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Bond graph model of an induction machine with hysteresis nonlinearities

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ABSTRACT

An induction machine is one of the most convenient devices for conversion of electrical energy to mechanical rotational energy. Induction machine is a typical member of a multi-domain, nonlinear, high-order dynamic system. To reduce its complexity, the mathematical models used for designing their control have several assumptions built into them. The most striking of these assumptions is that of linear magnetics. Bond graph is a convenient tool for modelling nonlinear elements. This paper proposes the use of the bond graph methodology to develop a model of an induction machine that includes the nonlinearities due to magnetics.

1. Introduction

Energy is mainly produced in the electrical form and consumed in the mechanical form. The induction motor is the most popular industrial system to convert electric power to mechanical power through the medium of magnetics. Thus there is an existence of multi-domain energy exchange in an induction machine. This increases the complexity of modelling of an induction machine. But for an efficient control of the electric–magnetic–mechanical energy the induction machine has to be accurately modelled [1].

Induction motors constitute a nonlinear system. A 3ϕ induction motor is described by a fifth-order nonlinear differential equation. Load disturbances and the parameter's variations have to be incorporated in the control to make it more realistic. Thus the challenge is to model a highly nonlinear system, with unknown time-varying parameters, where the output is perturbed by an unknown additive signal. Historically the motors have been modelled by the *abc* model, the *d*–*q* model etc.

The conventional dynamic models like the *d*–*q* model of 3ϕ induction machines are based on assuming linearity near the region of operation as the nonlinearity of the machine is difficult to model. In this paper, it will be demonstrated how the bond graph methodology handles the nonlinearities invariably present in natural systems.

The bond graph approach to physical system modelling was conceptualized by Henry Paynter on April 24, 1959 [2], inspired by the earlier work of Gabriel Kron [3]. Bond graph language is a port based graphical approach for modelling energy exchange between subsystems. This technique was further developed by Karnopp and Rosenberg [4–7]. Several books, special issues and articles on bond graph technique have popularised it for growing usage [8–20].

It can be expected that a modelling technique based on physical modelling laws—like the bond graph technique—leads to a more realistic model of physical systems. Hysteresis and saturation are common nonlinear occurrences in different domains. The capability of the bond graph modelling technique to model nonlinearities gives it an edge over other modelling techniques. In this paper, a model for representing hysteresis will be first developed and this model will be then used in an overall system model of a 3ϕ induction machine.

The organization of the paper is as follows. Section 2 explains the bond graph methodology for handling nonlinearities in a subsystem. Section 3 identifies the nonlinearities present in a rotating machine. Section 4 proposes the method to model hysteresis in a nonlinear magnetic system. Section 5 introduces the bond graph element of modulated Axis Rotator '*mAR*'.

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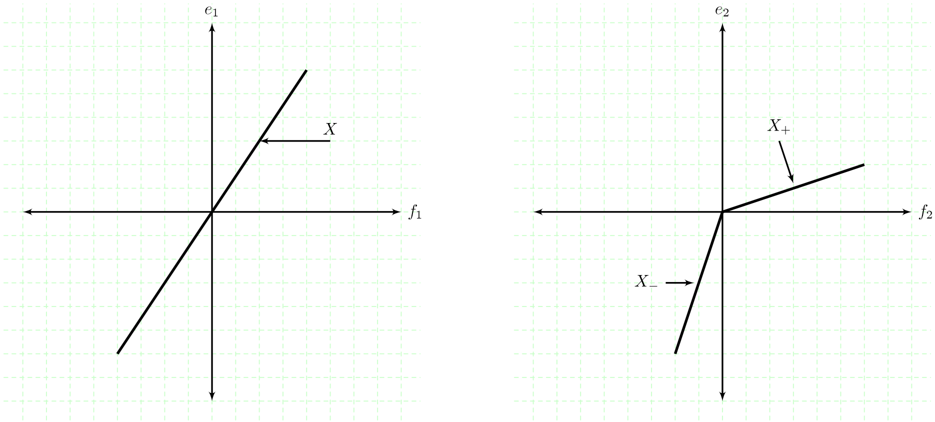

(a) Linear relationship. (b) Nonlinear relationship.

(c) 1-port resistor.

Fig. 1. Relationship between flow and effort for 1-port resistor elements.

Section 6 explains how the nonlinear magnetics of DFIM model is handled and shows the simulation results. Section 7 concludes the paper.

2. Bond graph nonlinear models

Bond graph models are ideally suited for modelling a nonlinear system. A bond graph model does not assume any linearity constraints. The model hides the complexity of nonlinearity from the user of the model. Once the modeller defines the nonlinear relationship in the model, it is the job of the underlying bond graph software to solve the model. The whole process is transparent to the user of the model.

2.1. Nonlinear elements

1-port element is the most basic of the bond graph elements. This element has a single port for energy exchange with its environment. There will be a constitutive equation depicting the relationship between the co-variables of the element bond. The only constraint on the constitutive equation is that the energy should be conserved as per the underlying physical law of bond graph modelling. Two different relationships between the co-variables (effort and flow) are depicted graphically in Fig. 1(a) and (b). The bond graph model for this relationship is depicted by 1-port elements in Fig. 1(c).

The constitutive relationship for the 1-port resistor elements are given in Eqs. (1) and (2). It can be seen that the model for both linear and nonlinear behaviour look-alike, with the constitutive relationship hiding the difference. It is the job of the solver software to simulate the model differently.

$$e_1 = \Phi_1 f_1 \tag{1}$$

$$e_2 = \Phi_2(f_2) \tag{2}$$

where,

$$\Phi_1 = X \quad \text{always}$$

$$\Phi_2 = X_- \quad \text{if } f_2 < 0$$

$$\Phi_2 = X_+ \quad \text{if } f_2 > 0.$$

2.2. Significance of causality

The governing principle in bond graph modelling is the law of energy conservation. In this modelling technique, the physical system is first modelled as a combination of various acausal bond graph elements and junctions. Later the causality is assigned to all the elements, with the assignments satisfying a set of computational rules [4–6]. A perpendicular stroke at one of the ends of the element, indicates the computational direction of the effort variable. Depending on whether the element is connected to 1-junction or 0-junction through the bond, it can be seen whether the element bond is going to compute its effort or flow variable. Refer to Fig. 2(a), the constitutive relationship is given by Eq. (3), similarly for Fig. 2(b) the constitutive equation is Eq. (4). Similar is the case for elements connected to 0-junctions.