is relatively cheap, enables system modifications in the design stage and can be easily adapted during programming, which saves time and facilitates project performance. The Arduino environment can be also extended through the use of libraries which facilitate the incorporation of new modules, including modules without memory that can be easily adapted to the project's needs.

The developed system can be upgraded and modified in the future. The following solutions could be considered:

– the parameters of the DC motor could be displayed on an LCD screen;

– three motors could be mounted on the same frame to build a robotic arm or a plotter;

– a proportional integral derivative controller could be incorporated into the program to control motor rotation;

– the code for receiving user commands could be expanded;

– a rotating encoder with a larger number of slits could be applied to increase control precision;

– rotational speed could be measured during the motor's operation.

References

ALI E., KHALIGH A., NIE Z., LEE Y.J. 2009. *Integrated Power Electronic Converters and Digital Control*. CRC Press, Boca Raton.

BOLTON W. 2006. *Programmable Logic Controllers*. Elsevier, Amsterdam, Boston.

BUSO S., MATTAVELLI P. 2006. *Digital Control in Power Electronics*. Morgan & Claypool Publisher, San Rafael, CA.

CHEN C.-T. 1991. *Analog and Digital Control system Design: Transfer Function, State Space, and Algebraic Methods*. Saunders College Publishing, Filadelfia.

DENTON T. 2016. *Electric and Hybrid Vehicles*. Routledge, San Diego.

DORF R.C., BISHOP R.H. 2008. *Modern Control System Solution Manual*. Prentice Hall, New Jersey.

FADALI S. 2009. *Digital Control Engineering, Analysis and Design*. Elsevier, Burlington.

FEUER A., GOODWIN G.C. 1996. *Sampling In Digital Signal Processing and Control*. Brikhauser, Boston.

GABOR R., KOWOL M., KOŁODZIEJ J., KMIECIK S., MYNAREK P. 2019. *Switchable reluctance motor, especially for the bicycle*. Patent No 231882.

GREGORY P. 2006. *Starr Introduction to Applied Digital Control*. Gregory P. Starr, New Mexico.

GLINKA T., FRĘCHOWICZ A. 2007. *Brushless DC motor speed control system*. Patent No.P195447.

HUSAIN I. 2003. *Electric and Hybrid Vehicles, Design Fundamentals*. CRC Press LLC, Boca Raton, London.

JONGSEONG J., WONTAE J. 2019. *Method of controlling constant current of brushless dc motor and controller of brushless dc motor using the same*. United States Patent Application Publication, US2018323736 (A1).

KHAJEPOUR A., FALLAH S., GOODARZI A. 2014. *Electric and Hybrid Vehicles Technologies, Modeling and Control: a Mechatronic Approach*. John Wiley & Sons, Chichester.

KOLANO K. 2020. *Method for measuring the angular position of the shaft of a brushless DC motor with shaft position sensors*. Patent No.P235653.

KOJIMA N., ANNAKA T. 2019. *Motor control apparatus and motor unit*. United States Patent Application Publication, US2019047517 (A1).

LANDAU I.D., Zito G. 2006. *Digital Control Systems Design, Identification and Implementation*. Springer, London.

LUECKE J. 2005. *Analog and Digital Circuits for Electronic Control System Applications Using the TI MSP430 Microcontroller*. Elsvier, Amsterdam, Boston

MI CH., MASRUR M.A., GAO D.W. 2011. *Hybrid Electric Vehicles Principles and Applications with Practical Perspectives*. John Wiley & Sons, Chichester.

MOUDGALYA K.M. 2007. *Digital Control*. John Wiley & Sons, Chichester.

MURRAY R.M., LI Z., SHANKAR SASTRY S. 1994. *A Mathematical Introduction to Robotic Manipulation*. CRC Press, Berkeley.

OGATA K. 1995. *Discrete Time Control Systems*. Prentice-Hall, New Jersey.

PISTOIA G. 2010. *Electric and Hybrid Vehicles Power Sources, Models, Sustainability, Infrastructure and the Market*. Elsevier, Amsterdam, Boston.

SIKORA A., ZIELONKA A. 2011. *Power supply system for a BLDC motor*. Patent No. P.394971.

SOYLU S. 2011. *Electric Vehicles – the Benefits and Barriers*. Edited by Seref Soylu, Rijeka.

STEVIĆ Z. 2013. *New Generation of Electric Yehicles*. Edited by Zoran Stević, Rijeka.

SYROKA Z.W., JAKOCIUK D, 2020. *Battery recharging system in electric vehicle*. Patent No. P431380, filing date: 17 January 2020.

SYROKA Z.W. 2019. *Electric Vehicels – Digital Control*. Scholars' Press, Mauritius.

SYROKA Z.W., MERCHEL D. 2021. *Optoelectronic control system for an alternating current motor*. Patent decision of 5 February 2021; patent No. PL 236459.

ŚLUSAREK B., PRZYBYLSKI M., GAWRYŚ P. 2014. *Hall effect sensor of the shaft position of the brushless DC motor*. Patent No.P218476.

WILLIAMSON S.S. 2013. *Energy Management Strategies for Electric and Plug-in Hybrid Electric Vehicles*. Springer, New York, London.