Mieczysław RONKOWSKI
Zbigniew KNEBA

BOND-GRAPHS BASED MODELLING OF HYBRID ENERGY SYSTEMS WITH PERMANENT MAGNET BRUSHLESS MACHINES

ABSTRACT *The paper presents the bond graphs approach to modelling the permanent magnet brushless machines (PMBM) for simulations the energy systems of hybrid physical nature. In the first part the fundamentals of bond graph modelling approach are presented. In the second part a model of PMBM in terms of bond graphs (BG) has been developed. Finally, as an example of hybrid energy system, a model of IC engine cooling system with coolant pump driven by a PMBM has been described.*

Keywords: *hybrid energy systems, modelling of PM brushless machines, bond-graphs*

1. INTRODUCTION

Modern hybrid energy systems (multi-physics systems, mechatronic systems) require to be modelled and designed as an integrated systems [2, 5, 10]. This paper discusses the background for a BG based (port-based)

Prof. Mieczysław RONKOWSKI, D.Sc.
e-mail: m.ronkowski@ely.pg.gda.pl

Zbigniew KNEBA, Ph.D., Eng.
e-mail: zkneba@pg.gda.pl

Gdansk University of Technology,
Narutowicza 11/12, 80-952 Gdańsk, Poland

approach to integrated modelling of these systems with PMBM. Such approach improves insight and direct feedback on modeling, simulation and design decisions.

The organization of the paper is the following : in section 2 we present the background for a BG based (port-based) approach. In section 3, model structure of hybrid energy systems in terms of BG is described. Section 5 is devoted to the basics of electric machine modelling in terms of BG. Section 5 is devoted to the modeling of PMBM. Finally, as an example of hybrid energy system, a model of IC engine cooling system with coolant pump driven by a PMBM has been described in section 6. And we conclude in section 7.

2. BASICS OF BOND GRAPHS FORMALISM

This has necessarily been a brief introduction to the BG modelling technique. The fundamentals of physical systems modelling in terms of BG have been presented in [1, 2, 10, 12, 17, 18].

At the beginning of the fifties of the last century H.M. Paynter [12] realized himself that the concept of a *port*, introduced in electrical circuit theory earlier by Wheeler [16], should be extended to arbitrary power ports that can be applied to any physical domain. Power ports include: mechanical ports, hydraulic ports, thermal ports, electric ports, etc. In the following decade Paynter designed a notation based on the efficient representation of the relation between two ports by just one line that he called a *bond*. This so-called *bond graph notation* was completed when Paynter finally introduced the concept of the so called *junction structures* which were manifestations of the constraints [12]. Later on, BG theory has been further developed by many researchers [1, 2, 10, 17, 18] who have worked on extending this modelling technique to power hydraulics, mechatronics, general thermodynamic systems, etc.

In the BG approach, power continuity equations are formulated instead of energy conservation laws. It turns out that, in any physical system, the power balance is a local property, i.e., for modelling the power balance the equations can be expressed for each subsystem separately, and then all the subsystems can be connected as long as the power is also balanced at all the ports between submodels [1, 2, 10, 17, 18].

The power in any physical system is written as the product of two conjugate variables (in general as function of time t):

$$p(t) = e(t) \cdot f(t) \tag{1}$$

called the *effort* (denoted by e) and the flow (denoted by f) in BG terminology. In a BG, energy flow from one port of a element/subsystem to another one is denoted by a harpoon (a semi-arrow), as shown in Fig.1a.

When similarities in various subsystem components in the model structure can be established, they can be represented in form of a concise notation called *vector* or *multi bond graphs* (Fig. 1b). The multi bond graphs are useful when initial ideas are being formulated, they may obscure many physical aspects of the system.

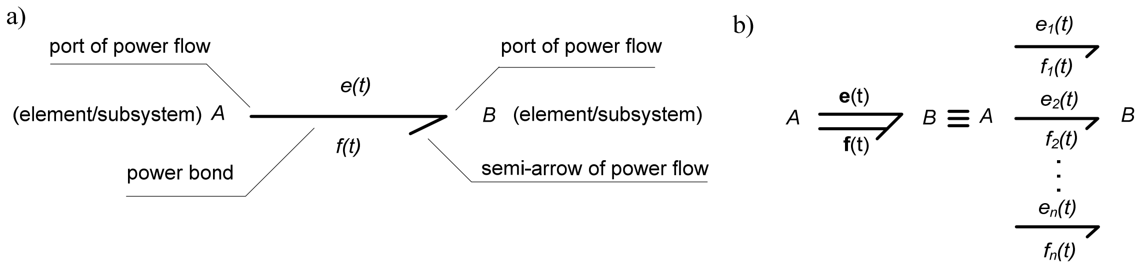

Fig. 1. Variables *e(t)* and *f(t)* modelling power flow from element/subsystem *A* to element/subsystem *B*: a) model representation in terms of bond graph, b) model representation in terms of multi bond graphs

In an electrical system, it is customary to select the voltage (or electrical potential) as the effort variable, and the current as the flow variable. In a translational mechanical system, the force will be treated as effort, and the velocity as – flow. In a rotational system, the torque is assumed as the effort, and the angular velocity as flow. However, the assignment is arbitrary. Effort and flow are dual variables, and the assignment could just as well be done the other way around.

BG is an explicit graphical tool for capturing the common energy structure, particularly of hybrid energy conversion systems. It increases one's insight into systems behaviour. By this approach, a physical system can be represented by symbols and lines, identifying the power flow paths. The sources of effort and flow (denoted respectively by *Se* and *Sf*), the lumped parameter elements of *resistance*, *capacitance*, and *inertance* (called *1-port elements* and denoted respectively by *R*, *C* and *I*) are interconnected in an energy conserving way by *bonds* and *junctions* (called *multi-port elements* that includes: *nodes* denoted by *0* and *1*, *transformers* denoted by *TF*, and *gyrators* denoted by *GY*) resulting in a network structure. From the pictorial representation of the bond graph, the derivation of system equations is so systematic that it can be algorithmized [2, 10].

The ports are classified as *active ports* and *passive ports*. The active ports are those, which give reaction to the source. The passive ports are used for the concept of modulated sources of effort and flow, transformers and gyrators that have been also introduced into BG. They are denoted respectively as following: *MSe*, *MSf*, *MTF* and *MGY*. These devices permit to control the output variables in terms of time or other variables of the considered system.

To establish graphically the cause and effect relationships between the factors of power flow in BG the causality symbol – *causal stroke*, has been introduced. The causal stroke indicates the direction in which the effort signal is directed (by implication, the end of the bond that does not have a causal stroke is the end towards which the flow signal is directed). Causality is simply the specification of which variables are independent and which are dependent. The distinction is quite significant for organizing equations. The basic concept of the causality has been shown in Fig. 2.

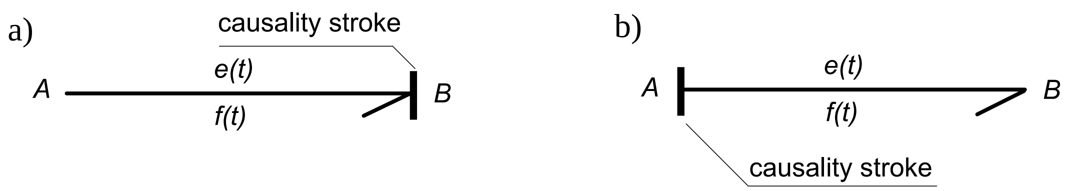

Fig. 2. Causality - the relation of cause and effect between *A* and *B* elements/subsystems and its representation in terms of bond graph: a) effort *e* – cause, flow *f* – effect; b) flow *f* – cause, effort *e* – effect

3. MODEL STRUCTURE OF HYBRID ENERGY SYSTEMS IN TERMS OF BOND GRAPHS

A general model structure of hybrid energy systems in terms of BG [2] is shown in Fig. 3a.

The model consists of the following elements:

- external elements: *S* – sources of energy (*Se* – effort, *Sf* – flow), *M* – receiver of energy; *C* – accumulators of potential energy, *I* – accumulators of kinetic energy, *R* – dissipaters of energy;
- internal elements: 1, 0 – junctions (nodes), *TF* – energy transformers, *GY* – energy converters.

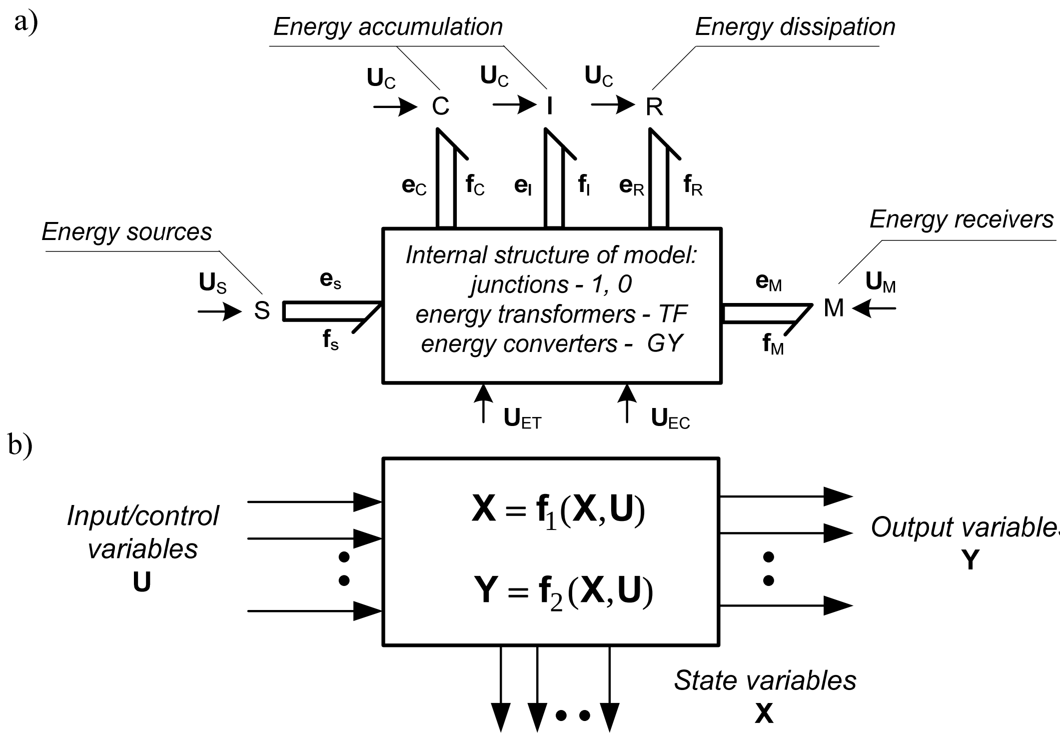

Fig. 3. General structure of hybrid energy system model:
a) in terms of bond graphs, b) in terms of state equations

The external elements, energy transformers and energy converters can be modulated, i.e., their energetic parameters either depends upon other model parameters or are independent functions of time *t*. In the later case, the independent functions are defined as control parameters and are denoted by a control vector **U**. Generally, the control vector consists of the following components: $\mathbf{U}_c$ – control vector of energy sources, $\mathbf{U}_M$ – control vector of energy receivers, $\mathbf{U}_c$, $\mathbf{U}_I$ – control vectors of energy accumulators, $\mathbf{U}_R$ – control vector of energy dissipaters, $\mathbf{U}_{ET}$, $\mathbf{U}_{EC}$ – control vectors of energy transformers and converters, respectively.

For the purpose of hybrid energy system analysis, identification, and synthesis its mathematical model is setting up. The type of model that will be found often is described as a „state-determined system". Such a system model often is described by a set of ordinary differential equations in terms of so-called state variables and a set of algebraic equations that relate other system variables of interest to the state variables [2, 10]. The system state equations are written usually in the form of vector and matrix notation (Fig. 3b). They can be set up by „hand" on the basis of system BG model or set up automatically – using a BG oriented simulation package, like 20-sim [9].

The model shown in Fig. 3 can be divided into submodels of subsystems and/or components that a considered hybrid energy system has been built up. It should be noticed that the BG submodels are reusable, and can have different levels of accuracy.

In the following sections some modelling basics of electric machines (EM) and a model of PMBM are preseted in terms of BG.

4. BASICS OF ELECTRIC MACHINES MODELLING IN TERMS OF BOND GRAPHS

An EM, according to its degree of freedom, has been represented as a multi-port electromechanical converter (transducer) with pair of terminals (ports), which are the winding and shaft terminals (ports). The machine dynamic is described by two power parameters at each pair of terminals (ports). It is assumed that fundamental quantities (variables) of the EM model are: voltages, currents, flux-linkages, rotor angular velocity and rotation torque – electromagnetic torque.

A general structure of EM model in terms of BG is shown in Fig. 4 [14].

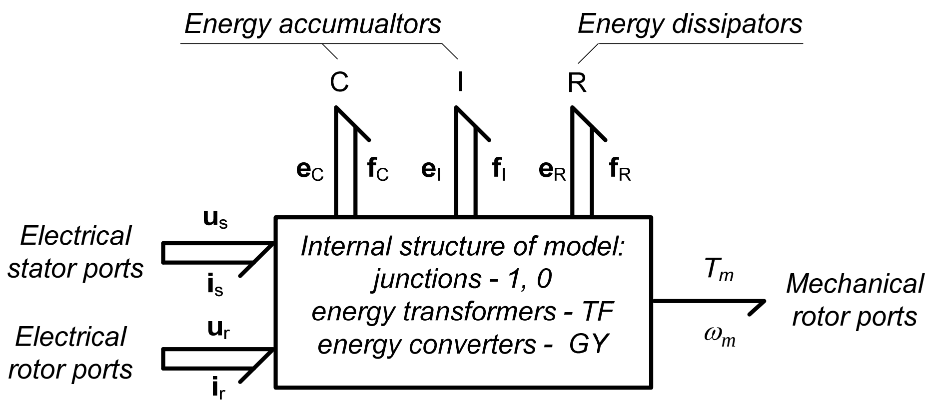

Fig. 4. General structure of electric machine model in terms of bond graphs

The ports variables are represented by: vectors of voltages ($\mathbf{u}_s$ - stator, $\mathbf{u}_r$ - rotor) and currents ($\mathbf{i}_s$ - stator, $\mathbf{i}_r$ - rotor), rotation torque (T_m) and rotor angular speed (ω_m). For electrical ports the voltages are assumed as efforts, and currents as flows, for mechanical port (denoted by subscript *m*) the torque is assumed to be effort, and the angular velocity as a flow. In turn the elements *C* and *I* are the energy storage elements, and *R* is dissipating energy element. The variables *e* and *f* represent the efforts and flows of these elements, respectively.

The internal structure of the model shown in Fig. 4 depends upon the models of the energy transformation and conversion processes in EM. The processes can be modelled in terms of modulated transformers and gyrators or in terms of IC field models [10], i.e., the multiport field and junction structures.

To enhance the analogy between the principles of circuit models and BG models development for all types of EM, the idea of two ideal couplings has been developed [13].

It has been assumed that generally in all types of rotating EM two fundamental couplings can be distinguished: referred to as *ideal transformer coupling* and *ideal electromechanical coupling* (Fig. 5). The couplings represent the processes of energy transformation and energy conversion, respectively. Using the lumped parameter models (circuit/BG representations) of the couplings as „building blocs" the models of basic EM can be easy developed. While building the EM models in terms of BG these couplings can be modelled in terms of transformers (Fig. 5b) and modulated gyrators (Fig. 5d).

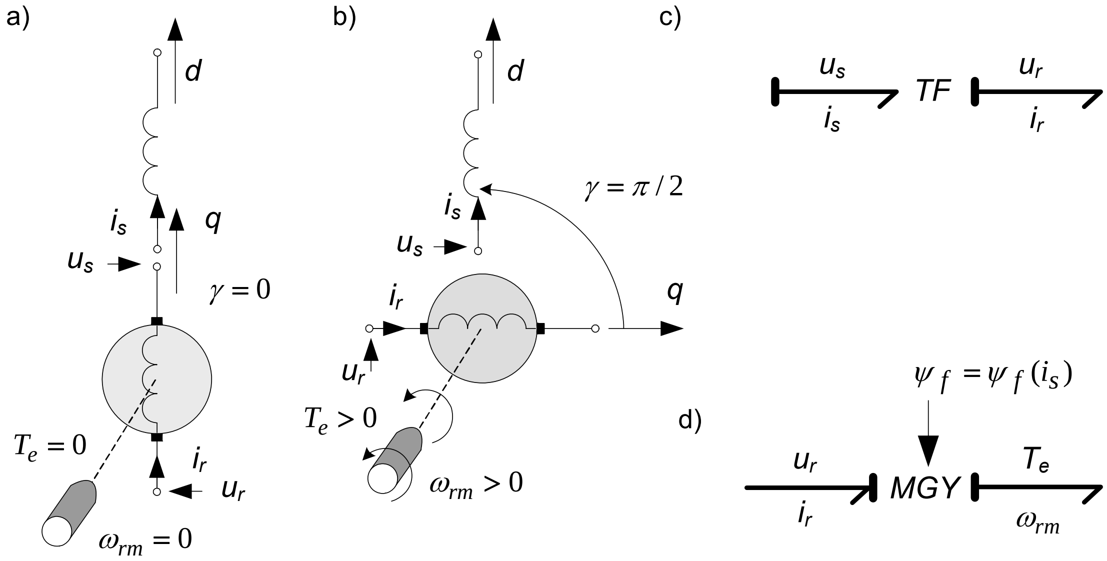

Fig. 5. Idea and models of fundamental couplings in electrical machines – assumed *qd* reference frame fixed to the stator: a) ideal transformer coupling – energy transformation; b) ideal electromechanical coupling– energy conversion; c) and d) models of fundamental couplings in terms of bond graphs

5. MODELLING OF PM BRUSHLESS MACHINES IN TERMS OF BOND GRAPHS

As an example a BG model of a PMBM with sinusoidal magnetic field distribution in air-gap, described in the *qd*-axes reference frame fixed to the rotor, has been developed (Fig. 6). The PMBM model has been built-up using the BG editor of the 20-sim package simulator [9].

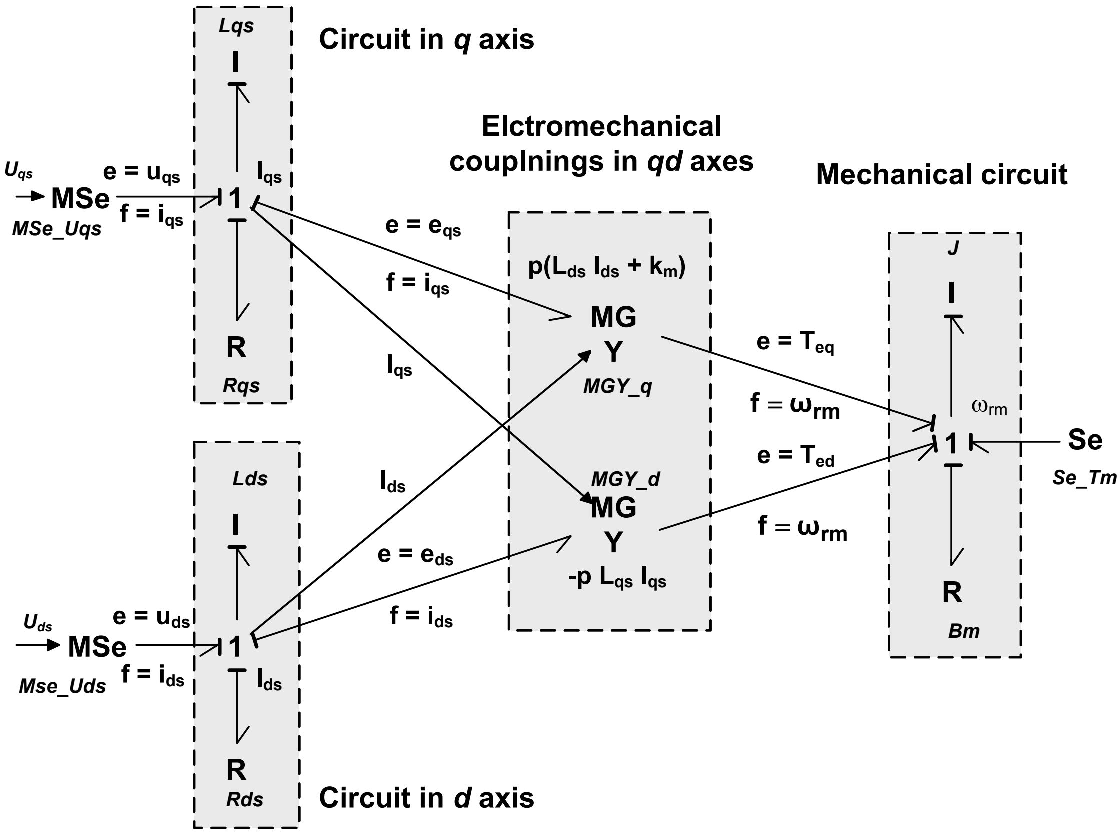

Fig. 6. Two-axes model of PMBM in terms of bond graphs – assumed *qd* reference frame fixed to the rotor

To build-up the PMBM model it has been assumed that the eddy currents in the rotor are neglected, i.e., the transformer coupling can not be considered. The energy dissipations is represented: in stator circuit by resistances *Rqs* and *Rds*, in mechanical circuit by *Bm*. The energy accumulation is represented: in stator circuit by inductance *Lqs* and *Lds*, in mechanical circuit by rotor inertia *J*.

The energy conversion from electrical to mechanical (and vice-versa) is represented by modulated gyrators *MGY_q* and *MGY_d* in *q* and *d* axes, respectively. The modulus of the gyrators are functions of: stator currents *iqs* and *ids*, the inductances *Lqs* and *Lds*, and coefficient *km* (representing the flux excited by PM) in the *q* axis. Thus, the efforts on the input ports of these gyrators represents the back EMFs, and on the output ports the electromagnetic torque components *Teq* and *Ted*, respectively.

The supply voltages in *qd* axes stator circuits are modelled by modulated effort sources *MSe_Uqs* and *MSe_Uds*. The modulating input signals are functions of supply voltages (output inverter voltages u_{as}, u_{bs} and u_{cs}) applied across the real 3-phases stator windings. The load torque is represented by effort source *Se_Tm*.

The BG model of a PMBM using a BG model of the Park's transformation has been developed in [15]. It should be noticed that for reduced level accuracy of a particular hybrid energy system analysis it can be assumed that the axis component of PMBM supply voltage $u_{ds.} = 0$.

6. MODELING EXAMPLE OF HYBRID ENERGY SYSTEM WITH PMBM

For the very recent modification of IC engine cooling system in passenger cars a coolant pump driven by an electric motor has been used [4, 6, 7, 8, 11]. The integrated set of the coolant pump and its controlled electric drive is called *electric coolant pump*.

The modern electric coolant pump is an integrated system consisting of pump, PMBM, electronic commutator (inverter) and control module [8]. The pump is driven independently of the car engine, i.e., by the PMBM supplied from the car board network (including electrochemical battery and alternator). Thus the controlled intensity of coolant flow can be provided at all time by adjusting the pump velocity. Controlling the coolant flow is an accurate way of controlling engine and coolant temperature, and it is also a reliable means of avoiding hot spots. It should be noticed that only one company (BMW) has introduced such a system in serially produced passenger cars [8].

An observation that in the most cases the coolant flow capacity of IC engine is too large was the reason for using the above mention system. In a conventional cooling system, where coolant pump can sometimes has a very high velocity, the cooling intensity is to high due to low torch of an IC engine. By an appropriate adjusting the pump velocity it is possible to get power savings, lower toxic emissions and better cabin car comfort. However, it is not very clear if the pump should be stopped during warm-up period of IC engine or should be driven. For example, in the paper [6] the authors have considered stopping the pump completely during warm up period of IC engine. It should be noticed that our first investigation results have shown that a hot coolant flowing through completely cold IC engine can warm-up its parts [11]. The main advantage achieved by this is the lower toxic emissions and better comfort of car cabin. To take the full advantages of electric coolant pump applications a further analysis of the IC engine cooling system has to be carried out. Since the considered engine coolant system is a hybrid energy (multi-physics) system the BG based approach to its modeling and simulation has been used.

A BG model of IC engine cooling system with electric coolant pump has been shown on Fig. 7 [2, 4]. It is composed of two energy converters models linked by signals:

- model of internal combustion engine (ICE) with the energy receiver (ER);
- model of cooling system consisting of the following submodels: car board network (CBN) including electrochemical battery and alternator, electric motor (PMBM), pump (P), combustion cell (CC), coolant tank (CT), radiator and fan (RF).

The signal links of the model (Fig. 7) represent:

- links of the temperature of ICE working space with the heat exchange processes between CC and coolant (ICE, S_{ICE});
- links of the coolant temperature with the air flux flowing through RF (ICE, S_o).

In the model of cooling system the two accumulators of the heat energy are indicated for coolant (C_C) and metal part of ICE (C_{CC}). The energy dissipations are represented by R with appropriate subscripts. The main source of energy is the flux of chemical energy contained in the fuel (product $G_e \cdot W_d$, where, W_d – caloric value of fuel [J/kg], G_e – fuel consumption [kg/s]). The other variables of the model represent: T_c, ω_c – torque and angular velocity of crankshaft; T_P, ω_P – input torque and angular velocity of coolant pump; u_{dc}, i_{dc} – supply dc voltage and current of PMBM; S_s – source of energy due to the thermodynamic process in ICE; S_o – source of energy supplied to ICE environment due to the thermodynamic process in ICE; T_{ICE}, T_o – temperatures [K] of ICE and its environment respectively; $\dot{S}_{ICE}$, $\dot{S}_o$ – flux of entropy [J/Ks] of ICE and its environment respectively; $\dot{m}_c$ – intensity of mass flow of coolant [kg/s]; i_{in}, i_{out}, i_{CC}, i_{RF}, – specific enthalpy of coolant [J/kg] in different part of its flowing path.

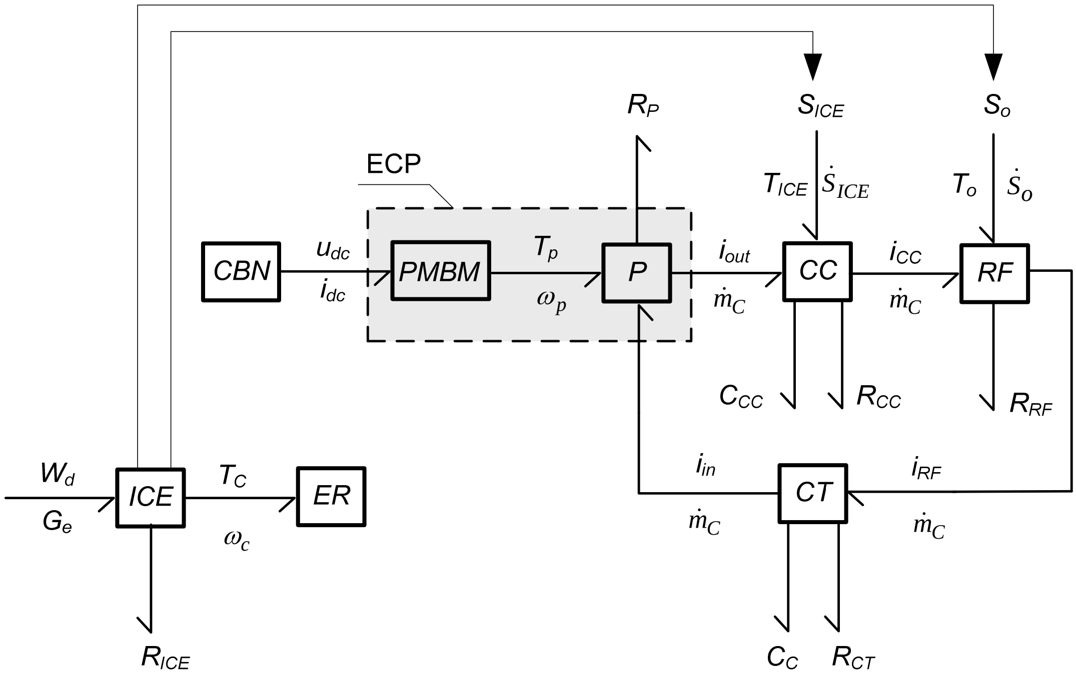

Fig. 7. A simplified model of IC engine cooling system with electric coolant pump in terms of bond graphs

For modelling the coolant system a simplified BG model of ICE [2, 3] and the elaborated above PMBM (Fig. 6) have been used. The ICE model is developed under an assumption that the input energy flux ($G_e \cdot W_d$) and output energy flux ($T_C \cdot \omega_C$) are averaged continues functions of time over the period of one cycle.

For carrying out the simulation of the considered coolant system the state equations on the basis of the BG model, shown in Fig. 7, should formulated using a computer program, for example the 20-sim package [9].

7. CONCLUSIONS

The bond graphs approach to modelling the permanent magnet brushless machines (PMBM) for simulations the energy systems of hybrid physical nature has been presented. As an example of hybrid energy system, a model of IC engine cooling system with coolant pump driven by a PMBM has been described.

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Manuscript submitted 14.11.2006
Reviewed by Krzysztof Kluszczyński

MODELOWANIE HYBRYDOWYCH SYSTEMÓW ENERGETYCZNYCH Z BEZSZCZOTKOWYMI MASZYNAMI O MAGNESACH TRWAŁYCH W UJĘCIU GRAFÓW WIĄZAŃ

M. RONKOWSKI, Z. KNEBA

STRESZCZENIE *Ważnym zagadaniem w analizie i syntezie hybrydowych systemów energetycznych jest forma reprezentacji ich modeli. Współczesny sposób analizy i wyrażania koncepcji projektowych (forma reprezentacji modelu, metoda wprowadzania do komputera), jest jednym z podstawowych zagadnień symulatorów wspomagających badania, projektowanie i dydaktykę zaawansowanych hybrydowych systemów energetycznych [2, 5, 10].*

Dotychczasowe doświadczenia wskazują, że oczekiwania te w znacznym stopniu spełnia metoda grafów wiązań (GW) (ang. bond graps) [1, 2, 10, 12, 17, 18]. Modelowanie układów fizycznych metodą GW, opartej na koncepcji H. M. Paynter'a [12], polega na jednolitym ujęciu procesów energetycznych zachodzących w układach fizycznych, niezależnie od ich domeny (natury) fizycznej.

Formułowanie równań dynamiki układu (równań stanu) odwołuje się do zbudowanego uprzednio grafu rozważanego systemu i wykorzystuje informacje o elementach systemu, które mogą być wyrażone analitycznie lub za pomocą charakterystyk graficznych.

Niniejszy referat jest kolejną próbą przedstawienia metody GW w zastosowaniu do modelowania hybrydowych systemów energetycznych z bezszczotkowymi maszynami o magnesach trwałych (BMMT, ang. PMBM).

W części pierwszej referatu omówiono ogólne formalizm GW (rys. 1 i 2). Następnie przedstawiono kolejno: ogólną strukturę modelu hybrydowego systemu energetycznego w ujęciu GW (rys. 3); założenia modelowania maszyn elektrycznych w ujęciu GW (rys. 4 i 5), model SBMT w ujęciu GW dla potrzeb modelowania napędu pompy cieczy chłodzącej w silnikach samochodowych (rys. 6), model w ujęciu GW nowoczesnego sytemu chłodzenia silnika samochodowego (rys. 7) – jako przykład hybrydowego systemu energetycznego.

W referacie do opracowania modelu procesu przetwarzania energii w SBMT wykorzystano ideę i modele sprzężeń wzorcowych: transformatorowego i elektromechanicznego (rys. 5) [13].

Modelowany system chłodzenia umożliwia sterowanie poziomem temperatury silnika samochodowego niezależnie od prędkości jego wału [8]. Modelowanie i symulacja takiego systemu chłodzenia nabiera szczególnego znaczenia przy wprowadzaniu coraz bardziej ostrych norm o emisjach szkodliwych składników spalin, ze względu na ważną rolę procesu rozgrzewania silnika w tworzeniu związków wydalanych spalin [4, 6, 7, 11].