EVS24
Stavanger, Norway, May 13-16, 2009

Modelling and Analysis of Energy Source Combinations for Electric Vehicles.

A. Jarushi and N. Schofield
The University of Manchester, UK

Abstract

The paper discusses a simulation platform developed in Matlab/Simulink suitable for the modelling and analysis of combined energy sources and components considered for electric vehicle power trains. While there are a number of similar simulation tools in literature, the simulation model elements each have suitable resolution to model detailed dynamic operation, an important consideration when assessing the specification requirements for the interconnection of multiple electrical components and their associated interface power electronics. Models are presented for a number of vehicle power-train components that can be interconnected to investigate alternative energy sources and power-train components proposed for electric vehicles, the combination of which is undertaken to exploit their various attributes. In particular, the paper considers the combination of an energy dense ZEBRA battery and power dense supercapacitor. The energy dense source is specified and operated to fulfil the requirements for vehicle range, while the power dense source provides the peak power for acceleration or regenerative braking and to help improve the regulation of the vehicle dc supply.

Keywords: Vehicle energy source combinations, electric vehicle models, ZEBRA battery, supercapacitors

1 Introduction

Historically, the on-board energy source for battery electric vehicles was based on lead acid technologies. Over the past 100 years, the specific power capability of this technology has increased whereas the specific energy has only slightly improved, effectively reaching a fundamental threshold dictated by the chemical composition of the cells. With the increasing interest in electrically powered vehicles, there has been a great deal of attention paid to improving batteries and producing new types of batteries with higher energy density than lead acid. Additionally, there has been great interest in using peak power buffers to mitigate against the high battery current transients encountered during urban driving. The paper discusses a simulation platform developed in Matlab/Simulink suitable for the modelling and analysis of combined energy sources and components considered for electric vehicle power trains. While there are a number of similar simulation tools in literature, the simulation model elements each have suitable resolution to model detailed dynamic operation, an important consideration when assessing the specification requirements for the interconnection of multiple electrical components and their associated interface power electronics. Models are presented for a number of vehicle power-train components that can be interconnected to investigate alternative energy sources and power-train components proposed for electric vehicles, the combination of which is undertaken to exploit their various attributes. In particular, the paper considers the combination of an energy dense ZEBRA battery and power dense supercapacitor. The energy dense source is specified and operated to fulfil the requirements for vehicle range, while the power dense source provides the peak power for acceleration or regenerative braking and to help improve the regulation of the vehicle dc supply.

2 Multiple energy sources

During urban driving the electric vehicle on-board energy source has to supply a mean energy input to the vehicle power-train and manage power peaks for vehicle acceleration and regeneration. These power transients stress the battery reducing lifetime. Also, the voltage regulation during these power transients results in an over-specification of the power-train traction components. To improve it is interesting to consider hybridisation of the on-board energy source, i.e. to combine the battery, and energy source, with a component that is more power dense. There are many options of energy source combinations for electric vehicles, as illustrated in Fig. 1. The combination studied in this paper will be an electro-chemical battery and supercapacitor combination

Supercapacitors are capable of supplying high power for short time durations without damage to their internal structure, thus the life-cycle of supercapacitor systems can be much greater than that of the battery [1, 2].

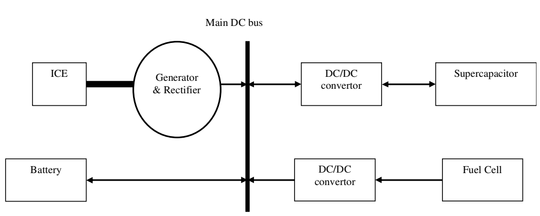


Fig. 1. Options for electric vehicle energy source combinations.

The combined use of different energy sources highlights the problem of their integration, these sources are generally characterised by different operating voltages, for this reason it is necessary to interpose power electronics between the sources and implement a control strategy that matches their output voltages achieve the desired management of power flow. Further, the addition of a power buffering system adds additional mass to the vehicle energy source which could be used more effectively to store electro-chemical energy, i.e. simply providing a larger battery mass. However, the power buffer unit not only reduces the power transients exchanged by the on-board energy source, but also helps to reduce the traction system voltage regulation, an important consideration in the sizing of the traction inverter and machine.

3 Vehicle systems

The vehicle model is structured into two kinds of components; the vehicle parameter components and energy system components, as shown in Fig. 2 showing the battery and supercapacitor configuration studied here.

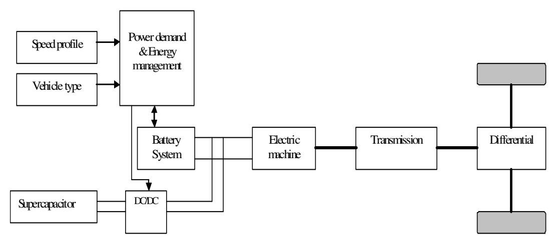


Fig. 2. Electric vehicle power-train model.

3.1 Vehicle parameters

In order to evaluate power-train performance under different modes of operation and to compare performance with different vehicle types, a number of vehicle driving cycles are defined comprised of standard and some operator specific cycles. Some driving cycles simulate urban driving while others are used to simulate out-of-city or motorway driving. In this model, number of driving cycles are included in the main library as well as gradient profiles for each driving cycle, as illustrated in Figs. 3 and 4.

The first simulation step in the vehicle modelling procedure is to calculate the torque needed to overcome the various forces acting on the vehicle and propel the vehicle forward. The vehicle traction force is calculated by considering the following forces:

- the force to overcome the rolling resistance caused by tyre-to-road power losses

- resistive force related to the road gradient
- drag force to overcome vehicle aerodynamic resistance, and
- transient force required to accelerate or retard the vehicle.

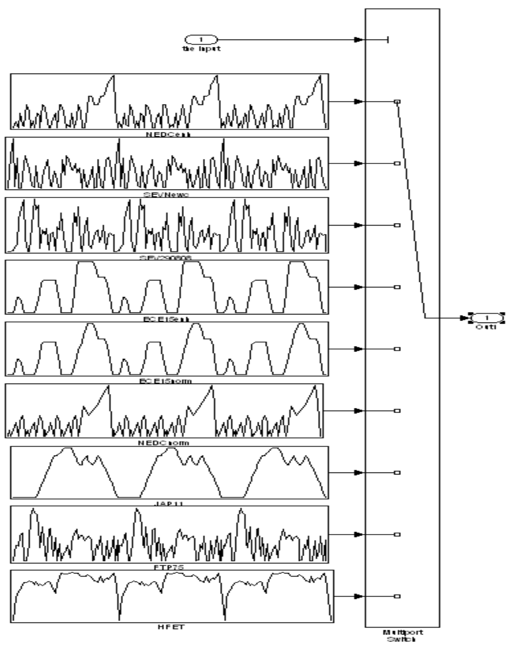


Fig. 3. Library of the driving cycles.

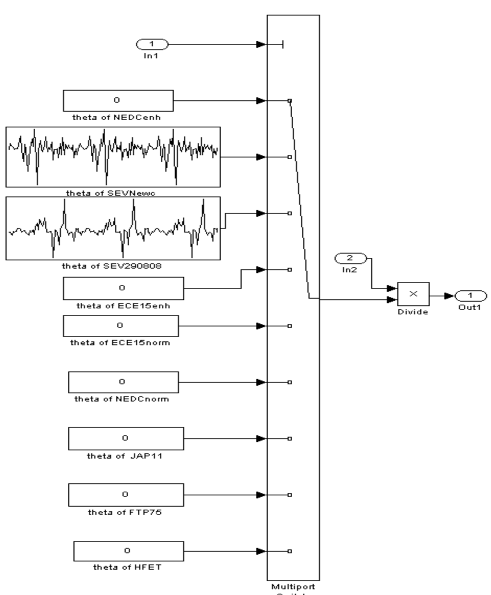


Fig. 4. Library of the driving cycles gradients

The vehicle traction torque is the summation of these elements and can be expressed as thus:

$$T_m = \left[\left(\frac{n_t J_m}{r_w} \right) + \left(\frac{J_w}{n_t \eta_t r_w} \right) + \left(\frac{r_w m}{n_t \eta_t} \right) \right] \frac{dv}{dt} + \left(\frac{r_w}{n_t \eta_t} \right) \left[(k_r \cos\theta + \sin\theta) mg + \frac{1}{2} \rho C_d A_f v^2 \right] \quad (1)$$

The parameters included in the equation depend on the vehicle type. In the model, a vehicle library contains many vehicles with their parameters, Table 1 gives some typical values.

The traction mechanical power is given by:

$$P_m = T_m \, \omega_r \quad (2)$$

where ω_r is the traction machine rotor speed. The battery power during motoring and regenerating periods is given by considering the traction drive system efficiency during motoring and generating:

$$P_{bat} = E_{eff} P_m \ or = R_{eff} P_m \quad (3)$$

where the respective efficiencies, E_{eff} and R_{eff}, are stored in a look-up table, as illustrated by Fig. 5. Battery energy is evaluated via:

$$W = \int_0^{DriveCycle} P_{bat} \, dt \quad (4)$$

Typical vehicle parameters used in the analysis are as defined in Table 1.

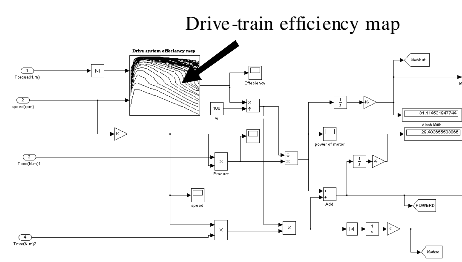


Fig. 5. Traction motor model

4 The Vehicle Energy System

The proposed energy system in this model consists of a ZEBRA battery (energy dense source) and a supercapacitor (power dense source).

4.1 The battery model

Many researches have published battery models identified via their specific chemistry [3]. Here, instead of chemical properties, the battery is modelled based on its electrical behaviour [4]. The battery model implements a detailed nonlinear characteristic of both discharge and charging resistances and open-circuit voltage.

Table 1: Vehicle Parameters

Variable	Name	Value	Units
m	Vehicle mass	2520	kg
J_m	Traction machine rotor inertia	0.57×10^{-3}	kgm^2
J_w	Wheel inertia	0.164	kgm^2
r_w	Wheel radius	0.334	m
n_t	Gear ratio	8.83	per unit
η_t	Transmission efficiency	0.95	per unit
g	Acceleration due to gravity	9.81	ms^{-2}
k_r	Tire-to-road rolling resistance	0.027	per unit
C_d	Drag coefficient	0.35	per unit
A_f	Frontal area	1.75	m^2
ρ	Air density	1.23	kgm^{-3}

Since the battery loadings are relatively low frequency (<100Hz) the battery equivalent circuit model can be simplified to that illustrated in Fig. 5. The open-circuit terminal voltage of the battery depends on battery state-of-charge (SOC), and the internal resistance depends on SOC and charging/discharging current [2, 4].

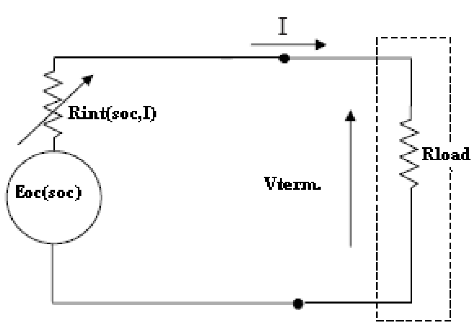


Fig. 6. Battery model

SOC is the related to the battery remaining stored energy (Ah) and is expressed as a percentage [5]. SOC of the battery is the key quantity as it is a measure of the amount of electrical energy stored, essentially working as a fuel gauge in a conventional vehicle. The available capacity of the battery changes as a function of discharge (or charge) current. For the SOC calculation, SOC is tracking according to the discharging current. The SOC calculated as from:

$$SOC = \frac{SOC' - \int I.dt}{Ah3600} \quad (5)$$

SOC' is the initial state-of-charge, I the discharging current, and Ah the capacity of the battery (Ampere-hour).

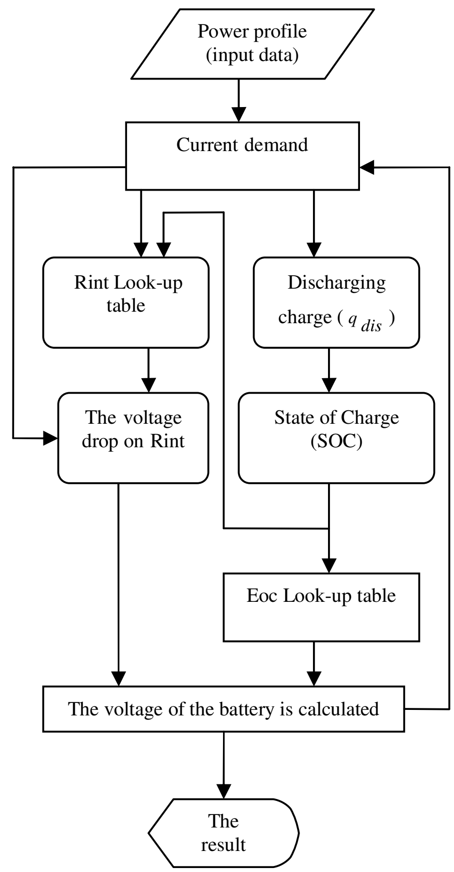


Fig. 7. The Battery Model procedure.

The model process is described in the flowchart in Fig. 7. The input of the battery model is current; the current is calculated from the power demand profile. By using the SOC equation, the internal resistance and then voltage drop on the resistance. The terminal voltage on the battery is calculated as:

$$V_{bat.} = E_{oc} - IR_{\text{int.}} \quad (6)$$

where E_{oc} is the open circuit voltage, and $IR_{\text{int.}}$ is the voltage drop due to the battery internal resistance. The proposed energy dense source is the ZEBRA Zeb5 battery details of which are described in [6].

4.2 Supercapacitor model

Unlike the battery, the supercapacitor is a very high power density device. It stores energy by accumulating, and separating, opposite charges physically where the battery stores energy chemically in reversible chemical reactions. Moreover, the supercapacitor demonstrates an excellent life cycle with the high cycle efficiency [7]. Because the SOC in the supercapacitor is directly proportional to the terminal voltage, its voltage operating range should be limited requiring electronic control of the varying voltage [7]. A unit supercapacitor of 2700 F based on a Maxwell device has been chosen to be the auxiliary energy source in the electric vehicle. The Maxwell supercapacitor model is implemented in Matlab/Simulink. The Maxwell model is composed of three primary RC branches as shown in Fig. 8.

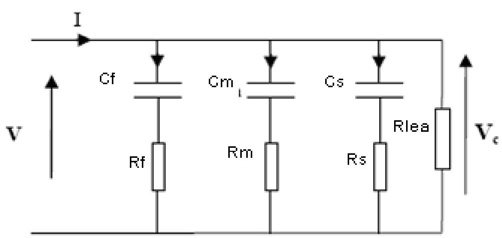


Fig. 8. Maxwell supercapacitor model [13]

5 Example simulation study

5.1 Objectives

This section presents results calculated for an all-electric urban vehicle, a 2.5 tonne taxi. The ZEBRA batteries is the primary energy source for the vehicle. The prime mover for the taxi is a brushless permanent magnet (PM) machine and integrated gear reduction and differential drive to the vehicle back-axle. The PM machine is controlled via a three-phase voltage source converter, the dc supply to which is provided by the traction battery and supercapacitor via a DC-DC converter. There are many parameters used for vehicle performance; in addition to the range that should be established by the vehicle, the regulated terminal voltage is a very important design criterion for the three-phase voltage source converter. The stored energy in the battery also needs to be used efficiently.

This study presents a comparison of three cases:

- Case1 is two ZEBRA batteries,
- Case 2 is two ZEBRA batteries plus a supercapacitor (SC) bank, and
- Case 3 is where battery system mass is increased by a mass equivalent to the SC bank and dc-dc converter mass.

The three cases have been simulated using the vehicle model to test the performance in terms of range, terminal variation voltage, and energy. The vehicle energy source performance is assessed over the NEDC driving cycle. The parameters of the high peak power (32kW) ZEBRA battery are given in [4]. The supercapacitor including the number of cells in series and parallel are set in the model.

5.2 Energy Management

By inspection of the NEDC speed profile, the high acceleration causes high current demand from the energy source. The function of the SC in this energy source combination is to enhance the demand. In order to keep the discharging battery current in battery limits, to extend the battery life cycle, thus the SC compensates the high current of the load. Power management of the system is realised by an algorithmic procedure. The principle operation is as follows:

(i) at high acceleration, the demand current is developed from the SC bank.

(ii) the batteries provide a current at a recommended rate to extend the battery life.

(iii) the remaining current demand is provided from the supercapacitor.

5.3 Results

Simulation results are illustrated in Fig. 9, and detailed in Table 2. For Case 1, the unregulated (voltage variation = 1.4V per cell), 2xZEBRA batteries could provide a range of 115 km. The traction system dc link voltage and current variation is illustrated in Figs. 10 and 11 respectively. The margin of voltage variation is approx. 300V. As the voltage regulation (variation) is tightened up, the vehicle range is decreased due to the minimum voltage limitation in the battery management unit. When the voltage minimum hits 243V (delta V= 1.13), the two batteries can not manage effective range and of energy utilisation is poor (0.61 SOC), as given in Table 2 and illustrated by the dc link voltage variation shown in Fig. 12.

In Case 2, the two ZEBRA batteries are supported by SC bank with a capacity of 50 F (54 cells of 2700F connected in series). The range is improved with good voltage regulation down to a voltage variation of 1.0V (per cell), and with good energy utilisation (SOC min. = 0.35). Fig. 13 compares the dc supply results for Cases 1 and 2 where it is clear that the SC provides the peak power for acceleration or regenerative braking and alleviates the peak power requirements of the battery.

In Case 3, the equivalent mass of the SC bank and dc-dc converter are added as additional battery, i.e. scaling the Ah, to compare with Case 2. It is noticeable from Fig. 9 and Table 2 that the range using extra battery mass is increased when compared to Case 1 which is to be expected from the additional energy. However, as with Case 1, range is compromised as the voltage variation specification is tightened below 1.15, whereas the SC and battery combination gives an acceptable range down to a voltage variation of 1.1V.

Table 2: The range of the three cases with battery states of charge.

ΔV	CASE 1		CASE 2		CASE 3	
	Range	SOC	Range	SOC	Range	SOC
1.4	115.1	0.2	133.8	0.1	138.1	0.22
1.3	105.9	0.28	133.8	0.1	128.9	0.28
1.25	103.7	0.29	133.8	0.1	126.6	0.29
1.2	103.7	0.29	133.8	0.1	126.6	0.29
1.15	103.7	0.29	110.4	0.26	117.4	0.35
1.13	57.78	0.61	110.3	0.29	70.38	0.61
1.12	23.37	0.84	108	0.28	34.84	0.81
1.11	11.9	0.93	108	0.28	11.9	0.93
1.1	3.8	0.98	108	0.28	3.8	0.98
1	0.4	0.99	96.58	0.35	0.4	0.99

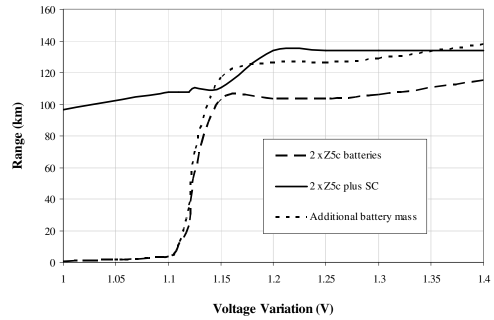


Fig. 9. Range at different voltage variation

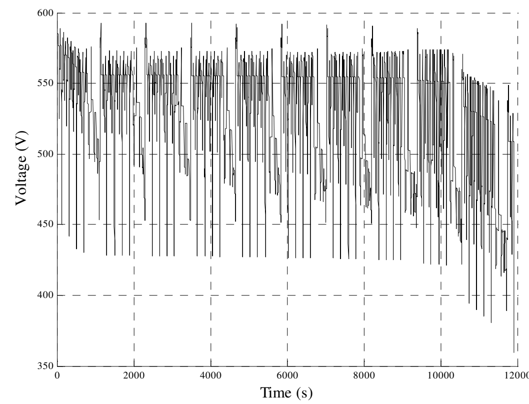


Fig. 10. Voltage for Case1 when ΔV=1.4

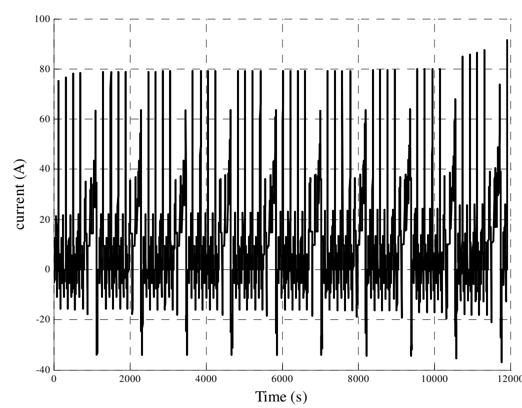


Fig. 11. Current for Case1 when ΔV=1.4

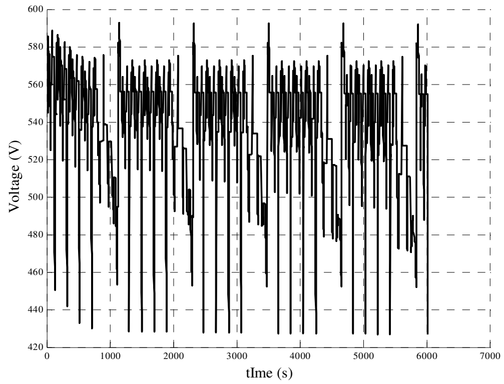


Fig. 12. Voltage of Case1 when ΔV=1.125

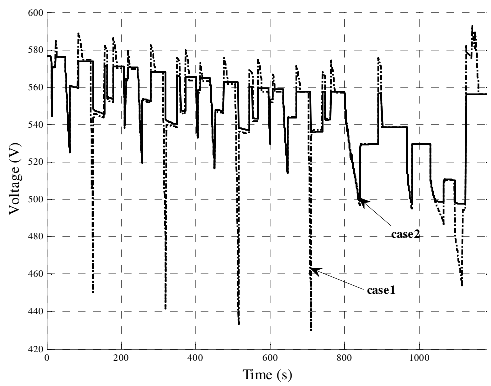


Fig. 13. Voltage for Case 1 and 2 when ΔV=1.125

6 Conclusions

The vehicle model has been simulated in Simulink/Matlab environment; the model contains many vehicle types and driving cycles libraries. Energy system components such as ZEBRA battery and supercapacitor have been modelled. The losses of the components in traction power train are considered.

One of the case studies, taxi vehicle, is studied to test the performance of the vehicle in terms of range, voltage variation, and energy. Three cases are considered, the first case is taxi powered by two ZEBRA batteries; the second case is two ZEBRA batteries with a supercapacitor and the third case presented by extra battery equivalent to the supercapacitor and dc/dc converter mass is added to the ZEBRA battery. The Cases 1 and 3 showed poor regulation of the vehicle traction system dc voltage.

Acknowledgments

The authors acknowledge the Libyan Government for provision of a Ph.D. research studentship.

References

[1] Mierlo j. V., Bossche P. V., Maggetto G., "Models of Energy Sources for EV and HEV: fuel cell, batteries, ultra capacitor, flywheel and engine-generator", journal of power sources 128, pp. 76-89, 2004.

[2] Schofield N., Yap H. T., "Hybrid Energy Sources for Electric Vehicle Propulsion", EET 2007 European Ele-Drive Conference, Brussels, Belgium, May 30 – June 01, 2007.

[3] Sutanto D., Chan H.L., and Fok C.C., Battery Model for use in Electric Vehicle and Battery Energy Storage System, EPE'99, Lausanne, 1999,pp.1-10.

[4] John C., Baskar V., "Estimating the state of charge of the battery", IEEE Transaction on control system technology, Vol 13, No. 3, May 2005.

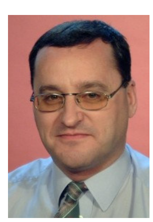
[5] Jarushi A., Schofield N., "Multiple Battery Systems for Electric Vehicles", EVS24, Stavanger, Norway, May 13-16, 2009

[6] Zubieta, B. Richard, "Characterization of double layer capacitors for power electronics applications", IEEE Transactions on industry applications, Vol.36, No. 1, January/ February 2000.

[7] Zubieta, B. Richard, "Characterization of double layer capacitors for power electronics applications", IEEE Transactions on industry applications, Vol.36, No. 1, January/ February 2000.

Authors

Ali M. Jarushi received the Master degree from the University of Putra, Malaysia (UPM) in electrical and electronic engineering in 2001. He is presently on PhD programme at The University of Manchester, UK. He is a member of the IEEE.



Nigel Schofield is a Lecturer in the Power Conversion Group in the School of Electrical and Electronic Engineering. He received the BEng and PhD degrees from the University of Sheffield, UK in 1990 and 1997 respectively. He is a Chartered Engineer in the UK and member of the IET and IEEE.