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Review

Coupled Models in Electromagnetic and Energy Conversion Systems from Smart Theories Paradigm to That of Complex Events: A Review

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Abstract: In this article, we evaluate the modeling of a real operation of a real system using the corresponding adequate theory. We show that the smart theories often used do not directly correspond to reality because these theories have been established in idealized frameworks. The need to adapt such frames to real landscape situations necessitates modifying the models used. This can be achieved by taking into account the different existing physical phenomena, which are normally overlooked in smart idealized models, in a revised coupled model. This contribution aims to analyze and illustrate the relationship between smart theories and coupled realistic models through a literature review. The strategy for constructing such models is discussed and highlighted. The understanding of this approach is illustrated by an application to the case of electromagnetic and energy conversion systems. In these systems, intelligent energy management, conversion and control involve the use of an accurate realistic coupled model in system design, optimization and control. It is a question of coupling and solving equations representing these systems by taking into account the real phenomena involved, which are electrical, magnetic, mechanical, thermal and material. The obvious advantage of using such realistic models in computer-aided design and optimization tools is illustrated. Moreover, the interest of using such models in the supervision of systems is assessed. These demonstrations are supported by a review of examples of work carried out in the field.

Keywords: electromagnetic; energy conversion; smart theories; postulations; coupled problems; complex procedures; electric machines; system supervision



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1. Introduction

The basis of fundamental theoretical research is established on elegant and coherent theories, which are essential for modern sciences. These theories are generally assigned to autonomous scientific fields. The coherence of a given theory in a given main scientific field comes from neglecting various secondary phenomena existing in the real world. Such postulations wring and idealize the existing reality. These secondary phenomena are generally related to the environmental atmosphere, e.g., temperature, pressure, etc., and behavior of matter, e.g., viscosity, density, etc. These secondary phenomena are generally governed by other secondary fields of science. Coherent theories apply perfectly to specific problems where the relative postulations are in phase. Otherwise, to model a real context, using principal field theory, where simplifying postulations seems illegal, we have to backtrack from such postulations.

The question of the correctness of the model and its matching to reality relates to the problem of uncertainty. Uncertainties can generally be categorized as random or epistemic. The latter is involved in the accuracy of the model. Such uncertainty of knowledge concerns the prediction modeling of natural or artificial phenomena by means of functions or processes having known behaviors. The management of this uncertainty could be attained by refining the model exercised for prediction. Many innovative experimental procedures in diverse sciences necessitate the elaboration of modeling. These models allow

for quantifiable comprehension and predictive reproductions of the consequent processes that cannot be accomplished by analyses built on observation alone. Conversely, the corroboration of predictive models by the elaboration of new experimental methodologies is an important deal in these sciences. These elucidations demonstrate the significance of the prediction–observation link. Regarding such a link in these types of processes, the concerned applications are broadly spread in industrial processes, Digital Twins, healthcare protocols, mobility vehicles, medical imaging, etc.

Let us illustrate the notion of elegance in theories that belong to basic science. When a theory or model describes a phenomenon clearly and directly, we say it is elegant. Moreover, a conception that is easy to understand can account for a large amount of information and can answer many questions. Therefore, the elegance definition as simplicity plus greater capacity seems fair. Note that this last affirmation is only valid when the theory is applied in its strict scope.

One of the most famous elegant unified theories is the set of Maxwell’s equations. These equations established by James Clerk Maxwell (1831–1879) involve an association of three experimental laws discovered by three of his predecessors. These are Carl Friedrich Gauss (1777–1855), André-Marie Ampère (1775–1836) and Michael Faraday (1791–1867). The association of Maxwell’s equations was only possible because Maxwell knew how to think ahead of his predecessors, by introducing into an equation a “missing link” named displacement current, whose presence guarantees the consistency of the unified edifice. This illustrates a significant touch to the unification elegance. Maxwell published his primary theory in 1865 by way of twenty equations [1]. In 1873, in the two-volume work, *A Treatise on Electricity and Magnetism*, Maxwell had reworked his theory in the form of eight equations. It was not until later, in 1884, that Oliver Heaviside (1850–1925) rewrote these equations as four vector partial differential equations.

The case of Maxwell’s equations has illustrated the interest in the elegance concept. However, later in this paper, in the application to electromagnetic systems, we will see that in real systems, the Maxwell’s equations could not always be applied straightaway. In addition, in many other circumstances, such elegance could be in conflict with real applications. Likewise, few years after Francis Crick co-discovered the DNA double helix and a few years before he co-won a Nobel Prize, he concluded that [2] the same is not necessarily true for all science activities: “In biology, it is possible to be elegant and to be wrong”.

In such cases, we have to perform a volte-face from elegance to reality reconsidering the corresponding committed approximations. We are therefore inclined to modify the model based on the theory of the main field, by associating the secondary fields in an amended model. Such a modified model resulting from “backward postulations” paradoxically seems to represent the real context. Note that coupled models belong to applied science.

The present contribution aims to analyze and illustrate the connection of intelligent theories and coupled models through a review of the literature. For this reason, the introduction includes few historical references such as traditional reviews; the review of the literature here is shown in the next sections of the article. In this work, after having discussed the notion of elegance of theories, we illustrate the postulations necessary to achieve such elegance. Then, we discuss the need to amend the models to remedy the approximate postulations. The proposed strategy for developing revised models will be illustrated with applications in electromagnetic and energy conversion systems where realistic models are discussed. This involves coupling and solving equations representing these systems by taking into account the real phenomena involved. These are electrical, magnetic, mechanical, thermal and intrinsic material. Furthermore, in addition to the obvious advantages of using such realistic models in design and optimization, we show their benefits in the supervision of energy conversion systems. These demonstrations are supported by a review of examples of work carried out in the domain.

2. Smart Theories and Postulations

In this section, the notion of elegance in theories will be analyzed and discussed. Often, the notion of elegance belongs to the philosophy of science. On the contrary, we make it clear here that the elegance of the theories in the present work belongs to fundamental science and that the coupled models belong to applied science.

Consider a real societal physical problem that can be represented mathematically by the field A , which is the association or the union of the functions $B, C, D \dots$ that depend on variables $x, y, z \dots$. Each of these functions relates to a different domain or area of science. In order to model this real problem, we generally need to consider different aspects related to different areas of science relative to the field A given by (1).

$$A: B(x, y) \cup C(y) \cup D(z) \quad (1)$$

$$A_1: B(x, y) \quad (2)$$

$$A_2: B(x) \quad (3)$$

Conversely, often, a domain is more concerned by the problem than the others; let us call this the main domain and represent it by the function B in (1). In general, one tends to consider this main area alone to practice modeling; this results in A_1 , given by (2). As well, almost all scientific theories generally relate to a single area of science. In addition, founding coherent and agreeable theories habitually requires postulations that squeeze and idealize the actual context of the investigation. Thus, the consistency and “elegance” of a theory requires idealized assumptions, resulting in A_2 given by (3). Accordingly, such a theory corresponding to A_2 can only be used correctly under the same conditions of these hypotheses. Moreover, the validation of this theory, which allows for its foundation, must also be performed under these conditions.

Therefore, when we model a real problem using main domain theory alone, the result will often be wrong. This is due to committing to two approximations. The first is relative to neglecting the other domain influences (replacing A with A_1), and the second is relative to using idealizing postulations (replacing A_1 with A_2). The more these two approximations are unjustified regarding the actual conditions, the more the obtained results using the main domain will be far from reality. In such a case, in order to amend this situation, we have to follow a reverse approximating procedure that will re-integrate in the model via coupling, with all the neglected aspects resulting from the used approximations. Figure 1 displays a recapitulated illustration of postulations operating in a real setting field and producing an elegant theory of the main field and its reversal. This last setting reveals how to exploit the elegant theory correctly across mathematical coupling to present a real setting.

We can note that the reduction of (1) to (3) for a principal domain represented by the function B , as described above, could apply in the same way to the functions $C, D \dots$. From this remark, we can expect that the domains affected by (1) may represent different actual societal physical problems with a different main domain and therefore with different reductions. In addition, for a given problem, we can investigate a specific behavior involving one of the domains more than the others. In this case, this area will be considered the main one in the reduction. In other words, we can study a given problem from different sides corresponding to different reductions involving different approximations. For example, we consider a problem involving thermal and chemical domains. When studying thermal performance, one may tend to introduce chemical approximations for reduction and reciprocally.

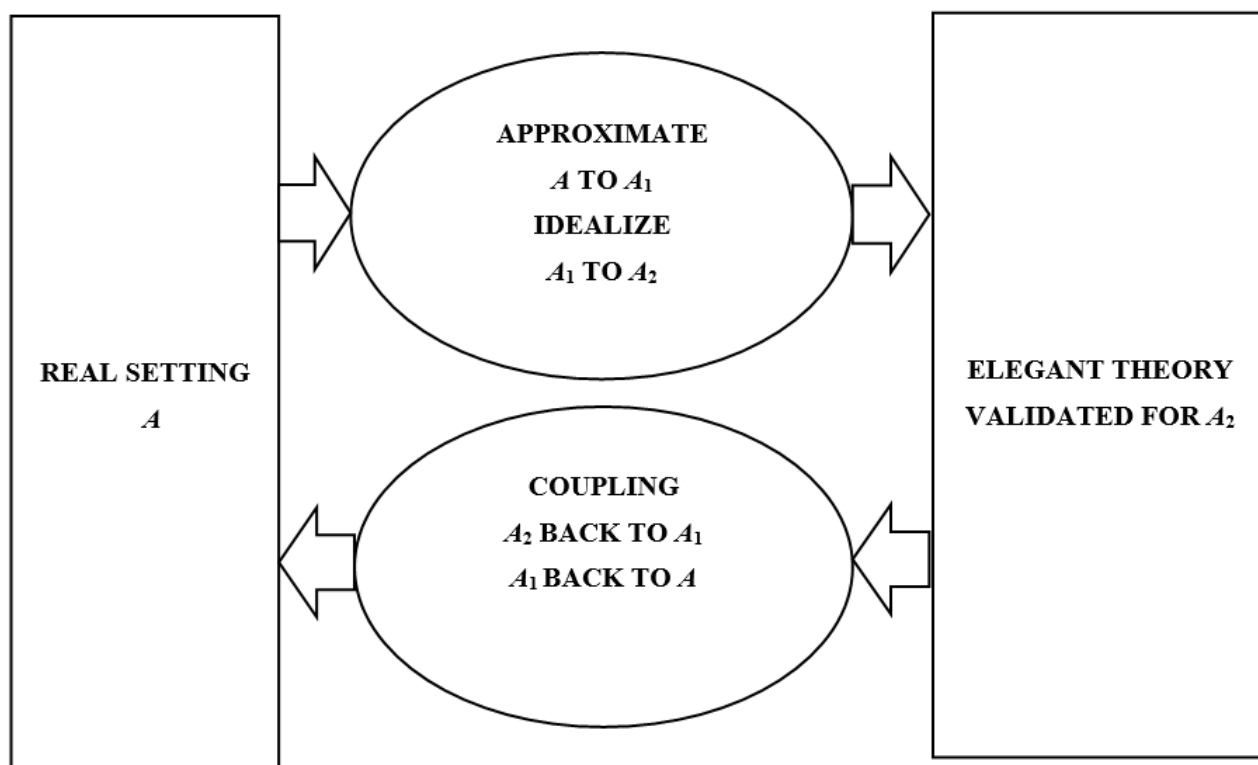


Figure 1. Representation of postulations applied to a real setting field, resulting in an elegant theory of the main field and its reverse. *A*: real field (1), *A*₁: main field (2), *A*₂: main idealized field (3).

3. Revised Coupled Models and Solution Strategy

The reverse approximating procedure will go through a kind of revised model comprising a principle theory associated with the other involved theories, all accounting for actual conditions. In addition, this can include other elements that relate to specific mathematical formulations, adequate boundary conditions, particular numerical techniques, etc. The revised model has to account for these elements using a suitable procedure to solve the integrated equations, equivalent to (1). This procedure relates to the scheme of coupled phenomena solutions.

In general, coupled problem schemes involve mathematical solutions of equations governing different phenomena. This concerns natural or artificial sets that behave under rules belonging to distinctive branches of theoretical spheres. The nature of the behaviors of these phenomena and their interdependence as well as the closeness of their temporal evolution (time constants) are directly related to the approach of solving the corresponding governing equations. Each of these behaviors may be linear or nonlinear and may possess high or low temporal evolution. Moreover, these behaviors may be independent or interdependent. In addition, such interdependence may or may not be linear. In one extreme, we have a case of linear behaviors that are independent with far time constants. In this case, we can solve the governing equations individually. In the other extreme, we have a case of nonlinear behaviors that are nonlinearly interdependent with near time constants. In this situation, we need a strongly coupled simultaneous solution of equations. In between these two extremes, one can solve the equations in consecutive progression mode by iteration, depending on the severity and degree of the complexity of behaviors.

The occurrence of the inverse approximation process, reintegrating into the model all the disregarded characteristics, evidently performs as a kind of coupled problem.

In the cases of general coupled problems as well as the situation of a reverse approximation procedure re-integrating in the model all the neglected aspects, we have to account for different specific elements. An important aspect of these elements concerns the form of the handled equations. In general, the source temporal evolution nature, the

matter behavior and the concerned geometry in real problems are more complex than those considered in theory. Consequently, the space and time behaviors of the different variables in the corresponding equations are also more complicated compared to elegant theories. Such a complex system of equations does not permit analytical solutions. To apply theories correctly, we often need to consider a discretized form in space and time of the equations. In such a case, the theories will operate locally in finite discrete domains for which the global solution of the assembly will be exercised in the discretized time domain. The space local non-linearity and the time evolution are considered through iterative procedures.

4. Case of Electromagnetic and Energy Conversion Systems

For a better understanding of the problem addressed, we will consider an application in the field of electromagnetic systems (EMSs) including energy conversion drives. These are present in many societal applications such as mobility, health, security, communication, etc. In these systems, intelligent energy management, conversion and control involve the use of an accurate realistic representation of the arrangement involved. A revised realistic coupled model achieves this goal through its use in system design, optimization, and control.

The main area in such a case is electromagnetics (EM), which is governed by Maxwell's equations. However, EMSs generally behave in four instances: electrical, magnetic, mechanical and thermal.

4.1. Maxwell's Equations

James Clerk Maxwell was a Scottish physicist and mathematician. He is mainly known to have unified, into a single set of equations, the Maxwell's equations, electricity, and magnetism, containing a key revision of Ampere's theorem. It is the most unified model of electromagnetism. The equations established by Maxwell involve an association of three experimental laws discovered by his predecessors:

- Maxwell–Gauss law relates the electric displacement d to the free electric charge density q .
- Maxwell–Ampère law links the h -magnetic field to the time-rate of the electric displacement d and the free total current density j .
- Maxwell–Faraday law relates the electric field e to the time-rate of the magnetic induction b .

Around 1865, Maxwell produced a harmonious synthesis of these experimental laws. As mentioned in the introduction, he introduced into an equation a term based on the called displacement current, whose presence guarantees the coherence of the unified edifice. As mentioned before, after the publication of the initial Maxwell's equations in 1865 and in 1873, Oliver Heaviside rewrote these equations as four vector partial differential equations.

This equation system can be formulated mathematically under different functional forms of the considered problem. One of the most common is the basic full-wave electromagnetic formulation given by:

$$\nabla \times \mathbf{H} = \mathbf{J} \quad (4)$$

$$\mathbf{J} = \sigma \mathbf{E} + j \omega \mathbf{D} + \mathbf{J}_e \quad (5)$$

$$\mathbf{E} = -\nabla V - j \omega \mathbf{A} \quad (6)$$

$$\mathbf{B} = \nabla \times \mathbf{A} \quad (7)$$

where \mathbf{H} and \mathbf{E} are the magnetic and electric fields, \mathbf{B} and \mathbf{D} are the magnetic and electric inductions, and \mathbf{A} and V are the magnetic vector and electric scalar potentials. \mathbf{J} and \mathbf{J}_e are the total and source current densities, σ is the electric conductivity, and ω is the frequency pulsation. The symbol ∇ is a vector of partial derivative operators, and its three possible implications are gradient (product with a scalar field), divergence and curl (dot and cross products, respectively, with a vector field).

The magnetic and electric behavior laws respectively between \mathbf{B}/\mathbf{H} and \mathbf{D}/\mathbf{E} are characterized by the permeability μ and the permittivity ϵ .

It may be noted that the above harmonic representation that seems simpler cannot be applied in the case of free transient variations, as for example, a capacitor discharge.

The solution of Equations (4)–(7) determines in a system the concerns of electromagnetic fields for a frequency pulsation, accounting for the magnetic materials behaviors through the permeability, for eddy currents in electric conductors through the electric conductivity and for displacement currents in dielectrics through the permittivity.

Often, EMSs involve fields other than EM, for example, mechanic, thermic, material, etc. In some cases, the influence of these other fields could be negligible, and it will then be possible to solve the problem correctly with only the Maxwell's equations, see, e.g., [3,4]. Nevertheless, in such a case, there is yet a conflict with real situations. In realistic applications, the electric current is delivered by a non-perfect current source as supposed by the elegant form in (4)–(7) that considers the current delivered by a current source. The committed assumption is that we consider in (4)–(7) the value of \mathbf{J}_e , which is known and could be imposed. In general, the current is delivered by a voltage source through an external electric circuit. We will consider this question later in the paper.

In general, to model an EMS, we need to account for other fields in addition to the EM field through coupling of the corresponding governing equations.

4.2. Physical Phenomena in EMSs

As mentioned before, EMSs behave under four phenomena: electrical, magnetic, mechanical, and thermal. The first three have small and relatively near time constants, while the thermal phenomenon has a relatively higher time constant.

The different mixtures of these phenomena can be classified into causal (system behavior), integrated (electrical and magnetic) and intrinsic material (functional). The latter mainly concerns intelligent materials such as magnetostrictive, electrostrictive, shape-memory, and thermoelectric. Frequently, these mixtures are treated separately with the understanding that the others do not affect every member of the mixture. Moreover, sometimes these others are simply ignored. Such an approximation might be permitted in few cases. Under general circumstances, this approximation leads to an erroneous result. Therefore, we have to consider the whole mix, taking into account each of its members and the interdependence involved in the mix.

5. Coupling and Solution of Equations in EMS

The solution of the equations of the influential events involved must take into account different specifications. The nature of the concerned system behavior implies either frequency domain or time domain analyses. The fact that EMSs often have complex geometries and involve materials with non-linear behavior laws implies going through local distribution of variables as fields, potentials, etc. Due to this aim, we use 2D or 3D discretized geometrical cells or elements with defined boundary conditions on the discretized domain limits, see, e.g., [5,6]. Such a performance obtains a local solution for nodes, edges, facets, etc. The degrees of discretization refinement of space and time depend on the geometry, temporal evolutions, and individual as well as interdependent laws of behavior of variables, see, e.g., [7,8].

The strategy of solution for phenomena couplings depends on different factors. In the circumstance of phenomena with different time constants, we have two situations. The first concerns the case of independent phenomena and linear behaviors. In this case, we can use simple solutions (direct separate solutions). The second involves the case of non-linear behaviors and/or variables that are interdependent. Here, we need a weak separately iterative coupling. In the circumstance of phenomena with the same order of time constants, in general, a simultaneous strong solution is needed. The non-linearity and the interdependence variables are included in the solution through an iterative convergence procedure.

5.1. Integrated Coupling

As mentioned before, generally in EMSs, the current is delivered by a voltage source through an external electric circuit. The general next relation between the voltage v and the current I in the external circuit (coil) governs this current:

$$v = 1/C \cdot \int i \, dt + r i + L \cdot di/dt + d\Psi/dt + \varkappa \quad (8)$$

In this expression, r is the total resistance of the circuit, L is linear inductance, C is capacitance, \varkappa is non-linear voltage drop (typically a semiconductor component, e.g., a diode) in the electrical circuit, and Ψ is the flux linkage in the coil.

The EM main domain normally involves electric and magnetic aspects and is represented by Maxwell's equations. Due to fact that current density and hence the current is delivered by a source that we know the voltage value while the value of the current is unknown. Therefore, the equations to solve are (4)–(8). This coupling between the EM domain (4)–(7) and the external electric circuit (8) is particular regarding other couplings with domains other than EM because it represents a “correction” inside the EM domain. We call it integrated coupling. Generally, the coupling of the EM domain with the external electric domain needs a simultaneous strong solution of the equations due to non-linearity of behaviors and closeness of the magnetic and electric time constants, see, e.g., [9–13].

5.2. Causative Couplings

This category of couplings is related to system behavior. In most of the EMS cases encountered in real situations, the areas other than EM cannot be neglected, and their equations must be considered in the solution of the problem. Typical situations in this category are the EMSs where the operation, the source, or the outcome is directly related to another domain. In addition, most of EMSs related to energy conversion are in this category. For instance, the mechanical source or outcome are respectively in electric generators [14,15] or motors [16,17].

These cases may involve behavioral modifications in the EM and other areas altered by each other. This happens when the behaviors are interdependent. The solution of the equations for a given EMS would be separate, iterative or strongly coupled, as mentioned before, depending on the severity of the behaviors.

5.2.1. EM and Mechanical

We consider the case of an EMS, where besides EM, the mechanical domain is involved in forms of displacement [18–21] or deformation [22].

Let us consider the example of the classical old electromagnet given in Figure 2, which is a typical EMS involving electro-magneto-mechanical aspects illustrating the consideration of the different domains [23]. It consists of an electromagnet composed of a stationary part constituting non-conducting magnetic material (μ) and a mobile armature constituting conducting magnetic material (μ, σ). A coil fed by a voltage source excites the stationary part, and the mobile armature is connected to a spring, a damper and an external force. The equations governing such a system are:

$$m \cdot d^2 X/dt^2 + c \cdot dX/dt + k X = F_{\text{mag}} + F_{\text{ext}} \quad (9)$$

$$d\Psi/dt + r I = U \quad (10)$$

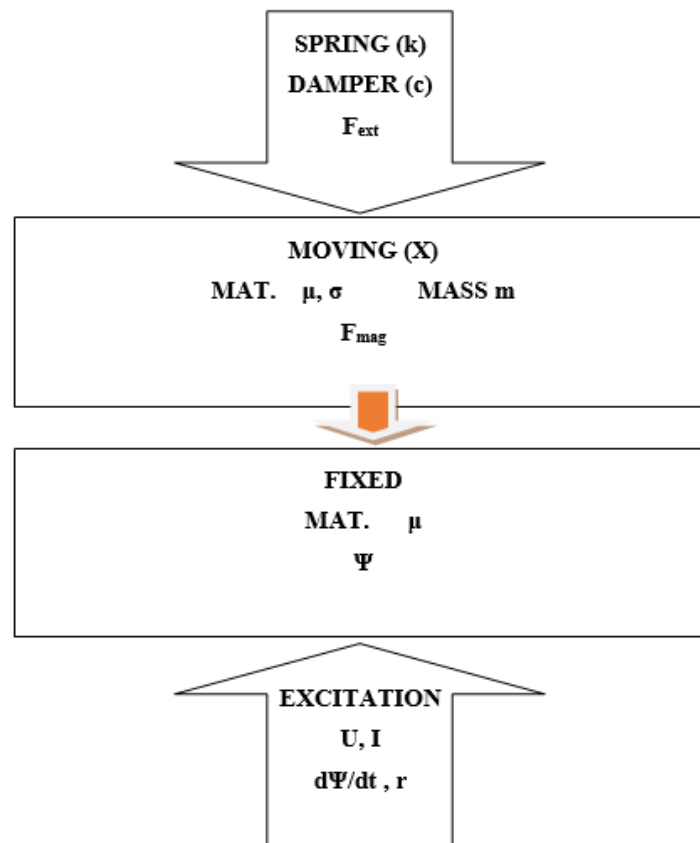


Figure 2. Example of an electromagnet involving electro-magneto-mechanical aspects. A step voltage U in the source of the exciting coil of the fixed part results in a current I across the coil and a displacement X of the moving part toward the fixed one (Equations (4)–(7) and (9) and (10)).

In these equations, r is the resistance, Ψ is the magnetic linkage flux, U is the source voltage, and I is the current in the exciting coil. X is the mechanical displacement, F_{mag} and F_{ext} are the magnetic and external forces, m , c and k are the mass of the moving object, the damping coefficient and the stiffness of the spring, respectively. It may be noted that (10) is a particular case of (8).

We consider for example a step voltage on the source in the exciting coil. The unknown variables in these equations are the current I across the coil and the displacement X of the mobile armature. In such a system, the magnetic linkage flux Ψ and the magnetic force F_{mag} could generally be nonlinear functions of the magnetic saturation and the mechanical motion.

To solve the problem, we have to consider the Maxwell's Equations (4)–(7) with the mechanical and circuit Equations (9) and (10). Generally, the coupling of the EM domain with the mechanical domain needs a simultaneous strong solution of the equations due to non-linearity of behaviors and closeness of the magnetic and mechanical time constants. The magnetic field solution could be performed using 2D or 3D discretized geometrical cells or elements with defined boundary conditions on the discretized domain limits. This can be achieved by, e.g., the finite element method (nodal, edge or facet). This obtains a local solution for nodes, edges or facets.

5.2.2. EM and Thermal

We consider the case of EMSs, where besides EM, the thermal domain is present in the form of heat developing [24] or results in undesirable heating [25–28].

Heat production by means of EMSs can be in the form of magnetic induction heating by eddy currents in conducting metals with high conductivity, or by electric induction microwave heating in dielectric materials possessing high permittivity [29,30].

The coupling of EM and thermal domains involves phenomena with different time constants. Moreover, the problem may include non-linear behaviors and/or variables that are interdependent. Here, we need a weak separately iterative coupling.

5.3. Material Intrinsic Couplings

This category of couplings is relative to a functional character regarding material intrinsic interactions. These mainly concern smart materials that each involve two phenomena: magnetostrictive (magnetic–mechanic), electrostrictive (electric–mechanic), shape-memory (thermic–mechanic), and thermoelectric (thermic–electric).

The couplings in these cases correspond to two groups. The first reflects linear behavior (electrostrictive) and/or different time constants (shape–memory, thermoelectric). In this case, we can practice separate solutions or coupled iterative solutions for respectively independent or interdependent behavior [31,32]. The second concerns non-linear behavior and/or close time constants (magnetostrictive). Regarding the complexity of the nonlinear relationships, we use strong coupling or multiscale methodologies [33,34].

6. Computer Aided Design of EMSs

The revised coupled models discussed in the last section can be beneficially practiced to determine a realistic behavior of EMSs, including energy conversion drives. Moreover, these complete models are often used to design and optimize these systems. This is accomplished through computer-aided design (CAD) tools.

For several decades, the research trend has been to move from real prototypes to virtual emulation tools. It becomes possible that some studies of a physical system can be simulated using computers. By understanding and mimicking the behavior of a particular system on a computer before physical creation, the number of tests and experiments can be greatly reduced. Due to these advantages, a number of virtual systems has been developed. This work was carried out for CAD purposes or to simulate the behavior of the system. Some of these simulations were performed to build a complete model, while others were performed to simulate a specific type of application. Examples of such virtual models can be found, e.g., in the case of electromagnetic systems, see for example [35–38].

The reliability of the behaviors provided by the virtual systems strongly depends on the level of emulation of the physical systems. However, due to the complexity of the system and the uncertainty of the process, it is often difficult to build a realistic virtual system compared to its specific physical counterpart. The complexity of a system is related to its operation as well as to its environmental conditions. Process uncertainty is related to the accuracy of the virtual model (mathematically and numerically). In such a case, we need composite 3D virtual models taking into account all the physical phenomena involved in the functioning of the system, see for example [39–41]. Note that the process described here is relatively cumbersome and usually involves some offline matching practice.

7. Supervised Energy Conversion Systems

Energy conversion systems are frequently used in a wide range of applications ranging from small everyday appliances of a few watts to heavy industrial megawatt demands, including applications in mobility, medical, robotics, etc. For example (only main data):

- A traveling wave mini piezoelectric pump: Use of two piezoelectric transducers (excited by a 28 kHz, 15 V source) to create a traveling wave on a flexible metal beam (aluminum $160 \times 30 \times 2.6$ mm) fixed between them. A fluid-containing component is bonded to the beam using a progressive wave velocity of 80 mm/s. For more information, see the Ph.D. thesis of C. Hernandez, GeePs, 2010.
- A miniature piezoelectric robot: Use of piezoelectric patches (of $32 \times 17 \times 0.27$ mm) excited by a 11.6 kHz, 30 V source, bonded on a flexible metal (aluminum $180 \times 17 \times 0.5$ mm) to create a controlled-direction movement on a solid surface with a velocity of 81.19 mm/s. For more information, see the Ph.D. thesis of H. Hariri, GeePs, 2012.
- Electric teeth brose: 5.8 W, 240 V, 50 Hz

- Vehicle alternator: max 140 A, 12–14.7 V
- Electric vehicle: engine power 100 kW, battery voltage 360 V
- Very high-speed train TGV: eight synchronous motors of 1.1 MW, 25 kV, 50 Hz (Alstom)
- Wind farm: five synchronous generators of 2 MW, 25 kV, 50 Hz, controlled to operate with 0 MVar under wind speed 15 m/s, (Hydro Quebec)

Energy conversion drives are supervised in several ways depending on the nature of the application with respect to the needed accuracy and the response time required, ranging from slow to instantaneous, see e.g., [42–48]. Nevertheless, we need the most accurate model of the drive involved in control, which allows for efficient and robust supervision.

7.1. Automated Systems

In various automated procedures, including those involving energy conversion drives, sensors are commonly used to determine specific operating variables and system parameters. However, estimation can be used for variables or parameters that are difficult to measure. Accurate parameter estimation plays a crucial role in the operation of drive systems. The implementation of an estimation algorithm on an embedded controller platform requires the simplification of the mathematical model of the drive. This is why we often have to perform this estimation offline to obtain reasonable accuracy. For this, one can use CAD tools based on complete models representing the drives in their environments (see last section). In such a case, the matching of the estimated parameters with the actual parameters would be successful. However, the problem is that pairing cannot be instantaneous with the system running. Various studies have proposed a compromise between the precision of the estimation and the quickness of the matching by implementing more sophisticated algorithms on specialized platforms of embedded controllers. For this, in automated drive systems, different types of observers, state filters and controllers are offered as estimators. The robustness of the controller is supported by the use of adaptive methods. Large-capacity microcontrollers can improve controller board design and software required for estimation, which iteratively targets the match simultaneously [42–48]. Figure 3 illustrates a conceptual representation of such iterative real-time matching.

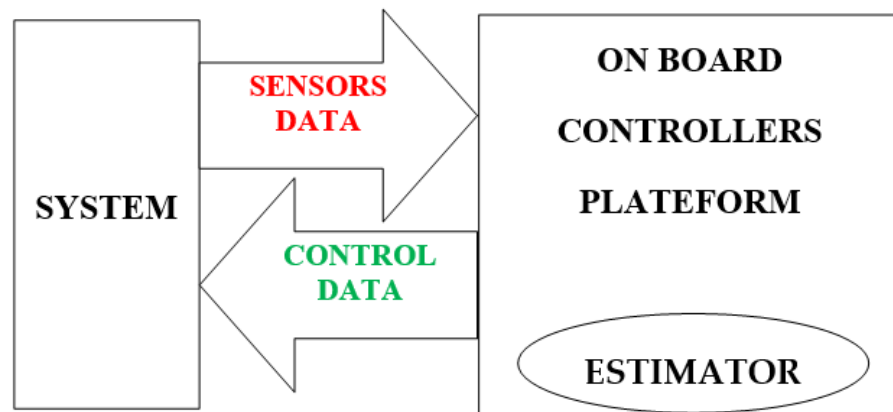


Figure 3. Conceptual representation of iterative real-time matching in automated system.

7.2. Complex Procedures

In the previous section, we discussed the role of the matching of estimated and actual parameters in automated procedures. This evaluation has illustrated the need to improve the matching of virtual models to their real procedures. In this section, matched twins in complex procedures will be examined, which help to expose the concept of digital twin. Let us first look at the definition of a complex procedure. Electromagnetic and energy conversion systems or involved procedures could be simple and direct in particular cases. Nevertheless, in most real applications, this is not the case, and either the system or the concerned physical phenomena or both present specific complexity.

7.2.1. Notion of Complex Events

Generally, in the called complex procedure, the complexity concerns components and involved physical phenomena. One can define complexity in terms of interactions [49]. The degree of interaction can be classified into three forms: simple, complicated, and complex interactions. The simple one behaves as direct or linear, the complicated interaction performs as linear and loosely coupled, while the complex interaction with tightly coupled links would be the feature of a complex system or procedure.

Such a classification reminds us of the one mentioned previously in the section—Coupling and solving equations in EMS—relating to the coupling of different phenomena. The three corresponding mentioned couplings concern the cases of the following phenomena:

- Independent (with different-order time constants) with linear behaviors requiring simple solutions (direct separate solutions);
- Having nonlinear behaviors and/or interdependent variables (with different-order time constants) requiring weak separately iterative coupling;
- Having the same order of time constants, in general requiring a simultaneous strong solution where nonlinearity and interdependence of the variables are included in the solution by an iterative convergence procedure.

This correspondence between the classification of complexity and that of the coupling of phenomena in events obviously seems understandable.

7.2.2. Matching Twins in Complex Procedures

We have seen that the nature of a real system and the uncertainty of the emulation process often make it difficult to build a realistic virtual system and that we need a trade-off between the accuracy of the estimate and the reaction efficiency in automated systems. These two observations are obviously linked to the improvement of the matching of virtual models to their real procedures. Such a pairing depends on the qualities of the virtual model as well as its interaction with the real object. The value of the virtual model is associated with its ability to account for the environmental phenomena involved in the actual procedure. The interactive characteristic of the “real-virtual” link is linked to the detection, processing and control capabilities. The weight of the improvement of the matching becomes particularly crucial in the compound procedures where the complexity relates to the various incorporated components accounting for the physical phenomena involved. To manage such complex procedures, one can practice the Internet of Things (IoT), which primarily deliberates in the physical domain via direct real-time data collection or CAD, which focuses exclusively on the digital domain.

However, it is essential to temper and control the irregular and unnecessary behaviors that occur in these complex procedures; these involve thoroughly complex interactions. Achieving such a goal requires a paired observational model twin practiced in the relevant procedure [50]. A consistent representation of such a matched twin is shown in Figure 4. Such a twin differs from both IoT and CAD by focusing on both the physical and digital spheres. This twin mainly involves detection (observation side), calculation (model side), information, and control processing (between observation side and model side). Detection on the observation side concerns the various recognitions of the sensors. Model-side computation could involve simulation, optimization, design, diagnosis, prediction, and testing. These operations can manipulate learned collected data in addition to sensor data. The link between the observation side and the model side is bidirectional. The observation part provides sensor measurements in processed forms to the model part, while the latter sends process and control information to the observation part.

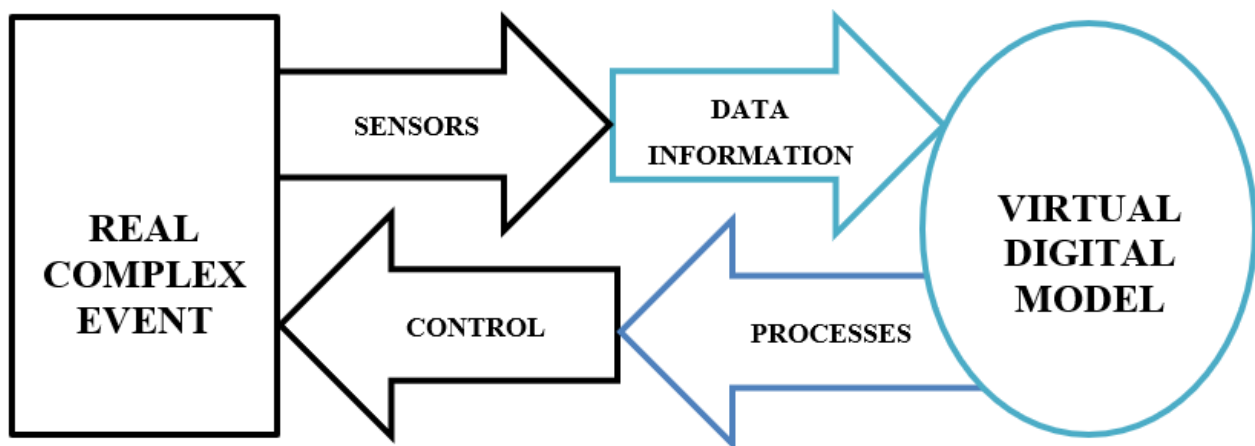


Figure 4. Representation of a real-time bidirectional matched observation model twin in a complex procedure.

The twin described in Figure 4 corresponds to the Digital Twin DT. This concept was first introduced in 2002 by Grieves M. [50], although similar uses existed before. It is characterized by beneficial two-way communication between the digital and physical domains. The three components of a DT are a paired physical observable element, a real-time replicated digital element, and their sensory, processing, control, and pairing links. The physical element dynamically adjusts its behavior in real time according to the instructions made by the digital element, while the digital item correctly reproduces the actual state of the physical event. Thus, DT offers a smart tie of the physical and digital domains [51]. Thus, in DT technology, physical observation and virtual modeling are interconnected in a reciprocal exchange in real time. The observed element corrects the virtual error, and the virtual element corrects the observed sensory data in an iterative process. The DT concept is mainly used for fault diagnosis, predictive maintenance, performance analysis and product design [52]. This relates to various fields and innovative industrial devices such as energy and utilities, aerospace and defense, automotive transport, machinery manufacturing, healthcare and consumer goods.

7.2.3. DT Concept and EMSs

EMSs and energy conversion drives and devices are often integrated into DT-assisted systems as those employed in the areas mentioned in the last section. Moreover, energy conversion drives employment can be directly involved in different tasks utilizing the DT concept; see, e.g., [53–58]. Moreover, potential uses of the DT concept can be practiced in different fields involving EMSs and energy conversion such as, for example, wireless power transfer in electric vehicles [59,60] and actuation in image-guided therapeutics. [61,62].

8. Conclusions

In this work, after having discussed the notion of elegance of theories, we have illustrated the postulations necessary to achieve such elegance. Then, we discussed the modeling of a real event and the need to amend the models to remedy the approximating assumptions. The proposed strategy for developing revised models was reviewed, supported by applications in electromagnetic and energy conversion systems using realistic models. Such a strategy aimed to couple by solving equations representing systems and taking into account the real phenomena involved, which are electrical, magnetic, mechanical, thermal and materials. Moreover, besides the obvious advantages of using such realistic models in design and optimization, their advantages in supervising energy conversion systems have been revealed. These demonstrations were supported by a review of examples of work carried out in the field.

This contribution has illustrated that the postulation reductions in virtual representations of real events lead to universal smart theories that can describe a phenomenon clearly and directly. Such intelligence facilitates understanding and can account for a large amount of information and answer many questions, reflecting simplicity and greater capacity.

At the same time, the investigation showed that an accurate representation of a specific real event implies modifying this universal model to take into account a realistic situation. This can be obtained by coupling the universal model with the theories corresponding to the postulation reductions practiced for intelligence.

Moreover, the review of the modeling of electromagnetic and energy conversion systems illustrated how the coupling makes it possible to involve phenomena that are absent in Maxwell's set of equations. This implication concerns the electrical, magnetic, mechanical, thermal and material instances. This review clearly illustrated the crucial role of coupled models in the design and control of energy conversion assemblies as well as complex EMSs in general. Furthermore, the analysis carried out showed that the correspondence between the classification of complexity and that of the coupling of phenomena in these systems is perceptibly comprehensible.

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