Differences and Common Aspects of POG and EMR Energy-Based Graphical Techniques

Roberto Zanasi
Department of Information Engineering
University of Modena and Reggio Emilia
Modena, Italy
Email: roberto.zanasi@unimore.it

Federica Grossi
Department of Information Engineering
University of Modena and Reggio Emilia
Modena, Italy
Email: federica.grossi@unimore.it

***Abstract*—Three main modeling techniques have been proposed in the past years: Bond Graphs (BG), Power-Oriented Graphs (POG) and Energetic Macroscopic Representation (EMR). These modeling techniques are energy-based graphical techniques which exploits the power interaction between subsystems as basic concept for modeling. In this paper a comparison between the POG and EMR techniques is presented. These techniques have many aspects in common and also differences that are pointed out in the paper. The POG schemes have a well-defined mathematical structure and use vectorial compact forms when the system complexity increases. The EMR constitutes a graphical tool useful for modeling, simulation and control of dynamical systems.**

I. Introduction

Nowadays, a lot of modelling methods are available to describe complex dynamic systems such as Bond Graphs [1]-[2], Causal Ordering Graph [3], Power-Oriented Graphs [4]-[5], Energetic Macroscopic Representation [6]- [7], etc. All these techniques use power interaction between subsystems as the basic concept for modeling. The Bond Graphs, introduced in 1959, is the most known technique and it is used in many areas. Some comparisons among the BG, POG and EMR graphical techniques can be found in [8]. The focus of this paper is on the comparison between the POG and EMR techniques to highlight differences and common aspects.

The POG technique is based on the same energetic approach of the Bond Graphs technique, but it uses a different graphical notation (i.e. simple 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. For these reasons the POG technique can be a useful tool for promoting the use of the energetic approach also between beginners and young researchers. The EMR clearly shows the power coupling among elements and the energy flows through the system without showing the mathematical details of the model. This technique is mainly focused on giving a methodology to build an effective control architecture that can be implemented in real-time. The structure is easy to be read, however it does not show the mathematical details of the model and in particular the dissipations are not explicitly shown.

II. Power-Oriented Graphs and Energetic Macroscopic Representation basic features

The Power-Oriented Graphs (POG) are signal flow graphs combined with a particular modular structure which essentially uses only two blocks, see [5]. The basic characteristic of this modular structure is the direct correspondence between pairs of system variables and real power flows: the product of the two variables involved in each dashed line of the graph has the physical meaning of "power flowing through the section". The two basic blocks are named "elaboration block" (e.b.) and "connection block" (c.b.) and they are shown in Fig. 1. While the elaboration block can store and dissipate energy (i.e. springs, masses and dampers), the connection block can only "transform" the energy, that is, transform the system variables from one type of energy-field to another (i.e. any type of gear reduction). The POG schemes are in direct correspondence with the state space notation of the system and some rules are defined to graphically check the correctness of the model. Moreover POG schemes can be directly implemented in general purpose simulators such as Simulink.

The Energetic Macroscopic Representation (EMR) is a graphical tool based on the action-reaction principle [7],[9]. It allows to define a compact representation of complex systems, respecting a functional description. Specific pictograms, shown in Fig. 1, are associated to each power component depending on their power function: energy accumulation (rectangle with an oblique bar), conversion without energy accumulation (square for monophysical conversion, circle for multiphysical conversion), interleaved pictograms for energy distribution, see [10] and [11]. This description points out the coupling devices which distribute the energy within the system. The EMR technique gives a methodology to build a control architecture starting from the model of the system. The control structure is obtained by a step by step inversion of the system decomposed into elementary subsystems. The EMR representation is planar, it clearly shows the coupling among elements and the energy flows through the system. The structure is easy to be read. However it does not show mathematical details of the model.

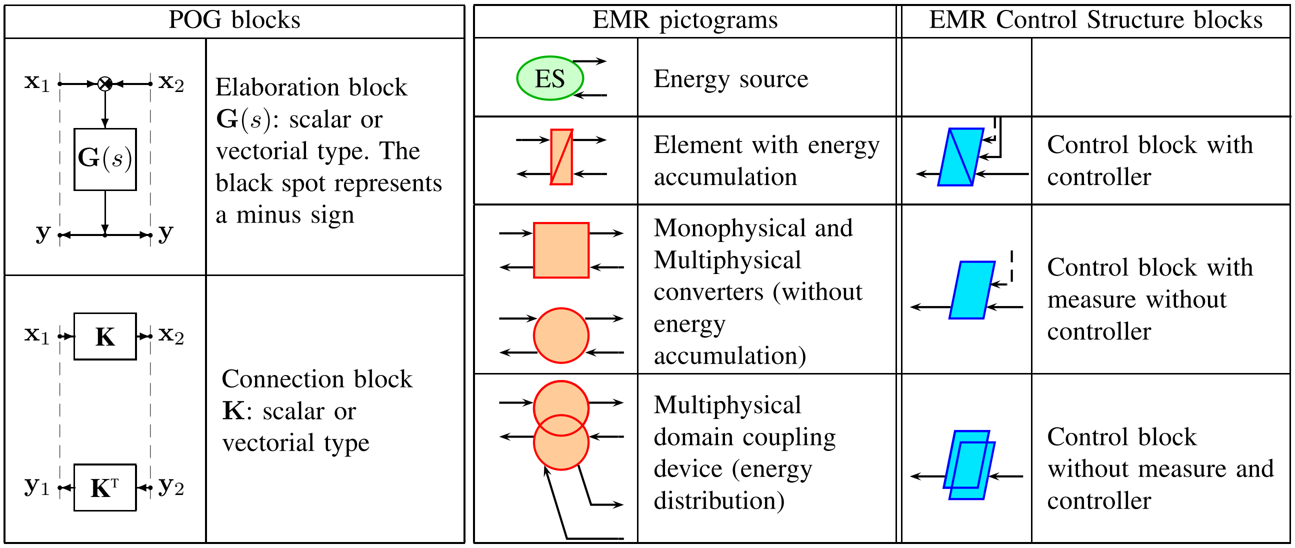


Fig. 1. Synoptic of the POG and EMR graphical descriptions.

A. Example: DC motor connected with an hydraulic pump

A DC motor connected with an hydraulic pump is shown in Fig. 2. This system involves three different energetic domains: electrical, mechanical and hydraulic. The corresponding POG

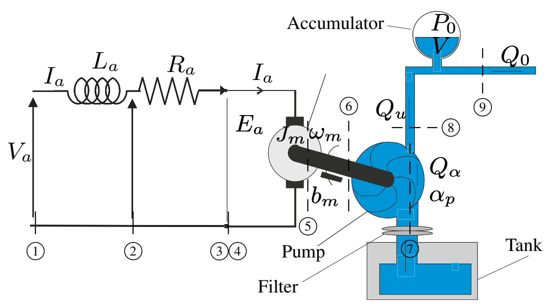


Fig. 2. A DC motor connected with an hydraulic pump.

graphical representation in shown in Fig. 3: the power sections present in the POG scheme have a direct correspondence with the real physical sections. The EMR of the system is shown in Fig. 4 where the power sections in correspondence with the POG scheme are put in evidence.

III. Comparison among EMR and POG blocks

A. Sources

In the EMR formalism the Energy Source, see Fig. 5, is an element collecting all that belongs to the environment (thus not being part of the system) and exchanging energy with the corresponding power section of the system. In the POG technique such element is simply described by a dashed line which represents an input/output power section separating the system from the environment, see Fig. 5.

B. Accumulation elements

The accumulation element in EMR, see Fig. 6, represents an energy storing between two sources. It can be described by a first order transfer function. It has always an integrative

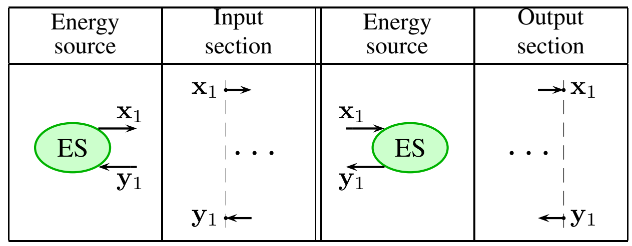


Fig. 5. EMR Energy source and POG input and output section.

relation between output and input and it can consider losses (dissipations) but they are not shown explicitly in the graphical pictogram of the block. It can not stand only for dissipations, the integrative relationship is mandatory. One can represent this in POG by an elaboration block with a first order transfer function $\frac{1}{Js+b}$ where $J > 0$ and $b \geq 0$, see Fig. 6.

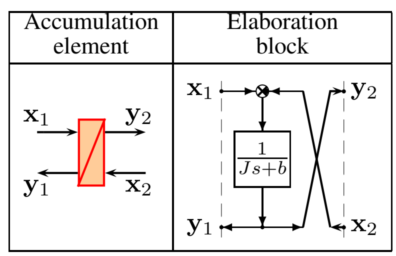


Fig. 6. EMR accumulation element and POG elaboration block (with $J > 0$ and $b \geq 0$).

In POG the elaboration block can store and/or dissipate energy. In general it can be described by a positive real transfer function matrix $\mathbf{G}(s)$ of any order. It can represent also "pure" dissipation. A POG elaboration block with a first order transfer function $\frac{1}{Js+b}$ can be represented in an equivalent way by two elaboration blocks as it is shown in Fig. 7: note that the block b represents "pure" dissipation. Some examples of this can be found in Fig. 3 between sections ①-③, ④-⑥ and ⑦-⑨.

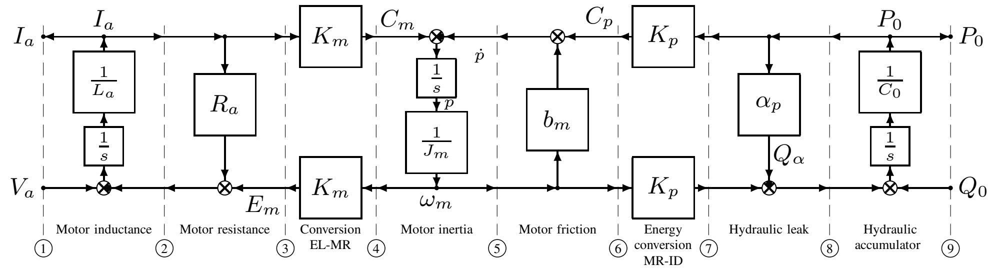


Fig. 3. POG scheme of the DC motor with hydraulic pump of Fig. 2.

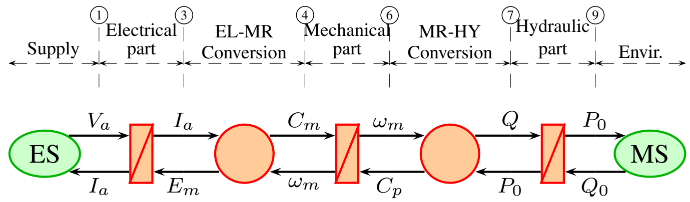


Fig. 4. EMR of the DC motor with hydraulic pump of Fig. 2.

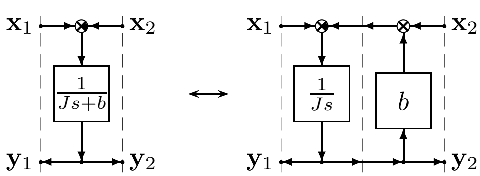
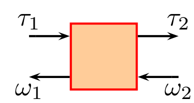


Fig. 7. Equivalence of POG elaboration blocks (with $J > 0$ and $b \geq 0$).



$$\begin{cases} \tau_2 = \alpha R \tau_1 \\ \omega_1 = R \omega_2 \end{cases} \quad (1)$$

Fig. 9. EMR of a reduction gear with efficiency and equations.

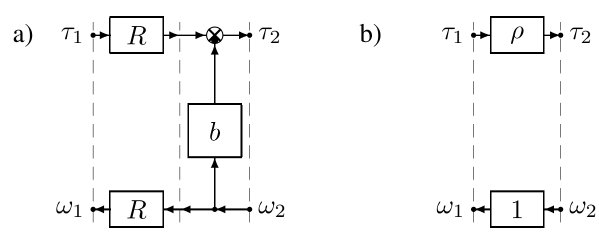
C. Conversion elements

The EMR conversion element, see Fig. 8, allows an energy conversion between two subsystems belonging to the same energetic domain (monophysical conversion) or to different domains (multiphysical conversion). The relationship between input and output is a static relation. This conversion has no energy accumulation, but it can have losses, often considered by means of an efficiency parameter. The conversion element can also have a control input whose power consumption is negligible with respect to the power conversion.

The essential difference between the EMR accumulation and conversion element is in the presence/absence of dynamic relation between input and output. In the POG formalism the connection block redistributes the power within the system without storing nor dissipating energy, therefore the input power is always equal to the output power: $\mathbf{x}_1^{\mathrm{T}}\mathbf{y}_1 = \mathbf{x}_2^{\mathrm{T}}\mathbf{y}_2$.

D. Dissipations

In the EMR the dissipations do not appear explicitly and can be present both in accumulation elements and in conversion elements. Fig. 9 shows a reduction gear represented in EMR by a conversion element and the correspondent equations defining it, where ω_1, τ_1, ω_2, τ_2 are the speeds and torques on the primary and on the secondary respectively. Parameter R is the gear ratio and α is an efficiency parameter ($\alpha < 1$). The output power is $P_o = \tau_2 \omega_2 = \alpha \tau_1 \omega_1 < \tau_1 \omega_1 = P_i$. This is correct from an energetic perspective only if positive power is flowing from left to right, but if for example the conversion element has a downstream connection with an element imposing a change in the sign of the power, the conversion element becomes a power generator and this is not phisically admissible.



$$\begin{cases} \tau_2 = R \tau_1 - b \omega_2 \\ \omega_1 = R \omega_2 \end{cases} \quad (2) \qquad \begin{cases} \tau_2 = \rho \tau_1 \\ \omega_1 = \omega_2 \end{cases} \quad (3)$$

Fig. 10. a) POG block scheme of a reduction gear with dissipation and equations, b) Block scheme with no corresponding physical element.

A reduction gear with dissipation can be represented by the POG scheme shown in Fig. 10.a, where b is the friction coefficient. The output power P_o is

$$P_o = \tau_2 \omega_2 = (R\tau_1 - b\omega_2)\omega_2 = \underbrace{\tau_1 \omega_1}_{P_i} \underbrace{\left(1 - \frac{b\omega_1}{R^2 \tau_1}\right)}_{\rho} = \rho P_i.$$

For $R = 1$ it is $\rho = 1 - b\frac{\omega_1}{\tau_1}$. Note that the efficiency ρ depends on ratio $\frac{\omega_1}{\tau_1}$ therefore given the friction coefficient b, then the efficiency ρ can be considered constant only for ω_1 and τ_1 satisfying $\frac{\omega_1}{\tau_1} = \frac{1-\rho}{b}$. Therefore a conversion block with efficiency corresponds to a physical element only in this particular case. One can state that there is no physical element which can be represented as shown in Fig. 10.b. The

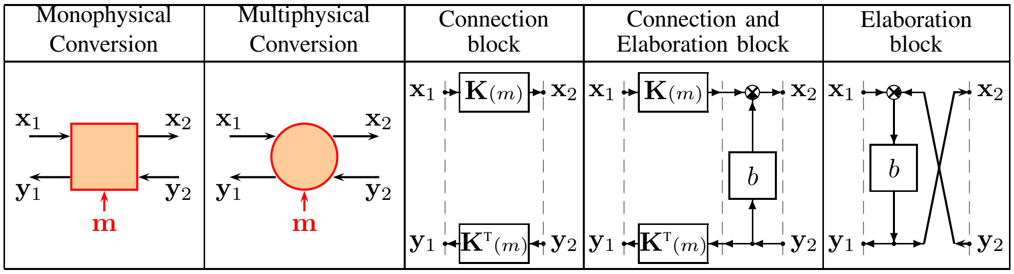


Fig. 8. EMR converters and POG connection block.

concept of efficiency is not admitted in the POG technique because efficiency describes only an average behavior, while the POG are a dynamic description in every condition. The POG formalism has a connection block which converts power without storing nor dissipating, it stands only for connections. When a dissipation is present an elaboration block must be added.

Since the dissipations are considered in different ways by POG and EMR, for this aspect the bijective correspondence among POG and EMR blocks cannot be given.

Let consider as an example the electrical circuit given in Fig. 11. The EMR and POG block schemes are given in the right part of Fig. 11 where also the power sections ①-④ are shown. Note that in the EMR a conversion element is used to represent the resistance R, while in the POG an elaboration block is used.

E. Coupling elements

The EMR shows the energy repartition by means of coupling elements, see Fig. 12. In general only the coupling elements useful for the control are shown, other couplings can be hidden within conversion or accumulation elements. Therefore many EMR representations are possible for the same system. In POG schemes a compact vectorial notation is preferred, however some n-way node can also be used in order to show the series/parallel connections of the elements of the system, see Fig. 12.

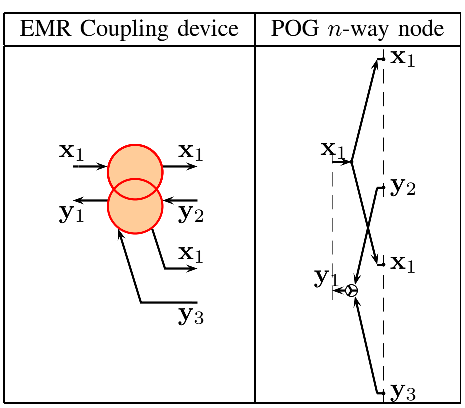


Fig. 12. EMR Coupling device and POG n-way node ($n = 2$).

IV. Inversion based control

The EMR provides a methodology to deduce a control structure for the system by a step-by-step inversion of each element of the system [15]. The POG have not any specific tool associated to the representation of the model to deduce a control structure, but the methodology provided by EMR can be applied also to POG schemes.

A. Exemple: five-phase permanent magnet synchronous electrical motor

Let consider a 5-phase permanent magnet synchronous electrical motor. The EMR and POG schemes are shown in Fig. 13, see [13] and [14]. Note that the power sections in EMR and POG schemes of Fig. 13 which are in correspondence are indicated by the same number. Let us introduce the following current and voltage stator vectors:

$$^t\mathbf{I}_s = \left[I_{s1}\; I_{s2}\; \cdots\; I_{sm_s}\right]^{\mathrm{T}},\; {}^t\mathbf{V}_s = \left[V_{s1}\; V_{s2}\; \cdots\; V_{sm_s}\right]^{\mathrm{T}}.$$

Using a coordinate transformation it is possible to write the dynamic model of the motor in a rotating reference frame and it can be proved that the 5-phase motor can be considered as a set of two (dq) separated fictitious machines $M1$ and $M2$. The transformed current and voltage vectors ${}^\omega\mathbf{I}_1$, ${}^\omega\mathbf{V}_1$ and ${}^\omega\mathbf{I}_2$, ${}^\omega\mathbf{V}_2$ respectively for $M1$ and $M2$ are:

$${}^\omega\mathbf{I}_1 = \begin{bmatrix} {}^\omega I_{d1} \\ {}^\omega I_{q1} \end{bmatrix},\; {}^\omega\mathbf{V}_1 = \begin{bmatrix} {}^\omega V_{d1} \\ {}^\omega V_{q1} \end{bmatrix},$$

$${}^\omega\mathbf{I}_2 = \begin{bmatrix} {}^\omega I_{d2} \\ {}^\omega I_{q2} \end{bmatrix},\; {}^\omega\mathbf{V}_2 = \begin{bmatrix} {}^\omega V_{d2} \\ {}^\omega V_{q2} \end{bmatrix}.$$

The motor torque is $\tau_m = \tau_{m1} + \tau_{m2}$, the motor velocity is ω_m and the external torque is τ_e.

The control structure for the control of the motor torque τ_m can be deduced by the EMR following three steps (see [15]): decomposition of the system into elementary subsystems, determination of the tuning chain (from the tuning input to the global output to be controlled) and finally inversion step by step of the tuning chain using the inversion rules. In this case the tuning input is the input voltage vector ${}^t\mathbf{V}_s$ and the output to be controlled is the motor torque τ_m. The tuning chain is highlighted in yellow in the EMR of Fig. 13. The maximal control structure (MCS) represented in Fig. 13 has been deduced by a step by step inversion of the tuning chain: given the torque reference τ_{ref} the control input ${}^t\mathbf{V}_{sreg}$ is provided. Note that in the two control blocks some additional

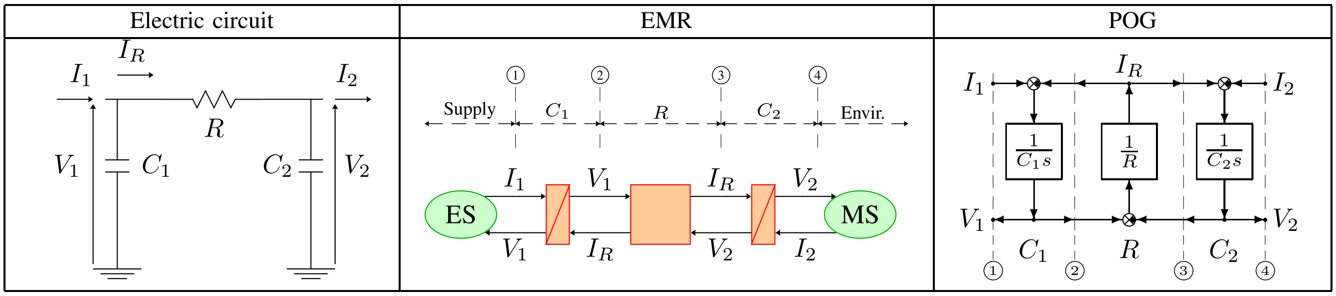


Fig. 11. Electric circuit: EMR and POG schemes.

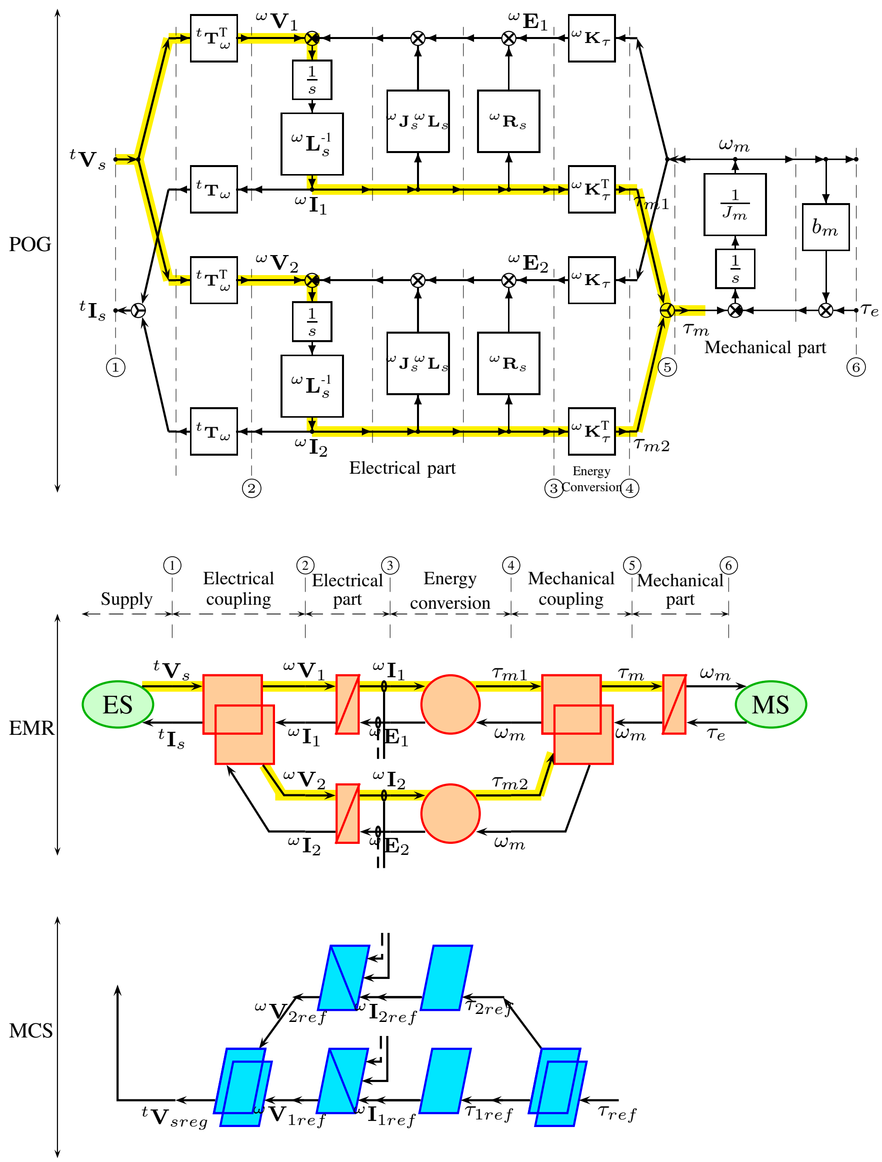


Fig. 13. EMR and POG schemes of a five-phase synchronous motor in rotating frame.

input are considered (the measured currents and the back electromotive forces) to provide a feedforward action.

The approach of the inversion based control can be applied also to the POG, taking advantage from the correspondence between power sections of EMR and POG, see Fig. 13 where the corresponding power sections are indicated by the same numbers. Therefore the control structure derived from the EMR can be applied to the POG model. In the POG scheme shown in Fig. 13 the corresponding tuning chain is highlighted in yellow.

V. Conclusion

In the paper a comparison between POG and EMR techniques is given to underline their common aspects and differences and the possibility of cooperation between the two techniques in order to merge their different features for the desired purposes. The main objective of the POG modeling technique is the analysis of physical systems, while EMR aims mainly at the control of the system. The POG schemes have a well-defined mathematical description thus allowing to write the dynamic model of the considered system and verify its correctness. The EMR provides a methodology to build the control starting from the representation of the considered system. The main difference between the two techniques concerns how dissipations are taken into account. If the correspondence between POG and EMR was bijective, it would be possible to take advantage of both POG and EMR features: apply the inversion based control also to POG schemes and the exact mathematical description to EMR.

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