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POG Modeler: the Web Power-Oriented Graphs Modeling Program

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Abstract: In this paper the Power-Oriented Graphs (POG) technique is introduced and a new modeling program named "POG Modeler", freely available on the web, is presented. In the POG Modeler program the physical systems can be defined graphically using an ascii commend-line interface and referring to predefined graphic symbols. The POG Modeler automatically analyzes the given physical system and provides the following outputs: 1) the differential equations of the given system in symbolic form: 2) The POG block scheme of the considered system; 3) the Simulink block scheme of the given system ready for the Matlab environment. The POG systems are simple block schemes that can be easily used also by beginners.

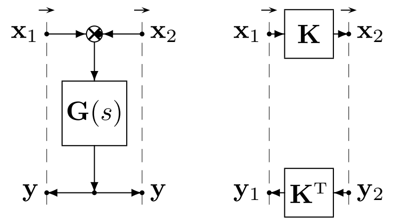
Keywords: Dynamic modeling, Dynamic simulation, Linear systems, POG Modeling technique.

1. INTRODUCTION

The Bond Graphs (BG) Paynter (1961), Karnopp et al. (2000), the Power-Oriented Graphs (POG) Zanasi (2010), Zanasi (1994) and the Energetic Macroscopic Representation (EMR) Bouscayrol ET AL. (2000), Mercieca ET AL. (2004) are graphical modeling techniques that use an *energetic approach* for modeling physical systems. The POG technique is based on the same energetic approach of the BG technique, but it uses a different graphical notation: instead of using the BG "bond/arrow" notation, it uses normal block diagrams for modeling the physical systems. The POG block schemes are easy to use, easy to understand and can be directly implemented in Simulink. The POG technique can be a useful tool for promoting the use of the energetic approach also between beginners and young researchers. A comparison between the BG, POG and EMR graphical techniques can be found in Zanasi et al. (2008). In this paper the basic concepts of POG modeling are introduced and the POG Modeler web side is presented. Examples of application of the POG graphical technique can be found in Zanasi (2010), Zanasi (1994), Morselli and Zanasi (2006), Zanasi et al. (2008), Zanasi and Grossi (2009) and Filippa et al. (2005) and the inside references.

2. THE POWER-ORIENTED GRAPHS TECHNIQUE

Basic blocks the POG technique uses only two basic blocks for modeling the physical systems, see Fig. 1:
a) the ***elaboration block*** (e.b.) is used for modeling all the physical elements that store and/or dissipate energy (i.e. springs, masses, dampers, capacities, inductances, resistances, etc.).
b) the ***connection block*** (c.b.) is used for modeling all the physical elements that "transform the power without losses" (i.e. *neutral elements* such as gear reductions, transformers, etc.). In the vectorial case matrix $\mathbf{K}$ can also be rectangular, time varying or function of other variables.



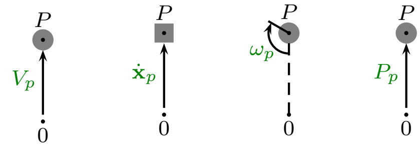
a) *Elaboration block* b) *Connection block*

Fig. 1. POG blocks: *elaboration block* and *connection block*.

Power sections the dashed lines in Fig. 1 represent the power sections which connect the two POG basic blocks with the external world. There are no restrictions on the choice of the vectors $\mathbf{x}$ and $\mathbf{y}$ involved in each dashed line except that the inner product $\langle \mathbf{x}, \mathbf{y} \rangle = \mathbf{x}^{\mathrm{T}}\mathbf{y}$ must have the physical meaning of *power flowing through the section.*

Energetic domains the main energetic domains in modeling physical systems are: electrical, mechanical (translational and rotational) and hydraulic. Each energetic domain has its own couple of power variables, see Fig. 2.

Power variables they can be divided in two groups:
1) the *"across-variables"* (i.e. voltage V_p, velocity $\dot{\mathbf{x}}_p$, angular velocity ω_p and pressure P_p) which are defined *"between two points P and 0"* of the space:



2) The *"through-variables"* (i.e. current I_p, force F_p, torque τ_p and volume flow rate Q_p) which are defined *"in each point P"* of the space:

		Electrical	Mech. Tras.	Mech. Rot.	Hydraulic
	$\mathcal{D}_e$	C Capacitor	M Mass	J Inertia	C_I Hyd. Capacitor
	q_e	Q Charge	p Momentum	p Ang. Momentum	V Volume
Across-Var.	v_e	V Voltage	v Velocity	ω Ang. Velocity	P Pressure
	$\mathcal{D}_f$	L Inductor	E Spring	E Spring	L_I Hyd. Inductor
	q_f	ϕ Flux	x Displacement	θ Ang. Displacement	ϕ_I Hyd. Flux
Through-Var.	v_f	I Current	F Force	τ Torque	Q Volume flow rate
	$\mathcal{R}$	R Resistor	b Friction	b Ang. Friction	R_I Hyd. Resistor

Fig. 2. Energetic domains: the physical elements $\mathcal{D}_e$, $\mathcal{D}_f$ and $\mathcal{R}$; the energy variables q_e, q_f; the power variables v_e, v_f.

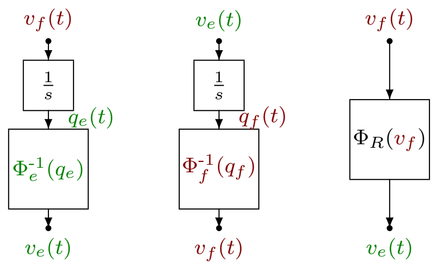


Fig. 3. *Dynamic elements* D_e, D_f and *static element* R.

Dynamic structure of the Energetic Domains each *energetic domains* is characterized by only 3 different types of physical elements:

- 2 ***dynamic elements*** D_e and D_f which store the energy (capacitors, inductors, masses, springs, etc.);
- 1 ***static element*** R which dissipates (or generates) the energy (i.e. resistors, frictions, etc.);

The system dynamics can be described using 4 variables:

- 2 ***energy variables*** q_e and q_f which define *how much energy is stored* within the *dynamic elements*;
- 2 ***power variables*** v_e and v_f which describe *the power flows* entering or exiting the physical element.

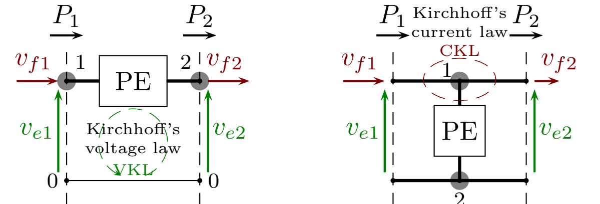
The dynamic/static elements and the energy/power variables for the considered energetic domains are shown in Fig. 2. The difference between the dynamic elements D_e and D_f is the following: the D_e elements provide the power across-variables v_e as output, the D_f elements provide the power through-variables v_f as output.

Mathematical structure of the physical elements the *dynamic element* D_e is characterized by:

1) an internal *energy variable* $q_e(t)$;
2) a *through-variable* $v_f(t)$ as input variable;
3) an *across-variable* $v_e(t)$ as output variable;
4) a *constitutive relation* $q_e = \Phi_e(v_e)$ which links the internal variable $q_e(t)$ to the output variable $v_e(t)$;
5) a *differential equation* $\dot{q}_e(t) = v_f(t)$ which links the internal variable $q_e(t)$ to the input variable $v_f(t)$;

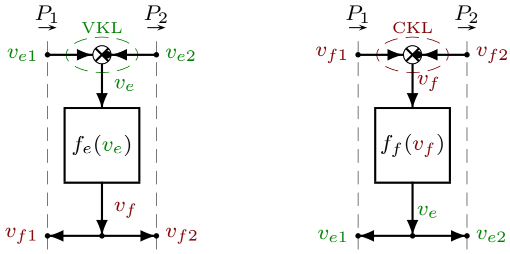
The energy E_e stored in the *dynamic element* D_e is function only of the internal *energy variable* q_e:

$$E_e = \int_0^t v_e(t)\, v_f(t)\, dt = \int_0^{q_e} \Phi_1^{-1}(q_e)\, dq_e = E_e(q_e).$$



a) Power sections in series b) Power sections in parallel

Fig. 4. Connections of the PE with the external world.



a) Connection in series. b) Connection in parallel.

Fig. 5. POG schemes of the *series* and *parallel* connections.

Integral Causality in the POG modeling technique all the dynamic elements are always described by block schemes using *integral causality*, see blocks in Fig. 3.

Power sections in series and in parallel each Physical Element (PE) interacts with the external world through the power sections associated to its terminals. The two basic power connections of the physical element PE with the external world are shown in Fig. 4: a) the connection *in series* when the two terminals share the same through-variable $v_f = v_{f1} = v_{f2}$; b) the connection *in parallel* when the two terminals share the same across-variable $v_e = v_{e1} = v_{e2}$.

The POG block schemes corresponding to the *series* and *parallel* connections reported in Fig. 4 are shown in Fig. 5:

a) The summation element present in the POG block diagram of Fig. 5.a is a mathematical description of the Voltage Kirchhoff's Law (VKL) applied to the *across variables* v_{e1}, v_{e2} and v_e involved in the *closed path* which is always present when the PE is connected in series, i.e. the green closed dashed path shown in Fig. 4.a.

b) The summation element present in the POG block diagram of Fig. 5.b is a mathematical description of the Current Kirchhoff's Law (CKL) applied to the *through variables* v_{f1}, v_{f2} and v_f involved in the "*node*" corresponding to terminal 1 of the PE connected in parallel, see the red closed dashed line shown in Fig. 4.b.

A simple example of POG modeling is shown in Fig. 6 where a C-parallel element is connected with an R-series element: this is a particular case of "*Parallel - Series*" connection: note the direct correspondence between the

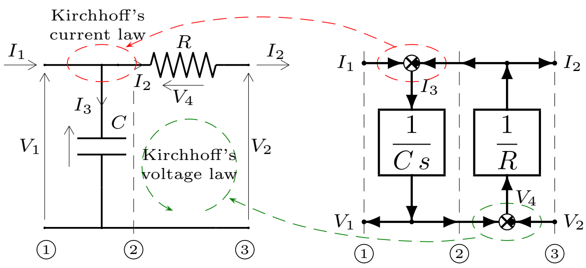


Fig. 6. POG modeling of an electrical RC circuit.

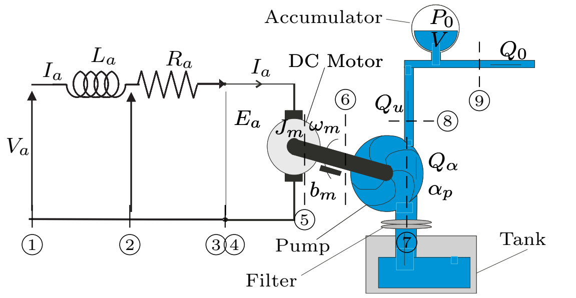


Fig. 7. A DC motor connected to an hydraulic pump.

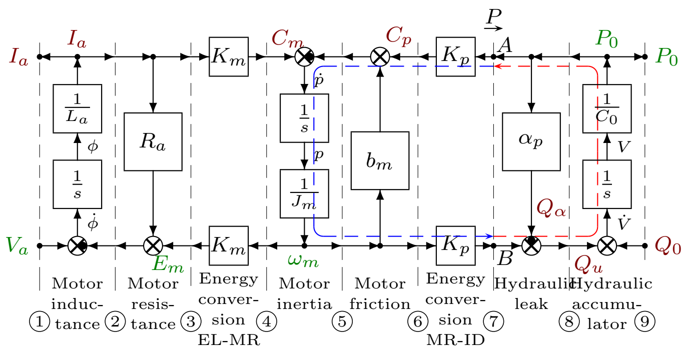


Fig. 8. POG scheme of the DC motor with hydraulic pump.

power sections ①, ② and ③ in the system and the dashed power sections ①, ② and ③ in the POG scheme.

Example of POG modeling a DC motor connected to an hydraulic pump is shown in Fig. 7. This system involves three different energetic domains: electrical, mechanical and hydraulic. The corresponding POG graphical representation in shown in Fig. 8: the power sections present in the POG scheme have a direct correspondence with the real physical sections. Let $\mathbf{x} = [I_a\ \omega_m\ V_0]^{\mathrm{T}}$ be the state vector of the system, i.e. the output variables of the dynamic elements. From the POG scheme one directly obtains the following state space dynamic model $\mathbf{L}\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u}$:

$$\underbrace{\begin{bmatrix} L_a & 0 & 0 \\ 0 & J_m & 0 \\ 0 & 0 & C_0 \end{bmatrix}}_{\mathbf{L}} \underbrace{\begin{bmatrix} \dot{I}_a \\ \dot{\omega}_m \\ \dot{P}_0 \end{bmatrix}}_{\dot{\mathbf{x}}} = \underbrace{\begin{bmatrix} -R_a & -K_m & 0 \\ K_m & -b_m & -K_p \\ 0 & K_p & -\alpha_p \end{bmatrix}}_{\mathbf{A}} \underbrace{\begin{bmatrix} I_a \\ \omega_m \\ P_0 \end{bmatrix}}_{\mathbf{x}} + \underbrace{\begin{bmatrix} 1 & 0 \\ 0 & 0 \\ 0 & 1 \end{bmatrix}}_{\mathbf{B}} \underbrace{\begin{bmatrix} V_a \\ Q_0 \end{bmatrix}}_{\mathbf{u}} \quad (1)$$

where $\mathbf{u}$ is the input vector. Matrices $\mathbf{L}$, $\mathbf{A}$ and $\mathbf{B}$ can be obtained by direct inspection of the POG scheme, see Zanasi (2010). In the considered case matrix $\mathbf{L}$ is diagonal and its elements are the coefficients of the constitutive relations ($\phi = L_a I_a$, $p = J_m \omega_m$, $V = C_0 P_0$) of the dynamic elements present in the system. The coefficients of matrices $\mathbf{A}$ and $\mathbf{B}$ are the gains of all the paths that link the state variables $\mathbf{x}$ and the input variables $\mathbf{u}$ to the inputs $\dot{\phi}$, $\dot{\omega}_m$, $\dot{V}$ of the integrators present in the system.

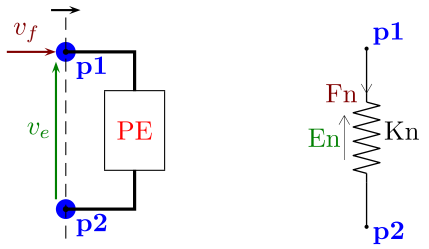


Fig. 9. The basic Physical Element "PE" of a POG system on the left, an electrical example on the right.

POG block schemes satisfy the following properties **1)** the *energy E_s stored in the system* can be expressed as $E_s = \frac{1}{2}\mathbf{x}^{\mathrm{T}}\mathbf{L}\,\mathbf{x}$; **2)** *the power P_d dissipated in the system* can be expressed as $P_d = \mathbf{x}^{\mathrm{T}}\mathbf{A}\,\mathbf{x}$; **3)** *all the loops present in a POG block scheme contains an "odd" number of minus signs* (i.e. of the black spots in the summation elements). **4)** *the direction of the power flowing through a section is positive if an "even" number of minus signs is present along one of the paths which goes from the input to the output of the section.* Let us consider, for example, the power section ⑦ of Fig. 8: the power flows from left to right because the red dashed path that goes from B to A contains "zero" minus signs (i.e. an even number).

3. THE POG MODELER

The POG Modeler is a modeling program available on the web (http://zanasi2009.ing.unimo.it) which provides the POG symbolic dynamic model of a physical system when a graphical representation of the system is given.

3.1 POG Modeler: assumptions and physical elements.

Each Physical Element "PE" of a POG systems, see the left part of Fig. 9, is characterized by the following properties: **1)** it interacts with the external world by means of two terminals **p1** and **p2**; **2)** the energy is stored or dissipated "within" the physical element; **3)** the energy enters or exits the physical element only by means of the two power variables v_e and v_f.

The POG schemes are based on the following Assumptions: **1)** The effort/across-variable v_e is positive if defined between terminals **p1** (top) and **p2** (bottom): $v_e = v_{p1} - v_{p2}$; **2)** The flow/through-variable v_f is positive if it enters terminal **p1** and exits terminal **p2**; **3)** The power is positive if it enters the Physical element "PE".

The Physical Elements "PE" are identified by means of a two-digit string "xX":
- Electrical: `(eC, eL, eR) and (eV, eI).`
- Mechanical trans.: `(mM, mK, mB) and (mV, mF).`
- Mechanical rot.: `(rJ, rK, rB) and (rW, rT).`
- Hydraulic: `(iC, iL, iR) and (iP, iQ).`

The graphical representation of the "*Internal Physical Elements*" and the corresponding two-digits string "xX" are shown in Fig. 10. For each Energetic Domain there are only three "*Internal Physical Elements*": the two dynamic elements $\mathcal{D}_e$ and $\mathcal{D}_f$, which store energy, and the static element $\mathcal{R}$, which dissipates energy. In Fig. 10 the mass and the inertia elements are defined between two points because the translational (or rotational) velocity of a physical element is always defined with respect an

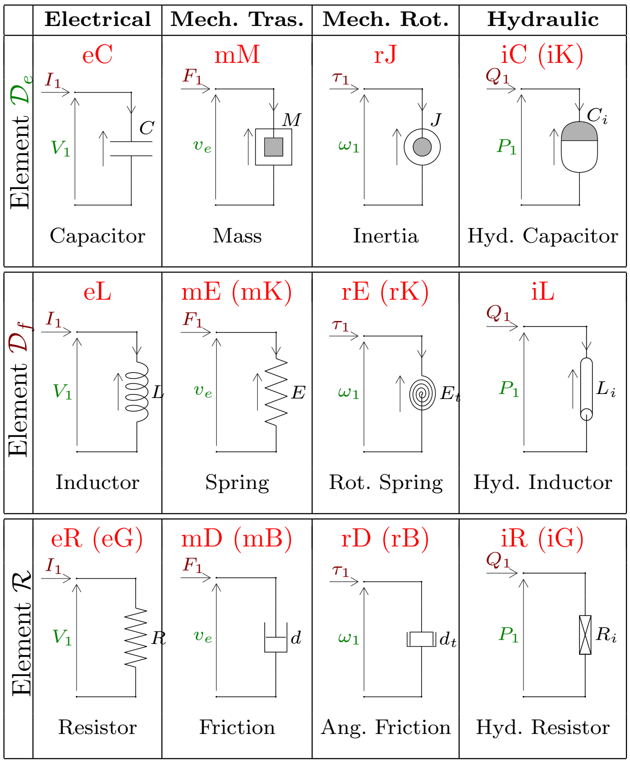


Fig. 10. Graphical representation of the "*Internal Physical Elements*" and the corresponding digit string "xX".

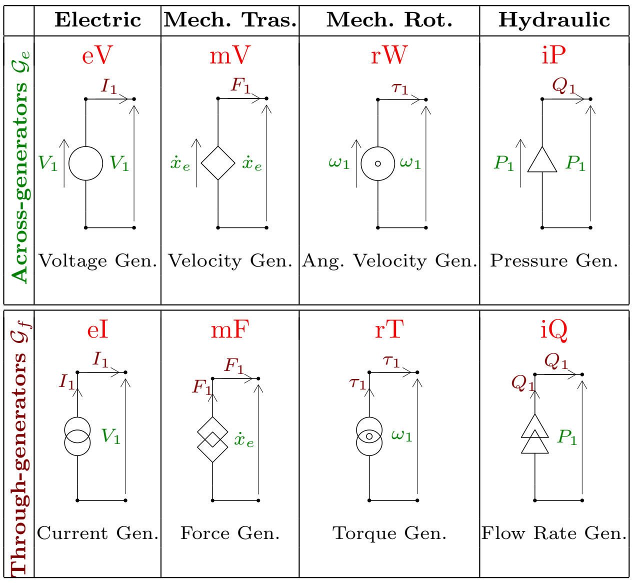


Fig. 11. Graphical representation of the "*External Physical Elements*" and the corresponding digit string "xX".

"*inertial reference frame*". It is easy to show that a similar consideration holds also for the hydraulic capacitor.

The graphical representation of the "*External Physical Elements*" and the corresponding two-digits string "xX" are shown in Fig. 11. For each Energetic Domain there are only two "*External Elements*": **1)** an across-generator $\mathcal{G}_e$ which generates the power across-variable v_e; **2)** a through-generator $\mathcal{G}_f$ which generates the power through-variable v_f. The "*External Physical Elements*" shown in Fig. 11 describe how the external world acts on the considered system.

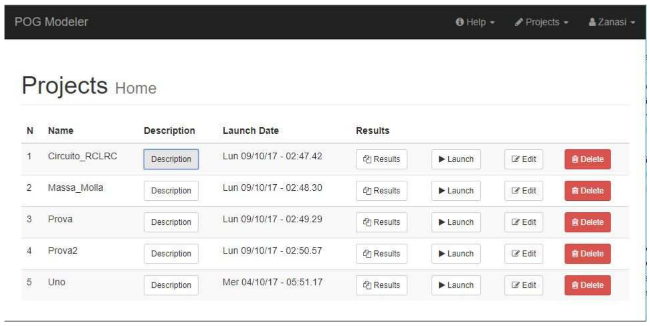
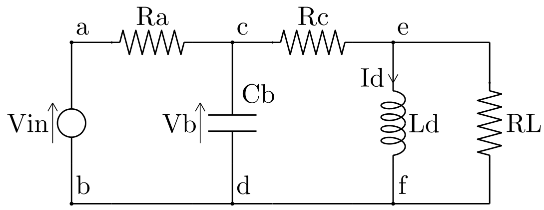


Fig. 12. Example of layout of the user home page.




```
'**, As, Yes'
'eV, a, b, An, -90, En, Vin'
'eR, a, c, Kn, Ra'
'--, b, d'
'eC, c, d, En, Vb, Kn, Cb'
'eR, c, e, Kn, Rc'
'--, d, f'
'eL, e, f, Fn, Id, Kn, Ld'
'eR, e, f, Sh, 0.6, Kn, RL'
```

Fig. 13. Electrical example: the physical system and the corresponding "command-lines".

3.2 POG Modeler: the Web Site.

The **POG Modeler** is available on the web at the following address: **http://zanasi2009.ing.unimo.it**. The use of the program is free, but the registration is required. An example of the user home page is shown in Fig. 12.

A Physical System can be introduced in the POG Modeler using an ascii "command-lines" interface. The electric circuit shown in the upper part of Fig. 13, for example, can be defined in the POG Modeler interface by using the ascii "command-lines" shown in the lower part of Fig. 13.

There are two types of command-lines:

1) the "***system command-lines***", such as `'**, As, Yes'`, which define commands and parameters that apply to all the physical elements of the considered system. The "*system command-lines*" have the following structure:

$$\underbrace{**,\ \mathbf{Par1},\ \mathbf{Val1}}_{\text{Mandatory}}\ \overbrace{[,\mathbf{Par2},\mathbf{Val2}]\ \ [,\mathbf{Par3},\mathbf{Val3}]\ \cdots}^{\text{Optional}}$$

The initial string "**" identifies the line as a "*system command-line*". Each couple "**, Parx, Valx**" is composed by a system parameter "Parx" and its value "Valx". At least one couple "**, Par1, Val1**" has to be present in each "*system command-line*". The command-line `'**, As, Yes'`, for example, tells to the POG Modeler "*compute the symbolic differential equations of the system*".

2) the "***element command-lines***", such as `'eR, a, c, Kn, Ra'`, which introduce new Physical Elements in the POG physical scheme and define their parameters. The "*element command-lines*" have the following structure:

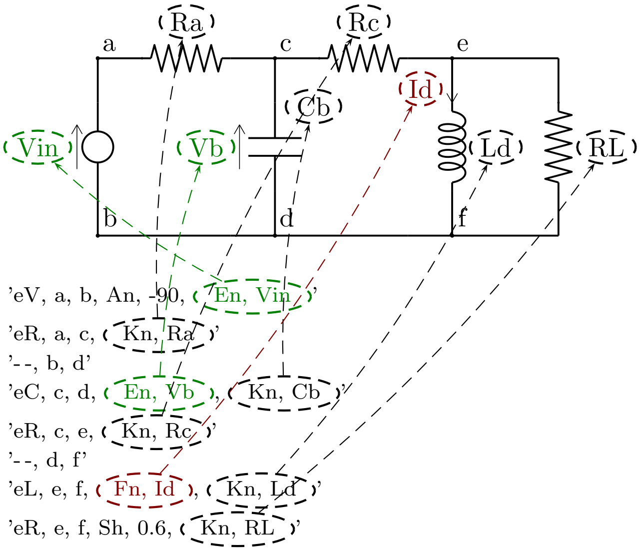


Fig. 14. How to set the names of the system parameters.

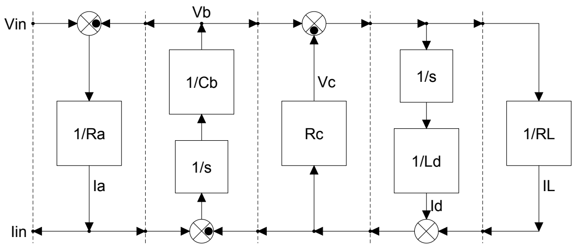


Fig. 15. "POG, Yes" provides the POG block scheme.

Mandatory: **xX, p1, p2** — Optional: **[, Par1, Val1] [, Par2, Val2]** · · ·

The two-digits string "xX" uniquely identifies the Physical Element. The two ascii labels p1 and p2 identify the positions of the first and second terminal of the the Physical Element. The command lines `'--, b, d'` and `'--, d, f'` present in the lower part of Fig. 13 are meant to tell the POG Modeler to introduce straight lines between the two nodes (b, d) and the two nodes (d, f), respectively.

Each optional term "[, Parx, Valx]" is composed by the name "Parx" of a parameter of the Physical Element, and its value "Valx". The list and the meaning of all the "system" and "element " commands of the POG Modeler can be found in the *Help Menu* of the user *Home Page*, together with a *Manual* which describes the basic properties of the program.

Each Physical Element is characterized by an across-variable v_e, a through-variable v_f and an internal-parameter $\mathcal{K}$, see the right part of Fig. 9. The names of the across-variable v_e, the through-variable v_f and the internal-parameter $\mathcal{K}$ can be defined by using the parameters "En", "Fn" and "Kn", respectively, see Fig. 14.

The POG Modeler provides the following important commands: **1)** "POG, Yes" provides the POG block scheme of the considered Physical System, see Fig. 15. **2)** "SLX, Yes" provides the Simulink block scheme of the considered Physical System, see Fig. 16. **3)** "As, Yes" provides the symbolic differential equations of the considered system:

```
% State space equations:      L*dot_X = A*X + B*U
%                                   Y = C*X + D*U
```

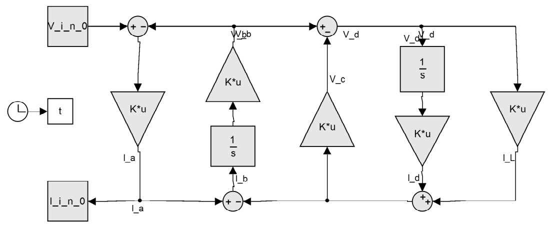


Fig. 16. " SLX, Yes" provides the Simulink block scheme.

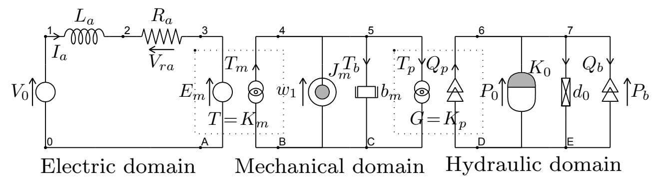


Fig. 17. POG representation of the system shown in Fig. 7.

```
L=[ C_b,    0;   0, L_d];
A=[ -1/(R_L+R_c)-1/R_a,       -R_L/(R_L+R_c);
          R_L/(R_L+R_c), -(R_L*R_c)/(R_L+R_c) ];
B=[  1/R_a; 0 ];       C=[ -1/R_a, 0 ];
D=[  1/R_a ]           X=[ V_b; I_d ];
U=[ V_i_n ];           Y=[ I_i_n ]
```

3.3 POG Modeler: a multidomain example.

Let us now refer to the physical system shown in Fig. 7 which involves three different energetic domains: electrical, mechanical and hydraulic. The POG symbolic representation of this system in shown in Fig. 17. This symbolic representation has been obtained using the following command-lines:

'**, Sn, Yes, Lw, 0.7'
'eV, 1, 0, An, -90, En, V_0, Fn, I_0'
'eL, 1, 2, Ln, 0.7, Zm,0.9, Kn, L_a, Fn, I_a'
'eR, 2, 3, Ln, 0.7, Zm,0.9, En, V_r_a, Kn, R_a'
'--, 0, A, Ln, 1.4'
'CB, [3; 4], [A; B], Kn, F2=K_m*F1, En, [E_m;w_2], Fn, [I_1;T_m], Sh, [0.2;-0.2], La,0.3'
'rJ, 4, B, Sh, 0.4, Kn, J_m, En, w_1'
'--, 4, 5, Ln, 0.8'
'--, B, C, Ln, 0.8'
'rB, 5, C, Kn, b_m, Fn, T_b'
'CB, [5; 6], [C; D], Kn, F1=K_p*E2, En, [w_1;p_2], Fn, [T_p;Q_p], Sh, [0.5;-0.2], La,0.3'
'iK, 6, D, Kn, K_0, En, P_0, Sh, 0.4'
'--, 6, 7, Ln, 0.8'
'--, D, E, Ln, 0.8'
'iG, 7, E, Kn, d_0, Fn, Q_d'
'iQ, 7, E, En,-P_b, Fn, Q_b, Sh, 0.4, Pin, 1, ShY,Yes, FnY,9'

The electrical part of the system is characterized by the physical elements 'eV', 'eL' and 'eR'. The mechanical rotational part of the system is composed by the elements 'rJ' and 'rB'. The hydraulic part of the system is composed by 'iK', 'iG', and 'iQ'.

The physical elements identified by the two-digits string "CB" are the "Connection Blocks". These blocks connect two different Energetic Domains without storing or dissipating energy. The first connection block 'CB, [3; 4], [A; B]' converts electric power to mechanical rotational power, and viceversa. The second block 'CB, [5; 6], [C; D]' converts mechanical rotational power to hydraulic power.

The string "Kn, F2=K_m*F1" present within the first connection block means that the Flow/Through variable

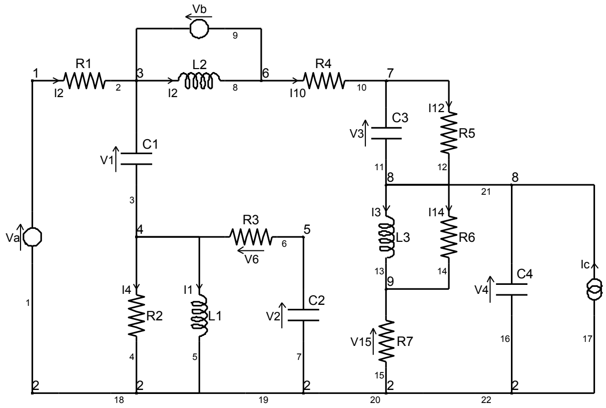


Fig. 18. Example of a large electric circuit.

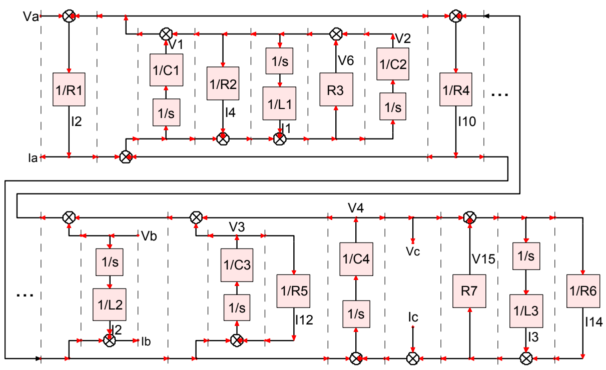


Fig. 19. POG scheme of the electric circuit of Fig. 18.

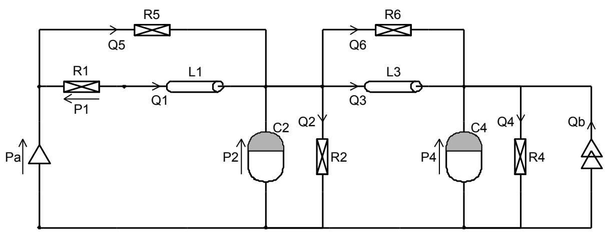


Fig. 20. Example of an hydraulic circuit.

F2 of the output power section is obtained multiplying the Flow/Through variable F1 of the input power section by the internal parameter "K_m":

$$\text{F2=K\_m*F1} \quad \Rightarrow \quad T_m = K_m I_1, \quad E_m = K_m w_2.$$

The string "Kn, F1=K_p*E2" present within the second connection block means that the Flow/Through variable F1 of the input power section is obtained multiplying the Effort/Across variable E2 of the output power section by the internal parameter "K_p":

$$\text{F1=K\_p*E2} \quad \Rightarrow \quad T_p = K_p P_0, \quad Q_p = K_p w_1.$$

The POG Modeler can both analyze simple and complex systems. The large electric circuit shown in Fig. 18, for example, can be easily analyzed by the POG Modeler: the corresponding POG block scheme is shown in Fig. 19.

Finally, let us consider the hydraulic circuit shown in Fig. 20. The corresponding POG block scheme provided by the POG Modeler is shown in Fig. 19.

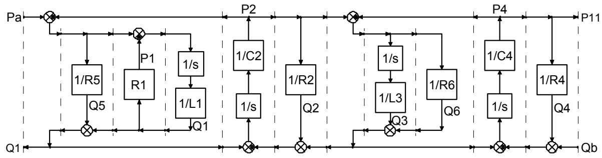


Fig. 21. POG scheme of the hydraulic circuit of Fig. 20.

4. CONCLUSIONS

In this paper the POG technique has been introduced and the modeling program named "POG Modeler", freely available on the web, has been presented. Using the POG Modeler one can obtain automatically the following outputs: 1) the differential equations in form of the given system: 2) The POG block scheme of the given system; 3) the Simulink block scheme of the given system suitable to be run in Matlab. The POG block schemes are easy to use, easy to understand and can be directly implemented in Simulink. The POG technique can be easily used also by beginners.

Anyone can log in anonymously the POG Modeler (http://zanasi2009.ing.unimo.it) using US: `Anonymous` and PW: `pogmodeler`. The examples presented in this paper are present in the home page.

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