A Fuzzy Decision Support System for Magnetic Component Design.

D. Holt U. Kaymak* J.B. Klaassens H.R. van Nauta Lemke

Delft University of Technology
Faculty of Electrical Engineering, Control Laboratory
P.O. Box 5031 2600 GA Delft, the Netherlands
tel: +31-15-2783371, fax: +31-15-2786679, Email: U.Kaymak@et.tudelft.nl

Abstract

In many areas of electrical engineering, magnetic components like transformers and inductors are necessary parts of an electrical circuit. Designing such a component means finding a suitable combination of a ferrite core and a copper wire, while a great variety of requirements have to be satisfied. However, finding the optimal combination is complicated because of the large number of available sizes and types of cores and wires. A Decision Support System (DSS) can assist a designer of magnetic components in selecting the suitable component alternatives and in ranking them, hereby improving the efficiency and the results of the design procedure. This paper describes the aims and the typical problems of magnetic component design, and discusses a Decision Support System for facilitating the design procedure. As an example, the structure of a DSS is described that selects an ac-inductor of a power converter circuit.

Keywords: Decision Support Systems, magnetic components, fuzzy sets, fuzzy multiple attribute decision making, fuzzy design.

Introduction

In many areas of electrical engineering magnetic components are necessary parts of an electrical circuit. For example in power electronics these components are essential for the operation of power converters, in addition to the power semiconductors and capacitors. Magnetic components utilize their magnetic circuit to store or transform energy in order to serve applications such as transforming power, filtering and resonating. The two most commonly used magnetic components are the transformer and the inductor, which are basically composed of a core of magnetic material (ferrite) and turns of copper wire.

Designing a magnetic component means finding the optimal combination of the core and the wire, while a great variety of requirements are satisfied. However, because of the large number of available sizes and types of cores and wires, a designer uses an iterative design procedure, while making extensive use of experience, physical and heuristic knowledge and rules-of-thumb. Even if a computer is used to perform the tedious calculations, still the human design method is inefficient because of the time that is involved in the design, and may cause a sub-optimal final design.

This paper describes how a Decision Support System (DSS) can be realized that assists the designer of magnetic components by selecting and ranking a set of feasible component alternatives. The paper is organized as follows. Section 1 describes magnetic component design and its problems. Then, in section 2, the information necessary to create the DSS is discussed and the structure of an example DSS is described. Finally, section 3 presents the conclusions and the expectations from the proposed DSS.

---

* Author to whom all correspondence should be addressed.

1 Magnetic component design

This section explains what magnetic components are, how they are designed and it treats the shortcomings of the traditional human design method.

1.1 Magnetic components

Basically, magnetic components are constructed of a core of magnetic material and one or more windings of isolated copper wire with a certain number of turns per winding. The component is assembled by winding the wire around a coil former and then joining the core halves together, as shown in Figure 1a. and Figure 1b.

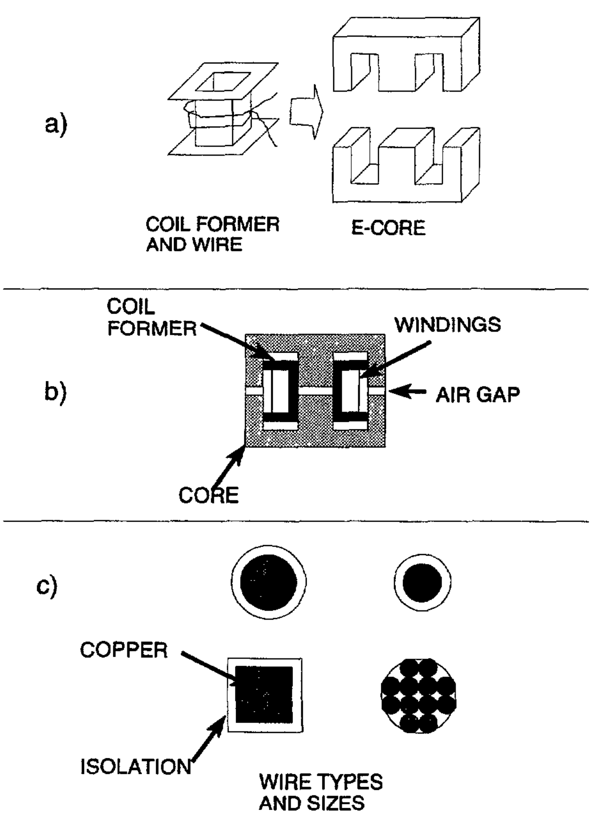

Figure 1 a) E-core, coil former and wire. b) an assembled component c) various types and sizes of wire.

Manufacturers offer a large number of types and sizes of cores and wires. More than 15 different ferrite core shapes can be obtained, all of them available in a range of sizes and most of them in several ferrite grades. Figure 1a. shows the example of an E-core. The available wire can be round, flat or bunched (Litze wire), each available in a range of copper cross-section areas and with different classes of isolation. Some examples of wire types and sizes are shown in Figure 1c. It is obvious that, to construct a component, a large number of combinations of cores and wires is possible. Applications like the inductor can have a varying discrete number of turns depending on the airgap width, which even increases the number of possible alternatives.

1.2 Design of magnetic components

The specific design of a magnetic component has an important influence on the overall performance and the cost of the system for which it is applied. This influence is caused by three troublesome characteristics of magnetic components: 1) usually they are relatively large and heavy items of a circuit, 2) they produce losses and heat and 3) they are not easy to wind and assemble automatically. Therefore, it is useful to find a component that has optimal performance concerning the requirements.

It has already been mentioned that a magnetic component has to be satisfy a great variety of requirements. The requirements imposed on a magnetic component are physical constraints, specifications and designer preferences. They depend strongly on the application for which the component is designed. Some examples of requirements are maximum storable energy, maximum allowable temperature rise, peak current, allowed power loss, weight and cost.

The role of decision making during the design is that a designer has to take decisions about which alternatives are not appropriate and which of the remaining alternatives are the best. The decisions are taken on the basis of how much each alternative satisfies the requirements. Because these requirements can be vague, imprecise or uncertain, a human designer makes design trade offs using his (or her) human ability to deal with vague information. Despite this ability to make fuzzy decisions, he has some shortcomings when dealing with large quantities of information, as explained in section 1.3.

1.3 Design problems and solutions

In order to manage the large number of component alternatives and the large number of requirements, a human designer uses several decision steps to come to the final design. The first step is the initial choice of a core by means of heuristic knowledge, experience or by using the catalogue suggestions. Then, the designer starts an iterative 'trial and error' decision procedure, repeatedly choosing a different wire or a different core and calculating the resulting values of the component characteristics.

This procedure has two drawbacks. The first drawback is that the designer has limited insight in the consequences of a decision. Because it is not clear whether a choice leads to a better alternative or not, many iterations may be necessary. The second drawback is that the designer may reject many alternatives too early in the decision process, because he does not assess all possible configurations of cores and wires. Hence, finding the optimal design may not be possible.

To get around the drawbacks of this method, designers are supported with tables in books or catalogues that simplify the initial choice of the core [5] [6] [11] [12]. The first computer algorithms were implemented in the 60's [4], taking over tedious calculations. However, the critical decisions have always been taken by the designer himself, because only human knowledge and experience can handle the complex dependencies and trade-offs.

With the developments in artificial intelligence and fuzzy logic, new doors have been opened towards computer design of magnetic components [1]. In the following section a fuzzy Decision Support System is introduced that assists the designer of magnetic components by selecting a set of possible alternatives and ranking them depending on how much they satisfy the design constraints and preferences.

2 DSS for component design

This section describes a Decision Support System (DSS) for designing magnetic components. The aims of the DSS and the information necessary to realize the system are explained. The last part proposes a structure of a DSS used to design an ac-inductor for a power converter circuit.

2.1 A Decision Support System

The proposed DSS will assist the designer of magnetic components by selecting a set of appropriate alternatives and ranking them depending on how much they satisfy the design constraints and objectives. The aim of the DSS is to select a few possible, good, alternative designs by performing preparatory decisions, selections and rankings. The designer's attention can then be focused on the evaluation of these designs. In this way the quantitative abilities of computers and qualitative abilities of humans are used efficiently.

To create the DSS, the information that is necessary to design a component has to be determined. This information can be retrieved by interviewing an expert. However, because not all information will be obtained at once, there is need for a continuing personal working relationship with the expert during the construction of the DSS. Two kinds of information have to be retrieved, namely the design constraints and objectives as well as the expert knowledge of the design procedure. In the next part a characterization of the information is given, illustrated by means of the design of an ac-inductor.

2.2 Fuzzy decision criteria

This paragraph describes the first type of information necessary to design a component, namely the constraints and the objectives of the design. The constraints and objectives are defined by 1) the physical boundaries, 2) the application specifications and 3) the designer preferences. Most of these are set up by means of expert knowledge. Because the information can be vague, imprecise or uncertain, a mathematical representation based on the fuzzy set theory is introduced. The constraints and objectives together are also called *fuzzy decision criteria.*

Physical constraints

The physical constraints are boundaries imposed by physical properties of the used materials. The boundaries are not exact, but contain a certain range of tolerance. In general, the tolerance can only be estimated by experts who have practical experience with the materials. The three physical constraints of the example of an ac-inductor are the maximum possible value of flux density B in the core, the maximum allowable airgap width l_g and the temperature (maximum environmental temperature θ_e and maximum allowable temperature rise $\Delta\theta$).

Specifications

The component specifications are the constraints imposed by the application. They form the necessary inputs to the DSS, such as current waveshape, maximum current, inductance, peak voltage, frequency and ambient temperature. The specifications usually also include maximum (or minimum) values for the inductor properties such as mass, volume, power loss and cost.

Specifications are often provided as exact (crisp) values, hereby forming strict limiting boundaries. However, this assumption of exact specifications does not always make sense, because in practice specifications have a range of tolerance. For example, an inductor used in a filter applications with a specified inductance L usually has a substantial range of tolerance around L. If this range of tolerance is allowed, then the set of suitable alternatives may be larger than the case when only a single value for L is allowed. The former set might contain better alternatives than the latter, so the assumption of exact specifications actually obstructs the finding of an optimal component.

Designer preferences

Although the designer has to take the specifications into account, he usually has some personal preferences about several properties of the component, like mass, volume, power losses, cost or temperature rise. The preferences of the designer depend on aspects such as the application, the specifications, knowledge and experience. To help a designer making realistic assumptions for his preferences, the DSS can be made interactive: the designer is allowed to change his preferences based on results of the DSS during the design procedure.

Most of the constraints and the preferences mentioned before contain vague, imprecise or uncertain boundaries. The fuzzy set theory is an advantageous way to represent these requirements.

Fuzzy logic and fuzzy sets theory

Fuzzy logic has been proposed by Zadeh in the 1960's [14] as a means to model uncertainty of non-probabilistic nature and is an extension of conventional (Boolean) logic. A good example of such uncertainty is the imprecision in human behaviour and reasoning. Fuzzy logic introduces the concept of partial truth values that lie between "completely true" and "completely false". There is a strong relation between *fuzzy logic* and *fuzzy sets theory*, similarly to the relationship between Boolean logic and conventional set theory. Fuzzy sets theory is introduced as an extension of conventional sets theory, allowing partial membership in the set. A fuzzy set A is defined in the universe of discourse X via its characteristic function, usually called membership function, $\mu_A(x) : X \rightarrow [0,1]$ that is defined as follows:

$\mu_A(x) = 1$ $\quad$ x belongs completely to A
$\mu_A(x) \in (0,1)$ $\quad$ x belongs partially to A
$\mu_A(x) = 0$ $\quad$ x does not belong to A

A fuzzy set can also be represented as a list of ordered pairs $\{x,\mu_A(x)\}$. The value of the membership function $\mu_A(x)$ is called *membership grade (degree)*. The terms "membership function" and "fuzzy set" are sometimes used interchangeably.

Examples

The uncertain, vague and imprecise nature of the criteria defined before can be represented by membership functions. A membership function gives the degree to which a criterion is satisfied as a result of a certain parameter value of a component alternative. This is illustrated in Figure 2, where some examples of membership functions are shown.

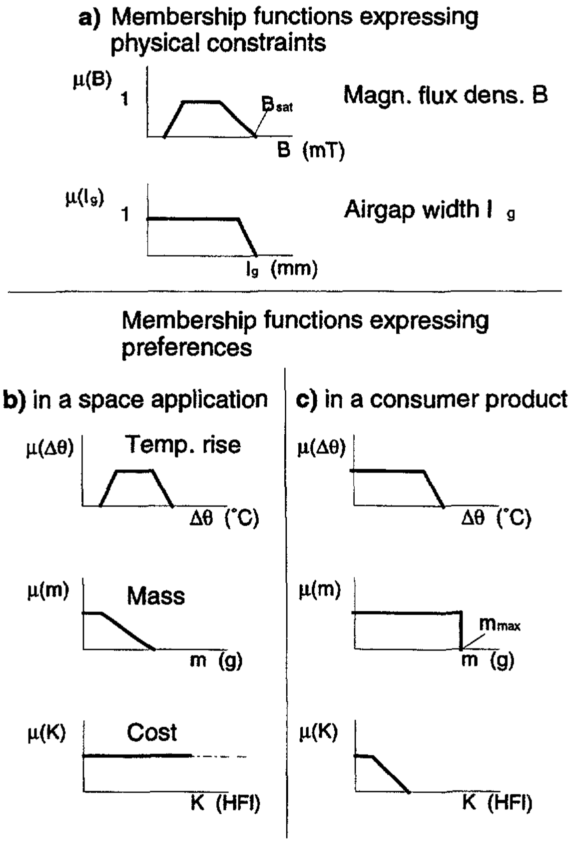

Figure 2 Examples of membership functions describing the fuzzy constraints and preferences.

In Figure 2a the membership functions are shown expressing the grade of appropriateness of the magnetic flux density B in the core and of the airgap width l_g. The upper boundary of $\mu(B)$ is the saturation flux density B_{sat} of the core material. The lower boundary of $\mu(B)$ is determined by the maximum storable energy. The fuzzy upper boundary of $\mu(l_g)$ of a specific core is determined by the information of an expert on the maximum allowable airgap width $l_{g,max}$.

Figure 2b and Figure 2c show the membership functions expressing the designer preferences of an inductor in a space application and a consumer product application. For example, the shape of the fuzzy set $\mu(m)$ shows that the mass of the inductor for the space application should be low, while the mass of an inductor for a consumer product is not important, except for a specified maximum allowable mass m_{max}. From the membership functions of the cost $\mu(K)$ it can be seen that there is no limiting boundary for the cost of an inductor in space design, but in the application of a consumer product the costs should be low.

By means of these fuzzy sets the fuzzy decision criteria are described. The following part discusses the design procedure. In order to realize an efficient decision procedure for the DSS, expert knowledge about the procedure has to be retrieved.

2.3 DSS structure

In this part, firstly the retrieved knowledge for designing ac-inductors is described. Secondly, a DSS structure is proposed using this knowledge.

Designer knowledge

Besides the expert knowledge included in the decision criteria, additional expert information is retrieved in order to realize a more efficient decision procedure. The expert information may consist of rules, procedures, assumptions or any other kind of applicable knowledge.

For the design of an ac-inductor, the following information is retrieved during the construction of the decision procedure:

1. The equations and assumptions expressing the relations between the component parameters.

Example: We assume that the the energy stored in the inductor is negligible, except from the energy stored in the airgap. We assume that the cooling factor α_{cool} is equal for all component alternatives.

2. The multi step character of the decision structure and the sequence of decision steps.

Example: The first decision steps distinguish the set of possible alternatives using the limiting boundaries. The most efficient sequence of the steps is found to be: 1) core selection, 2) calculation of the range of number of turns for each core, 3) wire selection for each core 4) determination of the inappropriate numbers of turns.

3. Heuristic information and the rules of thumb.

Example: The experience of the expert can be used to determine more preferable combinations of component parts or certain parameters that are needed by the decision system, such as the support and the kernel of the membership functions. For instance, round wires are easier to wind which simplifies the assembly of the magnetic component. Similarly, a very large airgap is not desirable since the fringing of the magnetic field causes eddy current losses in the copper.

Not all expert knowledge is useful for implementation in the DSS. Some rules-of-thumb, like for example the information that the temperature rise should not be too low, or the rule that the core window should be completely filled with wire, are rules that simplify only the human design method. However, for computer implementation, these simplifications reduce the set of possible alternatives unjustly.

DSS structure

The DSS has to be structured in such a way that the calculation effort should be reasonably small, while no alternatives are rejected unjustly. Based on the knowledge of the designer, a decision structure such as shown in Figure 3 is used.

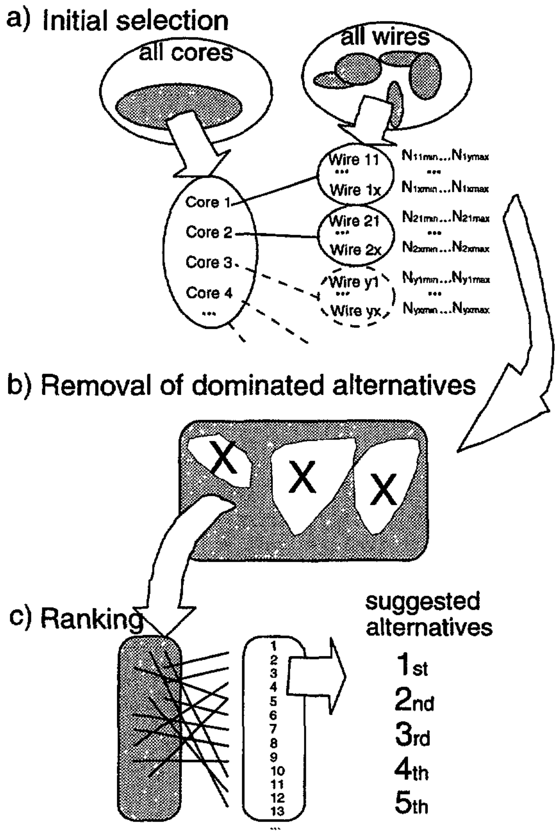

Figure 3 Decision structure of an example DSS for ac-inductor design.

The decisions are taken in a hierarchical manner. At each level of the hierarchy, a number of alternatives is rejected, which are not within the set of best alternatives. In this way, the computational effort is reduced considerably. The initial set of alternatives is the set of all possible combinations of cores and wires. Steps a. and b. distinguish the (groups of) suitable alternatives. Step c. is a ranking step.

a. Initial selection

The initial decision steps reject the totally inappropriate combinations using the limiting boundaries of some requirements. The outcome is the complete set of possible alternatives satisfying the constraints to some degree.

b. removal of dominated alternatives

The second decision step rejects the alternatives that are dominated by any other alternative. This means that the dominated alternatives, i.e. the alternatives that have a mass, volume, cost and power loss higher than some other alternative, are not considered further. Hence, the irrelevant alternatives are removed.

c. final ranking

The final step ranks the remaining alternatives depending on how much they satisfy the requirements. This ranking is determined by a decision function that combines the membership functions of the requirements, taking into account their weights. For the decision function, often called a goal function, various types of fuzzy mathematical operators can be used. In general, the goal function should reflect the aims and the preferences of the decision maker. Fuzzy sets theory provides a variety of decision operators for modelling conjunctive, disjunctive, averaging, compensatory and other types of decision behaviour. Examples of these functions can be found in [2] [7] [8] [9] [10] [13] and [15]. At this moment a parametric generalized goal function is implemented for fuzzy decision making with unequally weighted criteria [3].

Between the three decision steps, an interactive method of preference assignment can be implemented to enable the component designer to have direct influence on the decisions. After the final ranking step, the designer's attention can be focused on a few satisfactory remaining design alternatives. The determination of the best alternative will be a trade-off between the suggestions of the decision support system and the personal preferences of the designer.

3 Conclusions

In this paper the design of magnetic components has been considered. In order to manage the large number of component alternatives and the large number of requirements, a human designer uses several decision steps to come to the final design. Because of the drawbacks of the human design method, a Decision Support System is proposed that assists the designer of magnetic components with the selection and ranking of the component alternatives.

The aim of the DSS is to select a few possible, good, alternative designs by performing preparatory decisions, selections and rankings. The designer's attention can now be focused on a few satisfactory design alternatives, which can be studied further. In this way the quantitative abilities of computers and qualitative abilities of humans are used efficiently.

The proposed DSS for the design of magnetic components is now being implemented. The system uses expert knowledge and heuristic information in order to improve significantly the speed and the results of the design procedure. The structure of the proposed DSS is plain and transparent. All tedious operations, comparisons and classifications are performed by the system. An interactive method of preference and weight assignment will enable the component designer to have direct influence on the decisions of the system.

References

[1] Dhawan, R.K., P. Davis, R. Naik, Fuzzy Logic Select Core Geometry for HF Power Transformers, *PowerConversion & Intelligent Motion*, Vol.21,No.4, 1995, pp.44-49, Vol.21, No.5, 1995, pp.34-42

[2] Dubois, D., H. Prade, *Possibility Theory: an approach to Computerized Processing of Uncertainty*. Plenum Press, New York, 1988

[3] Kaymak, U., H.R. van Nauta Lemke, A parametric generalized goal function for fuzzy decision making with unequally weighted objectives, *Proceedings of the Second IEEE International Conference on Fuzzy Systems*, Volume 2, pp.1156-1160

[4] Kusko, A., T. Wroblewski, *Computer-Aided Design of Magnetic Circuits*, The MIT Press, 1969

[5] McLyman, Colonel Wm.T., *Transformer and Inductor Design Handbook*, Marcel Dekker Inc., New York, 1978

[6] McLyman, Colonel Wm.T., *Magnetic Core Selection for Transformers and Inductors*, Marcel Dekker Inc., New York, 1982

[7] Mesiar, R., Compensatory Operators based on Triangular Norms and Conorms, *Proceedings of the third European Congress on Intelligent Techniques and Soft Computing*, pp.131-135, 1995

[8] Mizumoto, M., Pictorial representations of fuzzy connectives, part i: cases of t-norms, t-conorms and averaging operators, *Fuzzy Sets and Systems*, 31:pp. 217-242, 1989

[9] Mizumoto, M., Pictorial representations of fuzzy connectives, part ii: cases of compensatory operators and self-dual operators. *Fuzzy Sets and Systems, Fuzzy Sets and Systems*, 32:pp. 45-79, 1989

[10] Nauta Lemke, van, H.R., J.G. Dijkman, H. van Haeringen, M. Pleeging, A characteristic optimism factor in fuzzy decision-making, *Proc. IFAC Symp on Fuzzy Information, Knowledge Representation and Decision Analysis*, pp. 283-288, Marseille, France, 1983

[11] PHILIPS data handbook, *Ferroxcube potcores, square cores & cross cores*, Components and materials Book C4, PHILIPS Electronic Components and Materials 1986

[12] SIEMENS Matsuhita Components handbook, *Ferrite und Zubehör*, 1994

[13] Yager, R.R., Ordered weighted averaging aggregation operators in multi-criteria decision making, *IEEE Trans. on Systems, man and Cybernetics*, 18:pp.183-190, 1988

[14] Zadeh, L., Fuzzy sets, *Information and control*, 8:pp.338-353, 1965

[15] Zimmerman, H.J., P. Zysno, Latent connectives in human decision making, *Fuzzy Sets and Systems*, 4:pp.37-51, 1980