Modeling of Physical Systems Using Energetic Graphical Techniques

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UNIVERSITÀ DEGLI STUDI DI MODENA E REGGIO EMILIA

AUTOLab
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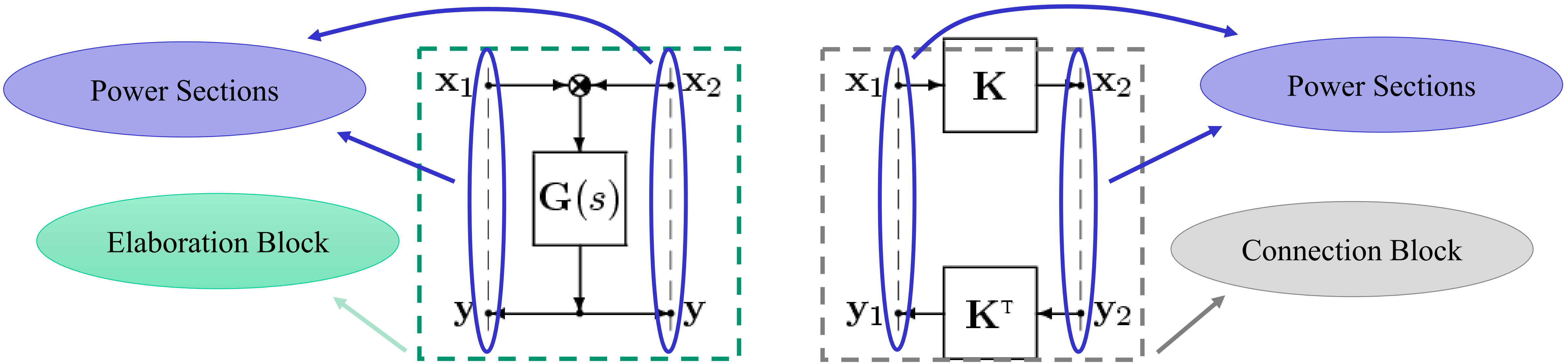
- Outline -

Introduction to Power-Oriented Graphs

Power-Oriented Graphs are "block diagrams" obtained by using a "modular" structure which is essentially based on the following two blocks:



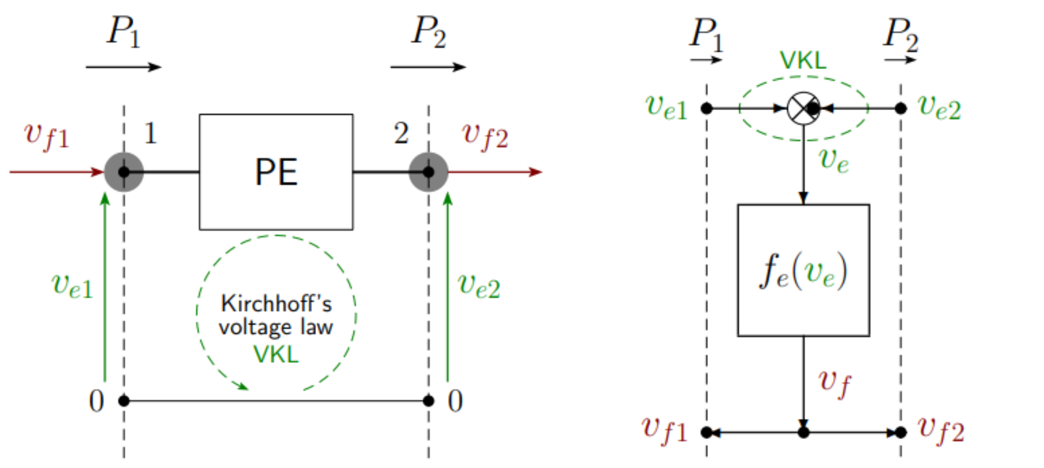
Power Sections: the POG maintains a direct correspondence between pairs of power variables and actual power flows: the product of the two power variables characterizing a section has the meaning of "power flowing through that section"

Elaboration blocks describe the dynamic/static elements that store/dissipate energy

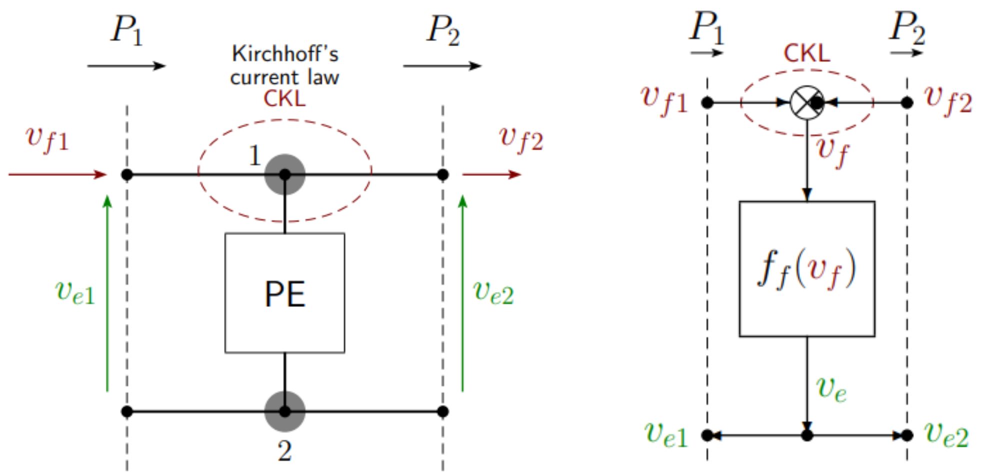
Connection blocks perform energy conversion either from one energetic domain to another or within the same energetic domain

Examples of Series/Parallel Connections

Series connection:



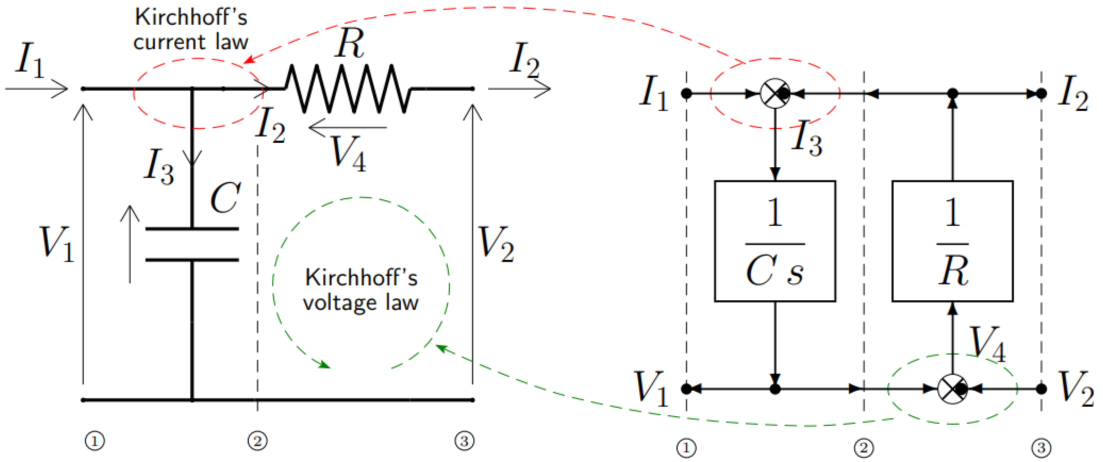
Parallel connection:



Energetic domains, physical elements, energy and power variables:

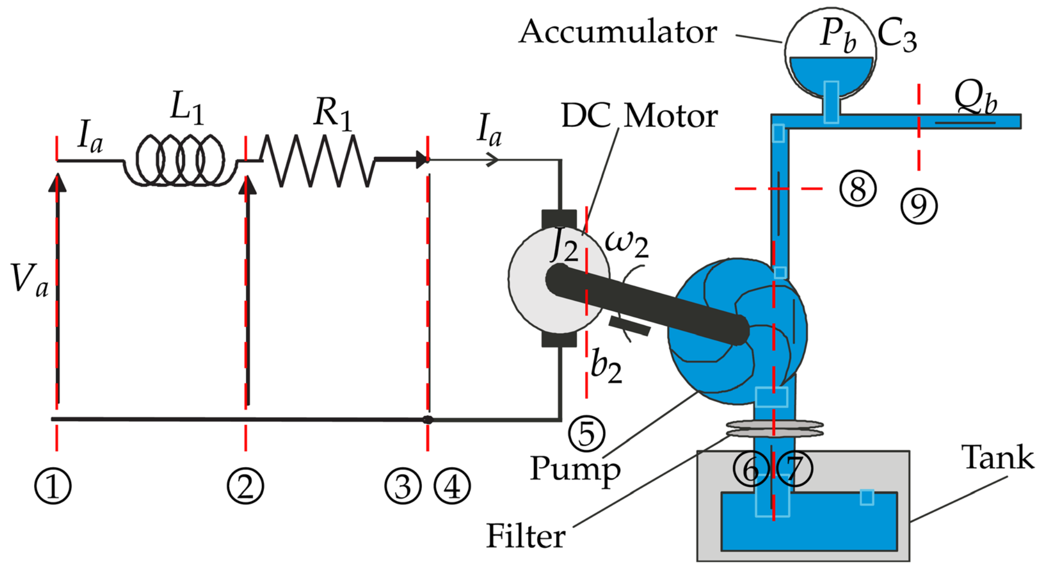
	Electrical	Mechanical Translational	Mechanical Rotational	Hydraulic
D_e	Capacitor C	Mass M	Inertia J	Hyrdaulic Capacitor C_I
q_e	Charge Q	Momentum p	Angular Momentum p	Volume V
v_e	Voltage V	Speed v	Angular Speed ω	Pressure P
D_f	Inductor L	Spring E	Rotational Spring E_r	Hydraulic Inductor L_I
q_f	Flux ϕ	Displacement x	Angular Displacement θ	Hydraulic Flux ϕ_I
v_f	Current I	Force F	Torque τ	Volume Flow Rate Q
R	Resistor R	Friction b	Angular Friction d	Hydraulic Resistor R_I

Modeling example:



First EMR-POG modeling case study: DC motor driving a hydraulic pump

DC Motor Driving a Hydraulic Pump

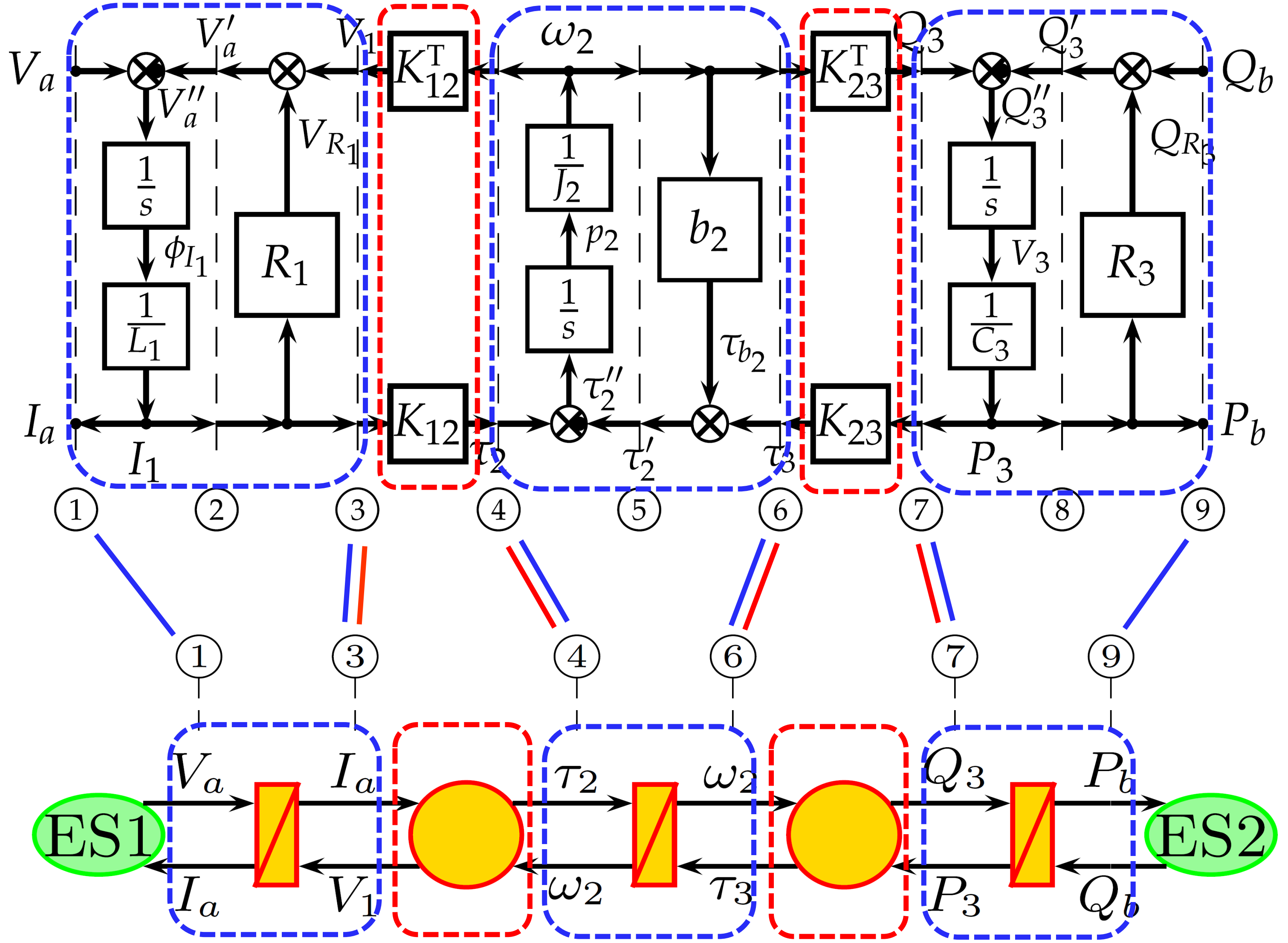


- L_1, R_1: inductance and resistance of the DC electric motor
- J_2, b_2: moment of inertia and friction coefficient of the DC electric motor
- C_3, R_3: hydraulic capacitor and hydraulic resistance of the hydraulic pump

- $V_a\ I_a$: electrical input power of the DC electric motor
- Electrical-to-mechanical energy conversion after dissipation due to R_1
- Mechanical-to-hydraulic energy conversion after dissipation due to b_2
- $Q_b\ P_b$: output power of the hydraulic pump

$$\underbrace{\begin{bmatrix} L_1 & 0 & 0 \\ 0 & J_2 & 0 \\ 0 & 0 & C_3 \end{bmatrix}}_{\mathbf{L}} \underbrace{\begin{bmatrix} \dot{I}_1 \\ \dot{\omega}_2 \\ \dot{P}_3 \end{bmatrix}}_{\dot{\mathbf{x}}} = \underbrace{\begin{bmatrix} -R_1 & -K_{12} & 0 \\ K_{12} & -b_2 & -K_{23} \\ 0 & K_{23} & -R_3 \end{bmatrix}}_{\mathbf{A}} \underbrace{\begin{bmatrix} I_1 \\ \omega_2 \\ P_3 \end{bmatrix}}_{\mathbf{x}} + \underbrace{\begin{bmatrix} 1 & 0 \\ 0 & 0 \\ 0 & -1 \end{bmatrix}}_{\mathbf{B}} \underbrace{\begin{bmatrix} V_a \\ Q_b \end{bmatrix}}_{\mathbf{u}}$$

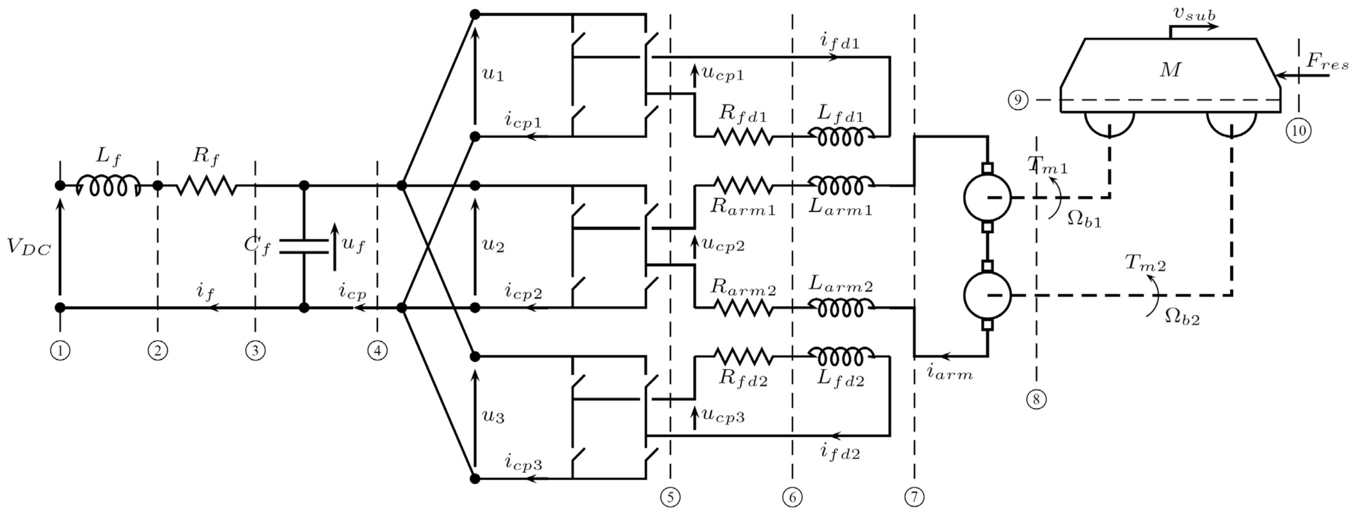
DC Motor Driving a Hydraulic Pump



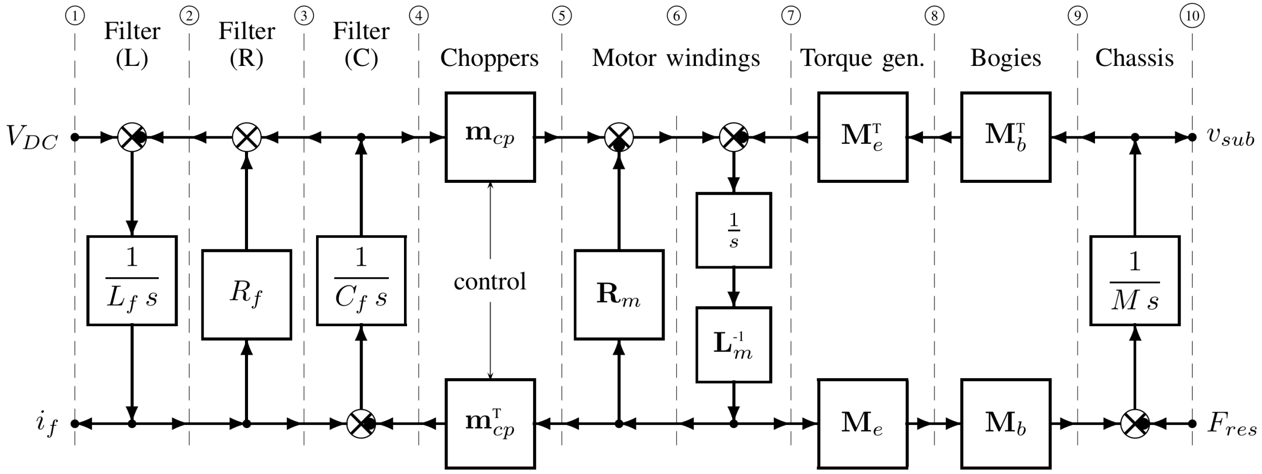
- L_1, R_1: inductance and resistance of the DC electric motor
- J_2, b_2: moment of inertia and friction coefficient of the DC electric motor
- C_3, R_3: hydraulic capacitor and hydraulic resistance of the hydraulic pump

Second EMR-POG modeling case study: subway traction system

Subway Traction System



- From sections 1 to 4: input filter
- From sections 4 to 5: choppers
- From sections 5 to 7: field and armature windings of the DC motors
- From sections 7 to 8: power links between DC motors and bogies

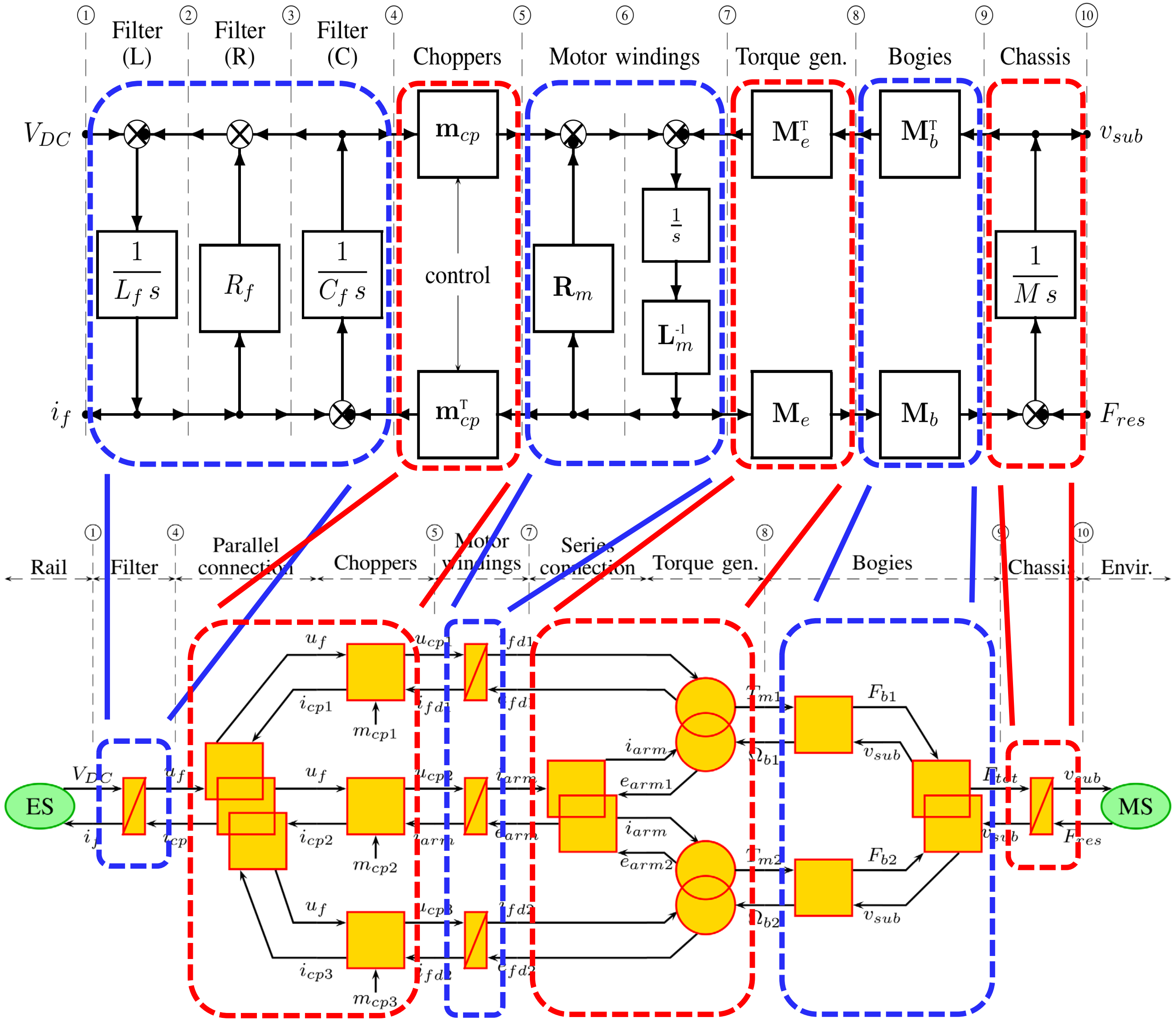


$$\mathbf{m}_{cp} = \begin{bmatrix} m_{cp1} \\ m_{cp2} \\ m_{cp3} \end{bmatrix} \quad \mathbf{R}_m = \begin{bmatrix} R_{fd1} & 0 & 0 \\ 0 & R_{arm} & 0 \\ 0 & 0 & R_{fd1} \end{bmatrix} \quad \mathbf{L}_m = \begin{bmatrix} L_{fd1} & 0 & 0 \\ 0 & L_{arm} & 0 \\ 0 & 0 & L_{fd1} \end{bmatrix}$$

$$\mathbf{M}_b = \begin{bmatrix} m_{b1} & m_{b2} \end{bmatrix} \quad \mathbf{M}_e = \begin{bmatrix} 0 & k_{dcm1}\, i_{fd1} & 0 \\ 0 & k_{dcm2}\, i_{fd2} & 0 \end{bmatrix} \quad \mathbf{u}_{cp} = \begin{bmatrix} u_{cp1} \\ u_{cp2} \\ u_{cp3} \end{bmatrix}$$

$$\mathbf{i}_m = \begin{bmatrix} i_{fd1} \\ i_{arm} \\ i_{fd2} \end{bmatrix} \quad \mathbf{e}_m = \begin{bmatrix} e_{fd1} \\ e_{arm} \\ e_{fd2} \end{bmatrix} \quad \mathbf{\Omega}_b = \begin{bmatrix} \Omega_{b1} \\ \Omega_{b2} \end{bmatrix} \quad \mathbf{T}_m = \begin{bmatrix} T_{m1} \\ T_{m2} \end{bmatrix}$$

Subway Traction System



- From sections 1 to 4: input filter
- From sections 4 to 5: choppers
- From sections 5 to 7: field and armature windings of the DC motors
- From sections 7 to 8: power links between DC motors and bogies

Comparison between EMR and POG Modeling Techniques

	POG	EMR
Energetic domains	*All known*	*All known*
Power variables	*Scalar and vectorial*	*Scalar and vectorial*
Causality	*Integral*	*Integral*
Symbolism	*Gain, Integrators and Summation Nodes*	*Pictograms*
Power Variables Direction Visibility	*Yes*	*Yes*
Main Scope	*Simulation and Analysis*	*Simulation and Control*
Simulation	*Directly in Simulink*	*Simulink library*
Graphical representation	*Linear*	*Planar*
Control structure	*No methodology*	*Methodology through inversion rules*

The POG_Modeler can be expanded towards EMR

A Matlab/Simulink program that automatically converts Simscape Schematics into the corresponding POG Model

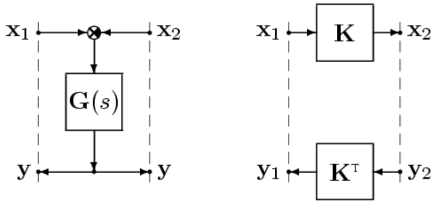
Simscape Schematic of the System → **POG Modeler Program**

Outputs of the POG Modeler Program:

- State-Space Equations of the System

$$\mathbf{S} = \begin{cases} \mathbf{L}\,\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u}, \\ \mathbf{y} = \mathbf{C}\mathbf{x} + \mathbf{D}\mathbf{u}, \end{cases}$$

- Power-Oriented Graphs Block Scheme of the System



- Ready-To-Run Matlab/Simulink Simulation Files of the System
- Latex Report containing the Model and Simulation of the System

Inputs and Outputs

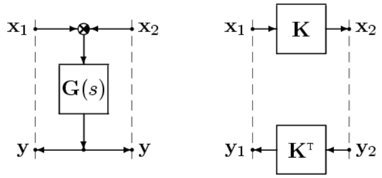
The EMR_POG_Modeler Program – Potential Extensions

Simscape Schematic of the System → **EMR_POG Modeler Program** →

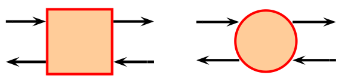
- State-Space Equations of the System

$$\mathbf{S} = \begin{cases} \mathbf{L}\,\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u}, \\ \mathbf{y} = \mathbf{C}\mathbf{x} + \mathbf{D}\mathbf{u}, \end{cases}$$

- Power-Oriented Graphs Block Scheme of the System



- Energetic Macroscopic Representation of the System



- Ready-To-Run Matlab/Simulink Simulation Files of the System
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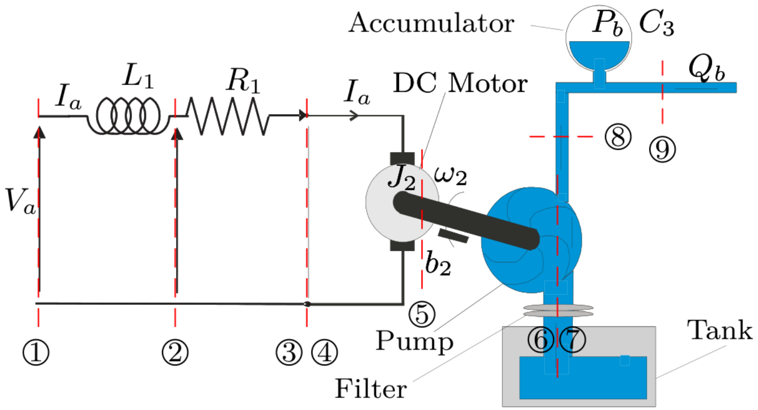
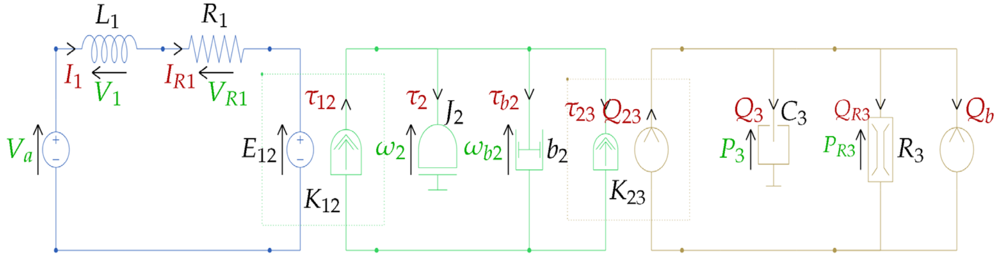
The Program – Example of Our Vision



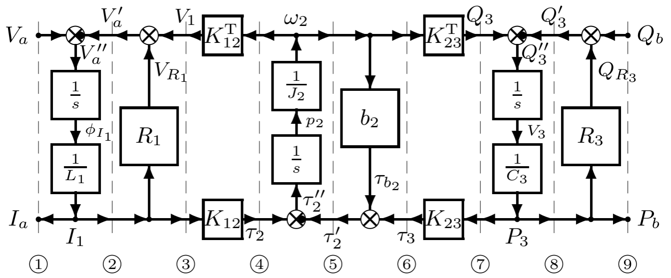
Simscape Schematic:



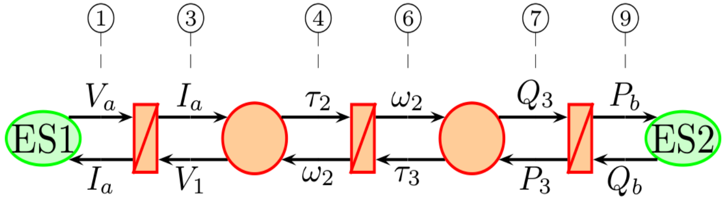
EMR_POG
Modeler
Program

State-Space Equations

POG



EMR



EMR

Control through Inversion Principle

Matlab/Simlink Simulation Files

Latex Report

Conclusions

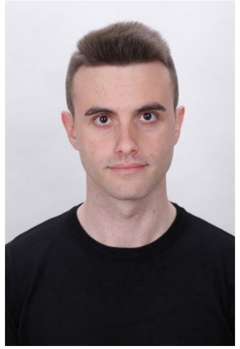
Conclusions

1. Energetic Macroscopic Representation (EMR) and Power-Oriented Graphs (POG) are energy-based techniques that can be used for modeling all types of physical systems involving power flows

2. The POG_Modeler can evolve towards a EMR_POG_Modeler

3. A unified MATLAB/Simulink program that automatically generates EMR and POG representations starting from the Simscape schematics can take advantage of both the POG state space modelling and the EMR control through inversion principle.

Biographies and references



Dr. Davide TEBALDI, University of Modena and Reggio Emilia, Italy
PhD in Information and Telecommunication Technology at University of Modena and Reggio Emilia in 2022
Assistant Prof. at University of Modena and Reggio Emilia since 2023
Associate Editor of IEEE Transactions on Transportation Electrification since 2025
Research topics: graphical modeling techniques applied to electro-mechanical systems and hybrid automotive systems, hybrid electric vehicles, power converters, electric machines, collaborative robotics

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PhD in System Engineering at University of Bologna (1992)
Full Professor at University of Modena and Reggio Emilia
Research topics: POG modeling of complex physical systems, advanced control techniques, trajectory planning, control in automotive systems

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[2] R. Zanasi "The Power-Oriented Graphs Technique: system modeling and basic properties", IEEE VPPC 2010 (Vehicular Power and Propulsion Conference), Lille, France, September 2010.

[3] R. Zanasi, G. H. Geitner, A. Bouscayrol, W. Lhomme, "Different energetic techniques for modelling traction drives", ELECTRIMACS 2008, 9th International Conference on Modeling and Simulation of Electric Machines, Converters and Systems, 8-11 June 2008.

[4] F. Grossi, W. Lhomme, R. Zanasi, A. Bouscayrol, "Modelling and control of a vehicle with tire-road interaction using POG and EMR formalisms", *ELECTROMOTION 2009*, EPE Chapter "Electric Drives" 8th International Symposium on Advanced Electromechanical Motion Systems, Lille, France, July 2009 (common paper University of Modena and L2EP Lille)

[5] F. Grossi, W. Lhomme, R. Zanasi, A. Bouscayrol, "Modelling and control of a vehicle with tire-road interaction using energy-based techniques" *IEEE VPPC 2009 (Vehicular Power and Propulsion Conference)*, Dearborn, Michigan, USA, September 2009 common paper University of Modena and L2EP Lille).

Thanks for your attention!