Lecture Notes in Mechanical Engineering

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Mechatronic Systems: Theory and Applications

Proceedings of the Second Workshop on Mechatronic Systems JSM'2014

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ISSN 2195-4356 ISSN 2195-4364 (electronic)
ISBN 978-3-319-07169-5 ISBN 978-3-319-07170-1 (eBook)
DOI 10.1007/978-3-319-07170-1
Springer Cham Heidelberg New York Dordrecht London

Library of Congress Control Number: 2014941629

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Introduction

Mechatronics combines all fields of mechanical and electrical engineering. Mechatronic systems, especially those with a high level of functional integration between mechanical systems, electronic and computer control, have become more and more important for industrial applications. They are employed in various fields, including power systems, transportation, optical telecommunications, and biomedical engineering.

This book includes 15 selected papers presented during the second edition of the Workshop on Mechatronic Systems. This event, held from March 17 to 19, 2014, in Mahdia, Tunisia, was organized within the framework of cooperation between the LAboratory of Mechanics, Modeling and Production (LA2MP) of the National School of Engineers Sfax, Tunisia, and the Laboratory Engineering of Mechanical Systems and Materials (LISMMA) of SUPMECA, in Paris, France.

The workshop provided an excellent forum where researchers from the two laboratories discussed and exchanged the latest advances in mechatronic systems, and presented their recent work and findings on the topic. The first two papers in the book deal with theoretical aspects of mechatronics, including some optimization issues and a topological approach for modeling complex mechatronic systems. The other papers present several applications of mechatronic systems, including considerations on the structural and dynamic behavior of machines. Among those applications, the use of mechatronic systems on gearboxes and the use of milling machines as rotating machines or as part of mechatronic systems highlight the importance of taking into account machine dynamic behavior in the process of designing mechatronic systems or implementing them. Other issues for mechatronic systems are dedicated to production. Collaborative networks partners and their influence on costs reduction are discussed. Products costs and quality level are investigated as objective functions to be optimized in multi-site and multi-plants manufacturing network. In this context, implementation of dedicated software is shown through practical case studies.

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Multidisciplinary Optimization of Mechatronic Systems: Application to an Electric Vehicle

Amir Guizani, Moncef Hammadi, Jean-Yves Choley, Thierry Soriano, Mohamed Slim Abbes and Mohamed Haddar

Abstract Preliminary design of mechatronic systems is an extremely important step in the development process of multi-disciplinary products. The great challenge in mechatronic design lies in the multidisciplinary optimization of a complete system with various physical phenomena related to interacting heterogeneous subsystems. In this chapter we combine model-based technique using modeling language Modelica with multidisciplinary optimization approach using ModelCenter framework for integrated modeling, simulation and optimization of mechatronic systems. This approach has been applied to the preliminary design of an electric vehicle. Modeling language Modelica has been used to model and simulate the electric vehicle and ModelCenter has been used for the multidisciplinary optimization of the electric motor and the transmission gear ratio. The presented integrated approach allows designers to integrate EV performance analysis with multidisciplinary optimization for efficient design verification and validation.

Keywords Integrated design · Multidisciplinary optimization · Mechatronic systems · Electric vehicle · Modelica · ModelCenter

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M. S. Abbes et al. (eds.), *Mechatronic Systems: Theory and Applications*,
Lecture Notes in Mechanical Engineering, DOI: 10.1007/978-3-319-07170-1_1,
© Springer International Publishing Switzerland 2014

1 Introduction

Mechatronic systems (MS) are considered as complex systems composed of many different components. Modeling, simulation and multidisciplinary optimization (MDO) of MS are extremely important steps in the design process (Craig 2009). Each component needs to be properly modeled in order to prevent wrong results and usage. The design or rating of each component is a difficult task as the parameters of one component can affect the power level of another one. There is therefore a risk that one component is inappropriately rated which might make the system unnecessary expensive or inefficient.

Several multi-domain modeling tools such as Bond-Graphs, VHDL-AMS, Matlab/Simulink and Modelica are currently used for preliminary design of MS. For instance, Modelica (Elmqvist et al. 1998) combines object-oriented concepts with multi-port methods for modeling and simulation of physical systems. It includes a declarative mathematical description of models and provides a graphical modeling approach. Multi-domain model library of lumped parameter elements can be created and added to the default Modelica library for future use. The end results of Modelica modeling approach are a system of differential-algebraic equations (DAE) that represents the complete mechatronic system (Hammadi et al. 2012a). So that, Modelica is considered as an ideal tool for preliminary design of MS. However Modelica language has limitations to integrate MDO of MS. One idea is to integrate Modelica language with MDO techniques.

ModelCenter (Long et al. 2008), developed by Phoenix Integration, is a software package that aids in the design and optimization of systems. It enables users to conduct trade studies, as well as optimize designs. It interfaces with other popular modeling tools, including Satellite Tool Kit, Matlab, Nastran and Microsoft Excel. ModelCenter has also tools to enable collaboration among design team members.

Combining ModelCenter with Modelica language allows mechatronic engineers to respond to an important need of integrated design of MS. For this reason, we propose to combine Modelica with ModelCenter to model and optimize an electric vehicle (EV). Optimization is carried out using algorithms available in ModelCenter libraries, especially the Nondominated Sorting Genetic Algorithm (NSGA II) (Deb et al. 2000).

This chapter is organized as follows: After the introduction, we present an analysis of existing solutions. Next, we describe the modeling of the EV. Then, we provide the simulation results of the EV. After that, the optimization of the EV is considered in order to demonstrate the efficiency of the developed models and the approach employed. Finally, we retrieve a conclusion.

2 Analysis of Existing Methods

Several approaches have been developed to solve the multidisciplinary design optimization problem such as concurrent subspace optimization (Braun and Kroo 1995), collaborative optimization CO (Sobieszczanski-Sobieski et al. 1998), multidisciplinary feasible design (Cramer et al. 1994), bi-level integrated system synthesis (Michelena et al. 1999), analytical target cascading ATC (Tappeta and Renaud 1997) and multi objective collaborative optimization MOCO (Choudhary 2004).

These approaches must be chosen and applied by the engineer, according to his knowledge of the problem and his skills. The functioning of these methods can vary greatly. For example Multi-Disciplinary Feasible Design (MDFD), considered to be one of the simplest methods, consists only in a central optimizer taking charge of all the variables and constraints sequentially, but gives poor results when the complexity of the problem increases (Yi et al. 2008). Other approaches, such as Collaborative Optimization or Bi-Level Integrated System Synthesis, are said bi-level. They introduce different levels of optimization (Alexandrov and Lewis 2002), usually a local level where each component is optimized separately and a global level where the optimizer tries to reduce discrepancies among the disciplines. However, these methods can be difficult to apply since they often require to heavily reformulating the problem (Perez et al. 2004) and can have large computation time. To reduce the computing time for the optimization of EVs (Hammadi et al. 2012b) proposed to combine surrogate modeling technique with Modelica language.

3 Electric Vehicle Modeling

3.1 Force Model

The forces which the electric machine of the vehicle must overcome are the forces due to gravity, rolling resistance, aerodynamic drag and inertial effect. The forces acting on the vehicle are shown in Fig. 1.

The total effort of resistance to progress that must defeat the propulsion system to accelerate the vehicle is given by (Janiaud 2011):

$$\begin{aligned} F_t &= F_a + F_r + F_g + F_I \\ &= \frac{1}{2}\rho_{air} \cdot C_{drag} \cdot A_{front} \cdot V_{car} + C_{rr} \cdot M_{car} \cdot g + M_{car} \cdot g \cdot \sin_\alpha + M_{car} \cdot \dot{V}_{car} \end{aligned} \tag{1}$$

where

$F_t[N]$	Traction force of the vehicle
$F_I[N]$	Inertial force of the vehicle
$F_r[N]$	Rolling resistance force

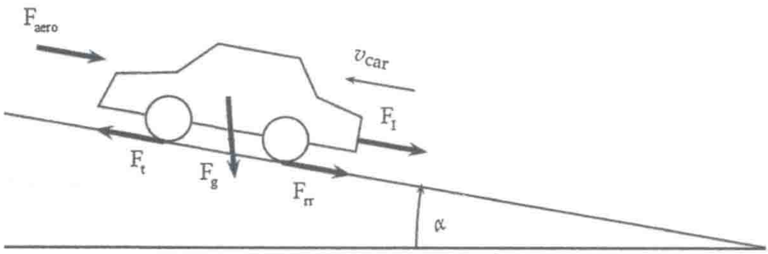

Fig. 1 Free body diagram of the forces (*thick arrows*) acting on the car

$F_g[N]$	Gravitational force of the vehicle
$F_a[N]$	Aerodynamic force
$\dot{V}_{car}[m/s^2]$	Acceleration of the vehicle
$V_{car}[m/s]$	Velocity of the vehicle
$\alpha[rad]$	Angle of the driving surface
$M_{car}[kg]$	Mass of the vehicle
$g[m/s^2]$	Free fall acceleration
$\rho_{air}[kg/m^3]$	Dry air density at 20 °C
$A_{front}[m^2]$	Frontal area
$C_{drag}[-]$	Aerodynamic drag coefficient
$C_{rr}[-]$	Tire rolling resistance coefficient

3.2 Transmission

The torque, angular velocity, and power of the transmission system are given by the following equations (Janiaud 2011):

$$\begin{aligned} \tau_t &= F_t.r_w \\ w_w &= \frac{V_{car}}{r_w} \\ P_t &= F_t.V_{car} \end{aligned} \tag{2}$$

where

τ_t [Nm]	Traction torque
$w_w[rad/s]$	Angular velocity of the wheels
$r_w[m]$	Wheel radius
$P_t[W]$	Traction power

The traction chain studied here is composed of a mechanical gearbox which connects the motor to the wheels' drive shaft. The gear is characterized by a reduction ratio Gr.

$$\begin{aligned} \tau_m &= \frac{\tau_t}{Gr} \\ w_m &= Gr.w_w \end{aligned} \tag{3}$$

where

τ_m[Nm]	Engine Torque
w_m[rad/s]	Rotation speed of the motor
Gr[-]	Gear ratio of differential

3.3 Electrical Machine: DC Motor

The functional diagram of the electric machine is represented in Fig. 2.

The electric machine is divided into an electric part and mechanic part (Krishnan 2001).

The electric part of the DC-motor is modeled by

$$U(t) = e(t) + R \cdot i(t) + L \cdot \frac{di(t)}{dt} \tag{4}$$

The mechanical part of the DC-motor can be modeled as follows:

$$J \cdot \frac{dw_m}{dt} = \tau_m(t) - \tau_f(t) - \tau_r(t) \tag{5}$$

The coupling between the electric and mechanic part is given by

$$\begin{aligned} e(t) &= K_e \cdot w_m(t) \\ \tau_m(t) &= K_c \cdot i(t) \\ \tau_f(t) &= a \cdot w_m(t) \end{aligned} \tag{6}$$

where

U[V]	Armature voltage
i[A]	Current in the armature
R[Ω]	Resistance of the armature
L[H]	Inductance of the armature
e[V]	Electromotive force
J[Kg.m^2]	Moment of inertia
τ_f[Nm]	Friction torque
τ_r[Nm]	Resisting torque

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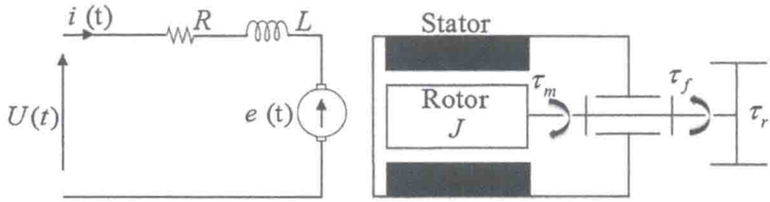

Fig. 2 The functional diagram of DC Motor

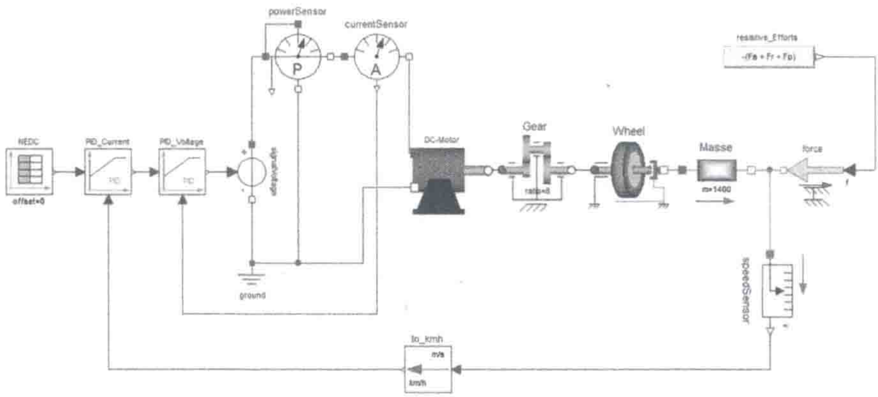

Fig. 3 Electric vehicle model performed by Modelica

K_e[V/rad/s]	Constant emf
K_c[Nm/A]	Torque constant
a[Nm/rad/s]	Coefficient of viscous friction

3.4 Modelica Modeling of the Electric Vehicle

Figure 3 shows the EV model performed using Modelica language. The EV model is composed of the following components: a step input model for velocity demand, a controller, a power sensor, a current sensor, an electric motor and a transmission.

The controller, shown in Fig. 4, is made of the association of two PID controllers (PID_current and PID_voltage), to control current and voltage, respectively. PID_current and PID_voltage have output limitations to define a maximal current Imax and a maximal voltage Umax. The controller input is connected to the velocity demand block.

A simple model of the electric motor is presented by Fig. 5. This model is used to evaluate the electrical power required by the EV. The motor model is composed of a resistance, an inductance and an electromotive component, to convert

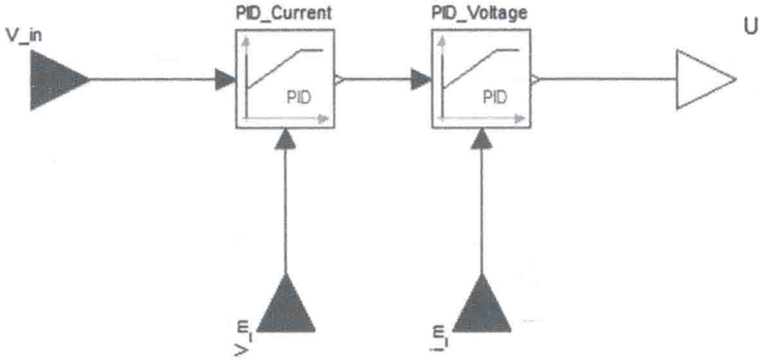

Fig. 4 Controller

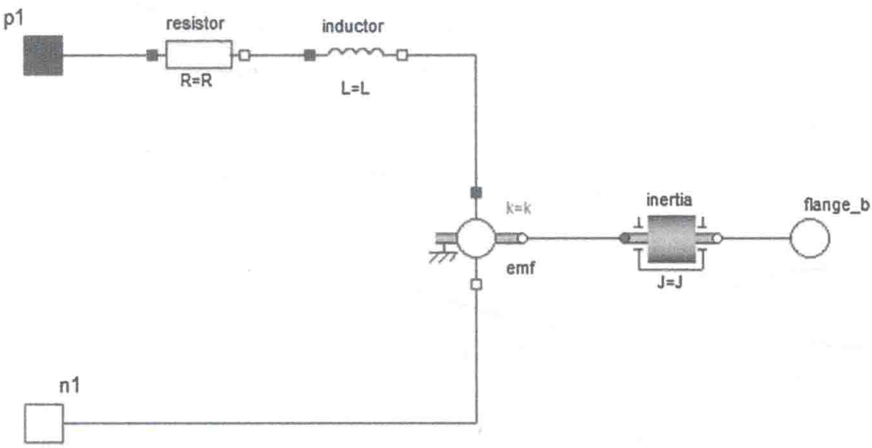

Fig. 5 Electric motor model

electrical power to mechanical power. The inertia component is added to model the motor shaft.

The transmission model is shown by Fig. 6. It is composed of an ideal gear block and a component to model the wheels supporting a tractive force F_t. The vehicle velocity V (km/h) corresponds to the transmission model output.

4 Simulation Results

In the framework of this study, a driving cycle expresses the speed evolution of the vehicle according to the time. It allows evaluating the parameter variations of the vehicle (current of the voltage source, power of the voltage source, tractive force, torque and rotational speed of the drive shaft, etc.).

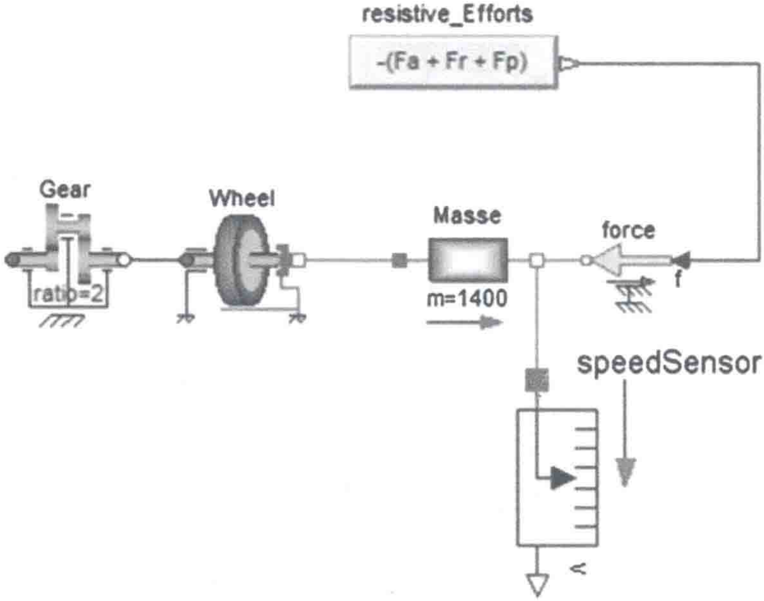

Fig. 6 Transmission model

For the sake of simulation and reproducing a road path with different driving conditions, we will be using the New European Driving Cycle NEDC (Eddine 2010).

In this study, the electromotive force EMF and the transmission gear ratio Gr are supposed known. The objective is to simulate the proposed model. Parameters used in the EV model are given in Table 1.

The simulation parameters of the vehicle according to the NEDC cycle are given by the Figs. 7, 8 and 9.

Figure 7 shows the input signal NEDC and the vehicle speed measured at the output of the component in km/h. This figure confirms that the measured velocity (red curve) follows the profile of the road (blue curve) with an error <2 %.

Figures 8 and 9 show the variation of the electric current and power during the performance test of NEDC. The electric current reaches a maximum of 280 A and the electric power reaches a maximum of 28 kW. The value of the maximum current helps in the choice of the battery.

5 Electric Vehicle Optimization

In this study, we have combined Modelica modeling language with ModelCenter for optimization of an EV. Optimization is carried out using algorithms available in ModelCenter libraries, especially a NSGA II.

Table 1 Electric vehicle parameters

Parameters	Value
Transmission parameters	
Mass of the vehicle M_{car} [Kg]	1400
Free fall acceleration g [m/s^2]	9.81
Dry air density at 20 °C ρ_{air} [Kg/m^3]	1.204
Frontal area A_{front} [m^2]	1.8
Aerodynamic drag coefficient C_{drag}	0.013
Tire rolling resistance coefficient C_{rr}	0.2
Angle of the driving surface α [rad]	0
Radius of the tire r_w [m]	0.3
Gear ratio Gr	8
Electric motor parameters	
Internal resistance R [Ω]	0.02
Inductance L [H]	0.01
Inertia of the motor I [kg/m^2]	0.03
Motor EMF [Nm/A]	0.3
Parameters to simulate	
Speed vehicle V [km/h]	variable
Electric current I [A]	variable
Electric power P [W]	variable

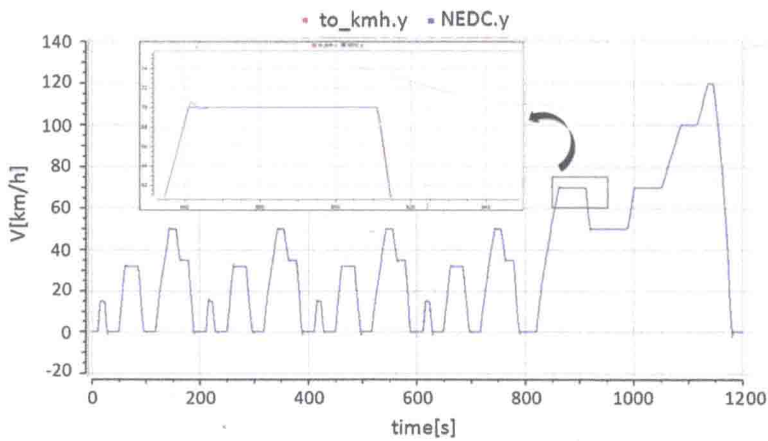

Fig. 7 Speed vehicle for NEDC input

NSGA II algorithm is adapted for multi-objective non-linear optimizing problems. Instead of finding the best design, NSGA tries to find a set of best designs (e.g., Pareto set). A design is said to be dominated if there is another design that is superior to the design in all objectives. The Pareto set consists of non-dominated designs, which are all best in a sense. The Pareto set shows trade-off among competing objectives.

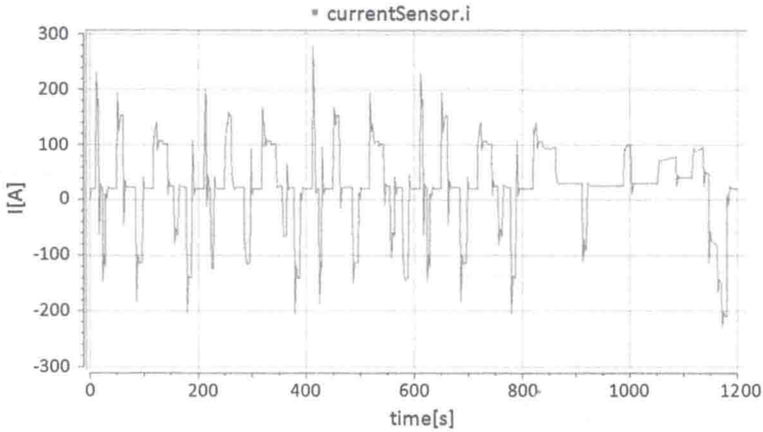

Fig. 8 Electric Current for NEDC

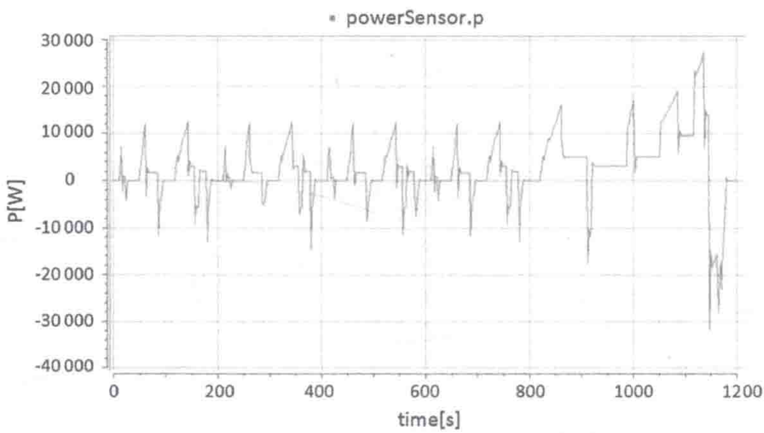

Fig. 9 Electric Power for NEDC

In this study, we are interested in optimizing the road EV in the following cases:

- horizontal road (grade = 0 %).
- 30 % grade road.

The performance requirements needed for the design of a road EV are defined in Table 2.

Based on the precedent mathematical formulation, a Modelica model of the EV has been elaborated to be simulated on an interval time of 100 s. Before starting the optimization, the NEDC cycle is replaced by a constant input V_{max} = 120 km/h (maximum speed of the vehicle).

Table 2 Performance requirements of a road electric vehicle

	V_{10} (km/h): desired velocity at time t = 10 s	V_{max}(km/h): maximal velocity	Power consumption
Optimization 1 (horizontal road)	$V_{10} = 110$	$V_{20} = 120$	Should be minimized
Optimization 2 (30 % grade road)	$V_{10} = 40$	$V_{40} = 80$	Should be minimized

Table 3 Definition of optimization problems

	Design variables	Subject to constraints	Objectives functions
Horizontal road	$2 \le Gr \le 15$	$98 \le V_{10} \le 102$	min I_{max}
	$0.1 \le EMF \le 1$	$117 \le V_{max} \le 122$	min U_{max}
30 % grade road	$2 \le Gr \le 15$	$38 \le V_{10} \le 42$	min I_{max}
	$0.1 \le EMF \le 1$	$80 \le V_{max} \le 85$	min U_{max}

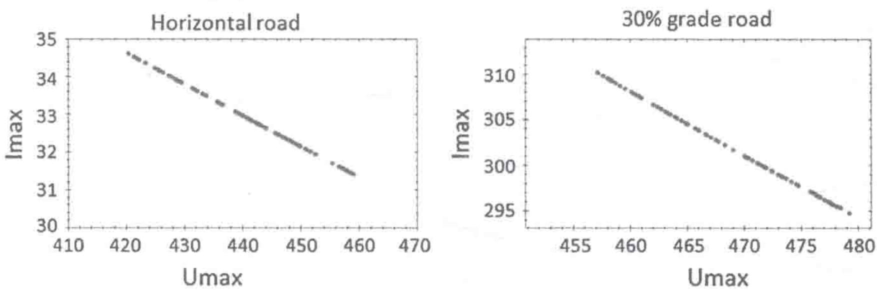

Fig. 10 Pareto front (total solution) for two optimization problems

The input design vector X for ModelCenter is defined as:

$$X = [Gr, EMF]$$

The output variables are defined with V_{10}, V_{max}, I_{max} and U_{max} which are determined by the Modelica simulations at every input design point.

$$Y = [V_{10,}\ V_{max,}\ I_{max,}\ U_{max}]$$

Optimization problems are formulated in Table 3.

Since the optimization is multi-objective, these problems have not a unique solution, but an ensemble of solutions (Pareto Front) given by the Fig. 10.

Each point of the Pareto front is characterized by an input vector X (design variables to optimize) and an output vector (objectives functions and constraints to be respected).

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