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## DESIGN OF STATIC CONVERTERS: AN EXPERT SYSTEM APPROACH

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**Abstract.** In order to design the structure of static converters a new approach is presented. Required specifications are described by the waveforms of input and output voltages and currents, which are expected to be generated by the converter. These data are analysed by use of design rules and methods; it permits to identify the stresses on the commutation cells, which themselves lead to the synthesis of the switches: identification of the type (diode, thyristor, transistor or dual thyristor), description of electrical constraints and firing orders. Rules and methods are implemented on a micro computer by use of an 'expert system generator'; the actual system establishes the feasibility in the domain of the direct converters and enables the use of these tools in the education domain: deductions and used rules can be exhibited, making this software a powerful tool to help students understanding the design methods.

**Keywords.** Static converters, design, knowledge-based systems.

### I- INTRODUCTION

The present study is a part of a project for the realisation of a system for the computer aided design of static converters. In order to fulfil the requirements of the specifications, the aim is to determine the topological structure of the power converter, to define its command and control law and to specify the dimensioning of its components. As the 'know-how' of the designers is generally expressed in term of rules, the system is shaped by use of a "knowledge based systems".

We present here the results of this approach in the domain of direct converters and point out the interest of using these tools in the education domain.

### II- THE KNOWLEDGE MODEL

In this study, we consider only the direct converters. Basically, these circuits are only composed of switches, devoted to the control of the power flow between a generator and a receiver; this power flow may be reversible. The use of switches to realise every connections to allow any power exchange between the input and the output leads to a full bridge structure, composed of four switches. These switches are coupled by pairs inside commutation cells [3] [1] [5]. The basic structure of these converters is indicated in Fig. 1.

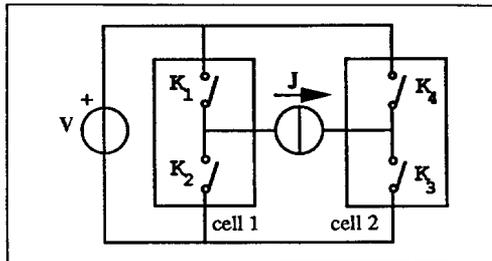


Figure 1: direct converters.

This study is carried out under the following assumptions: voltage and current sources are supposed perfect; switches are ideal in that they commutate instantaneously and are considered as short circuits in ON state and as open circuits in OFF state.

To fulfil the fundamental laws of interconnection of sources (a current source cannot be opened and a voltage source cannot be short circuited), any combination (corresponding to the states of the switches) is not allowed. These constraints are defined by the operation of the commutation cells. The structure defines an elementary converter, which associate two switches and realises the interconnection between a voltage source and a current source (Fig. 2). As will be detailed in II-2-3- the operation of the switches in a commutation cell have to be complementary [3].

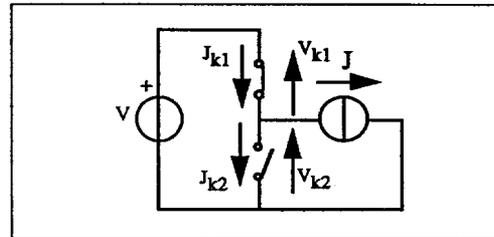


Figure 2: commutation cell

In a commutation cell, the Kirschoff laws are given by the following equations:

$$V = V_{k1} + V_{k2} \quad (1)$$

$$J = J_{k1} - J_{k2} \quad (2)$$

The direct static converters, which associate two commutation cells, can be considered as an interconnection matrix between a current source and a voltage source. The specifications are described by current and voltage waveforms of input and output sources, which are expected to be generated by the converter. From that point of view, the problem is to determine the characteristics of the components of the matrix.

### III- DEFINITION OF THE KNOWLEDGE BASE

To solve this problem, a knowledge base has been deduced from the analysis of the knowledge model; switches are first considered as independent components; in a second approach, their behaviour is analyzed, taking into account the constraints defined by the commutation cell in which they take place. We consider the commutation cell in two different operating modes: in steady state, the analysis of the reversibilities of the source leads to the static

characteristics of the switches; the analysis of the transient state leads to the description of their dynamic characteristics.

### III-1- Steady state analysis

Due to the assumptions concerning the switches, these components have to be considered in continuous rating in only one of the following states: ON state or OFF state. Simple rules are able to define the conditions related to these states and to associate them to the currents and the voltages of the switches:

- rule (state-1):    Let    K a switch  
                      If     state of K is OFF  
                      Then  current in K = 0
- rule (state-2):    Let    K a switch  
                      If     state of K is ON  
                      Then  voltage across K = 0
- rule (state-3):    Let    K a switch  
                      If     voltage across K  $\neq$  0  
                      Then  state of K is OFF
- rule (state-4):    Let    K a switch  
                      If     current in K  $\neq$  0  
                      Then  state of K is ON

Let a switch considered as a dipole, according to the reference directions described in Fig. 3. In the  $(V_k, J_k)$  plane, the operating domain of a switch is defined by two branches: one is placed on the  $(V_k = 0)$  axis and corresponds to the ON state; the other one is placed on the  $(J_k = 0)$  axis and is associated with the OFF state; each one of these branches is either uni-directional or bidirectional.

The steady state analysis enables to describe the ON state current and the OFF state voltage, according to the uni-directional or bidirectional property of the voltage across the voltage source and of the current in the current source, which are connected to the commutation cell. According to the reference conventions of Fig. 2, it can be pointed out from the relations (1) and (2) that:

- if  $K_1$  is ON, then  $K_1$  is OFF and :  $J_{k1} = J$  and  $V_{k2} = V$ ,
- if  $K_2$  is ON, then  $K_2$  is OFF and :  $J_{k2} = -J$  and  $V_{k1} = V$ .

In term of rules these conditions are expressed as follows:

- rule (reversibility-1):       the voltage reversibilities of the switches are the same as the voltage reversibility of the voltage source.
- rule (reversibility-2):       the current reversibilities of the switches are the same as the current reversibility of the current source.

As a conclusion to the steady state analysis, it can be mentioned that the identification of the static characteristics of the switches can be achieved by the study of the reversibilities of the sources. These characteristics are made of two, three or four half axes of the the coordinate axes in the  $(V_k, J_k)$  plane.

### III-2- Transient state analysis

This chapter deals with the study of the commutations; it analyzes the mechanism related to state change of a switch i.e. the displacement of its operating point in the  $(V_k, J_k)$  plane from a given branch associated with a given axis to another associated with the perpendicular axis. The trajectory of the operating point describes the dynamical characteristic of the considered switch.

Neglecting the second order phenomena such as reverse currents, as the switch is a dissipative component, the trajectory of the operating point must stay in the quadrants of the  $(V_k, J_k)$  plane where:

$$V_k J_k \geq 0$$

Fig. 3 shows the voltage and current reference conventions and the forbidden quadrants:

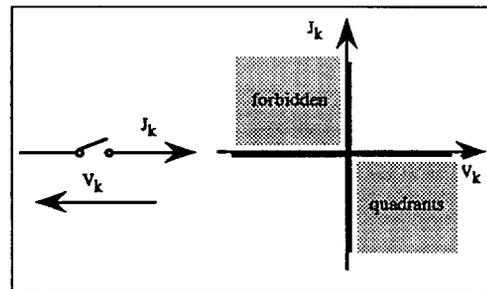


Figure 3: reference conventions and forbidden quadrants

#### III-2-1- Type of the commutations

By comparison of the current and the voltage related to a given switch before and after its state change we can define if the associated commutation is a turn-on commutation or a turn-off commutation. The following rules, gathered in pairs which present a redundancy with respect to their right side, but which are different with respect to their left side, permit the definition of the type of the commutation:

- rule (turn-off-1):    Let    K a switch  
                          If      $V_k$  before commutation = 0  
                          And     $V_k$  after commutation  $\neq$  0  
                          Then  the commutation is a turn-off commutation
- rule (turn-off-2):    Let    K a switch  
                          If      $I_k$  before commutation  $\neq$  0  
                          And     $I_k$  after commutation = 0  
                          then  the commutation is a turn-off commutation
- rule (turn-on-1):    Let    K a switch  
                          If      $V_k$  before the commutation  $\neq$  0  
                          And     $V_k$  after the commutation = 0  
                          Then  the commutation is a turn-on commutation
- rule (turn-on-2):    Let    K a switch  
                          If      $I_k$  before commutation = 0  
                          And     $I_k$  after the commutation  $\neq$  0  
                          Then  the commutation is a turn-off commutation

### III-2-2- Nature of the commutations

In order to achieve the characterization of the commutations the next step is to analyse the change from a given axis of the  $(V_k, J_k)$  plane to the other. In this aim two cases are considered:

- the trajectory of the operating point follows the static characteristic and the commutation, which happens with minimal losses (null with respect to our assumptions) is spontaneous. It is the only possible solution when the operating point passes from a given quadrant to the other one.

- the trajectory of the operating point does not follow the axis, and stays in the same quadrant; the commutation, which is dissipative, must be controlled. This characterization of the commutation is translated in term of rules as follows:

- rule (*commut-spontaneous*):  
 Let K a switch  
 If during the commutation the operating point of K changes of quadrant  
 Then the commutation of K is spontaneous

- rule (*commut-controlled*):  
 Let K a switch  
 If during the commutation the operating point of K stays in the same quadrant  
 Then the commutation of K is controlled

Fig. 4 shows several commutation types: controlled turn-off and turn-on (4.1 and 4.2); spontaneous turn-off and turn-on (4.3 and 4.4)

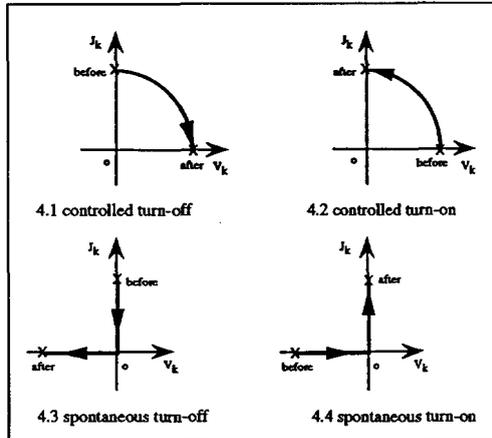


Figure 4 : several commutation cases

### III-2-3- Commutations inside a cell

The former rules consider the commutation from a local point of view. They do not take into account the fact that the switches which they are related to operate inside a commutation cell.

Taking into account these constraints (expressed in terms of voltage and current laws in equations (1) and (2)) leads to the conclusion that the switches of a commutation cell cannot turn on or turn off independently. The two switches of a cell must have complementary commutations; following rules are expressing this property:

- rule (*complementary-type-1*):  
 Let CC a commutation cell  
 If a switch of CC turns off  
 Then the other switch of CC turns on

- rule (*complementary-type-2*):  
 Let CC a commutation cell  
 If a switch of CC turns on  
 Then the other switch of CC turns off

The same reasoning concerning the nature (spontaneous or controlled) of the commutations of the switches in a cell also leads to a complementarity property, as expressed in the following rule:

- rule (*complementary-nature*):  
 Let CC a commutation cell  
 If a switch of CC has a controlled commutation  
 Then the other switch of CC has a spontaneous commutation

### III-3- Electric stresses

Kirschhoff laws of the commutation cell can be expressed with computation rules. Combined with the rules which associate the state of a switch with the value of its current or with the value of its voltage (rule *state-1*, rule *state-2*, rule *state-3*, rule *state-4*), they permit to determine the electric stresses related to any switch of a cell (references used in these rules are presented in Fig. 2):

- rule (*KVL-1*):  
 Let CC a commutation cell, K1 and K2 its switches and V its voltage source:  
 If the value of  $V_{k1}$  is known  
 Then  $V_{k2} = V - V_{k1}$

- rule (*KVL-2*):  
 Let CC a commutation cell, K1 and K2 its switches and V its voltage source  
 If the value of  $V_{k2}$  is known  
 Then  $V_{k1} = V - V_{k2}$

- rule (*KCL-1*):  
 Let CC a commutation cell, K1 and K2 its switches and J its current source  
 If the value of  $J_{k1}$  is known  
 Then  $J_{k2} = J_{k1} - J$

- rule (*KCL-2*):  
 Let CC a commutation cell, K1 and K2 its switches and J its current source  
 If the value of  $J_{k2}$  is known  
 Then  $J_{k1} = J_{k2} + J$

### IV- MODEL FOR THE REASONING OF THE EXPERT

The previously described set of rules may be used by a human expert to realise the design of a static converter. We propose here a model for the design process and we point out the most important steps. Each step of the process is associated with an intermediate result in the design and a subset of rules which enables to reach it. Fig. 5 shows this reasoning model.

To determine a static converter which is able to fulfil the specifications, a human designer proceeds several tasks:

\* First, he analyses the specifications and deduces the structure of the converter, the number of switches, and their place in the structure. In

the present case, this choice is yet implicitly made, since only direct converters are considered.

\* A second step is the analysis of the reversibilities of the sources; the result of this analysis enables the determination of the static characteristics of the switches. The set of rules which is used in this step consists of:

- rule reversibility-1
- rule reversibility-2
- rule state-1
- rule state-2
- rule state-3
- rule state-4

\* The aim of the next step is to determine the dynamic characteristics of the switches; two methods can be considered: in the first one, commutation rules are used inside the two commutation cells, after selection of the operating sequences. Following rules are used:

- rule complementary-type-1
- rule complementary-type-2
- rule complementary-nature

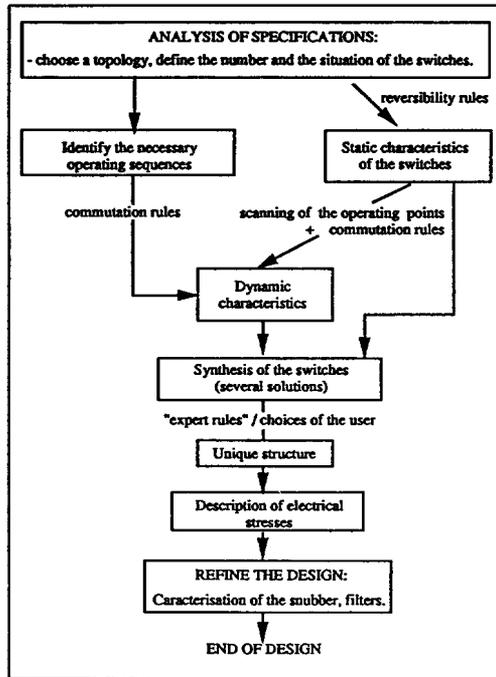


Figure 5: model of the design process

A second method is to scan the displacement of the operating point of each switch on its static characteristic at any time of the studied time interval. The previous selection of the operating sequences is not necessary: they are "discovered" during scanning. The rules which are fired by that method are the previous commutation rules which ensure the complementary operation of the switches and the rules for the identification of the type of the commutations:

- rule turn-off-1
- rule turn-off-2
- rule turn-on-1
- rule turn-on-2

This design process, which uses the identification of the static characteristics and the determination of switching operation does not lead to a unique solution. Adding expert rules (devoted to layout, for example) enables a choice in the set of the possible solutions. This choice being made, the switches being completely identified, the design is continued by the following steps:

\* synthesis of the switches;

\* identification of the waveforms (current and voltage) related to each switch; the subset of rules which is used to achieve this identification comprises the rules for the analysis of switch states and the production rules:

- rule state-1
- rule state-2
- rule state-3
- rule state-4
- rule KVL-1
- rule KVL-2
- rule KCL-1
- rule KCL-2

\* definition of firing orders waveforms related to any switch.

At this time, the design can be refined by adding and characterising the environment of the converter and of the switches: filters, snubbers ...

## V- IMPLEMENTATION

The process which has been described uses precise and well defined rules and lies on a deductive reasoning. This kind of knowledge could be implemented on a computer by mean of a classical program, using language such as FORTRAN or C. Nevertheless adding rules to translate the human know-how, about layout for example, would become difficult. In the aim of integrating into the final system knowledges devoted to different contexts the use of "knowledge based systems" has been considered. In the educational domain these systems which offer interesting capabilities of explanation and which are able to exhibit their reasoning are very interesting: this property must confirm the idea that designing a converter is not an intuitive or exhaustive process (identification of yet studied cases) but is really the result of a logical reasoning.

A module for the design of the direct static converters has been implemented by mean of the KAPPA-PC software [1] [2]. The knowledge model of the converter as been described as a set of objects: sources (voltage and current), commutation cells including two switches [6] [7]. Fig. 6 shows the slots used to define the objects of the switch class.

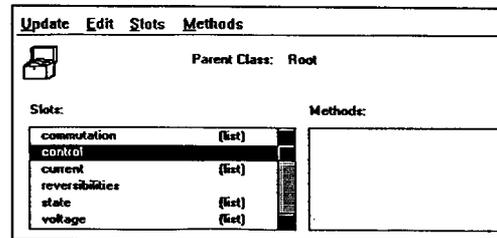


Figure 6: slots of the objects of the switch class.

The rules are implemented as they are described in chap. III: they handle the slots which describe the objects. Fig.7 shows the computation rule *KVL-1* which is devoted to the determination of voltage across switches:

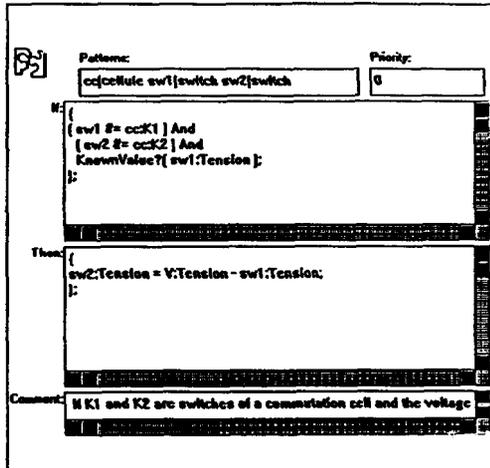
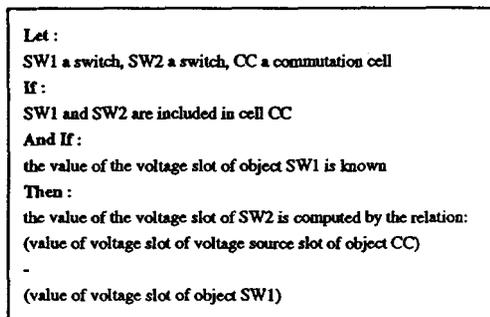


Figure 7: rule *KVL-1* as it has been implemented in KAPPA-PC

In natural language, this rule should be read as follows:



The specifications are described by the user: he enters the waveforms which are expected to be generated at input and output of the converter. For each one of the four switches, the system gives the following results: voltage and current waveforms, state change and firing orders at any time in the studied interval. These data are presented through the graphical user interface as a set of curves.

The system is shaped to reproduce as near as possible the model of the design process of the human expert which has been presented in chap. IV: the design is splitted into sub goals which are treated sequentially.

At the reasoning level, the inference mode which is selected is the forward chaining: the system considers the known facts and fires the rules which assumptions are true, until it reaches the current goal (usually the determination of the value of a given slot). The operation of the system is based on a loop which is made of two main steps: a decision step and an action step. The decision step includes the selection of the applicable rules (if their premise are true) and the choice of one rule among the previous set. At the action step, this rule is fired and a new state of the inference process is created (the value of a given slot is modified).

The inference process is traced in a resolution tree: any change of the value of any slot of any object is stored in a node; the branch which joins two nodes squares to the rule which caused the change. The analysis of this tree enables the explanation in natural language and the exhibition of the reasoning by mean of the comments associated with each rule.

## VI- EXAMPLE - APPLICATIONS

The following figures present the system through its graphical user interface. Fig. 8 corresponds to the specifications (voltage and current waveforms at input and output); in this example, the input of the converter is supposed to be a voltage source and the output a current source.

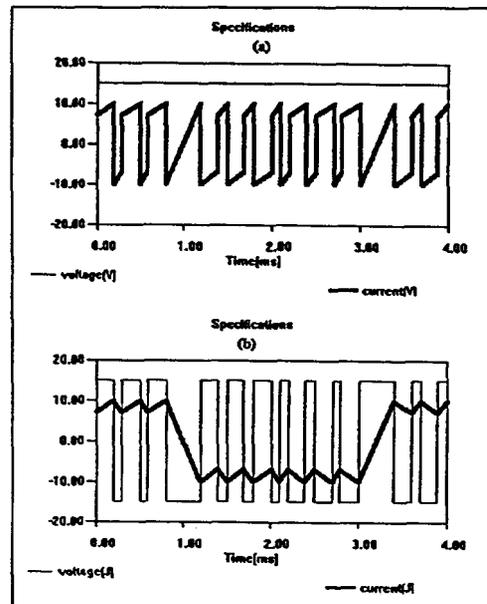


Figure 8: specifications (voltage(I)): deduced from voltage(V), current(V), current(I).

A structure which enables a full voltage and current reversibility is able to fulfil the requirements of the specifications.  $K_1$ ,  $K_2$ ,  $K_3$  et  $K_4$  are respectively identified with a transistor and an anti-parallel diode. Their characteristic is presented in Fig. 9.

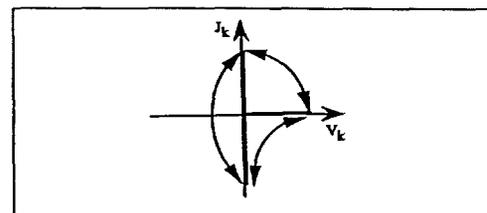


Figure 9: static characteristics of switches  $K_1 / K_2 / K_3 / K_4$ .

Fig. 10 shows the results of the analysis of electrical stresses and the firing orders related to switch  $K_1$ .

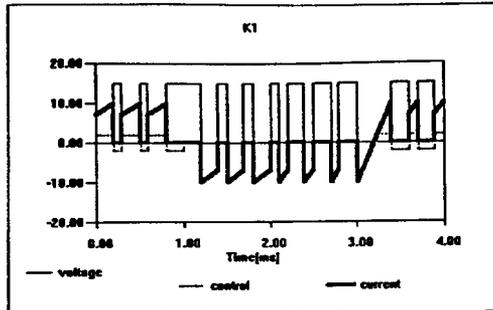


Figure 10: electrical stresses and firing order of the transistor-diode  $K_1$

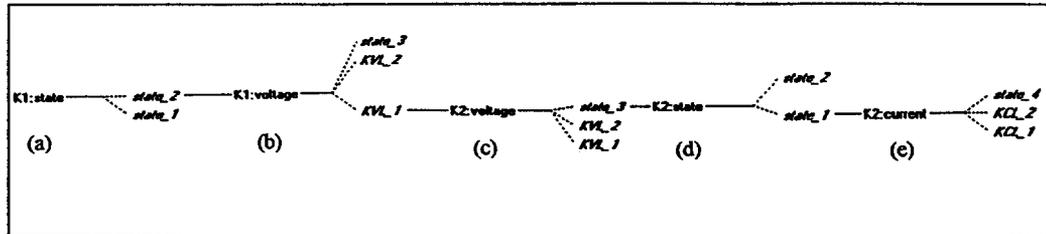


Figure 11: inference tree

Switch  $K_1$  has a 3 branches static characteristic because of:  
**rule (charact-3-branches)**  
 which states:  
**If** : the switch is bi-directional in current  
**And If** : the switch is uni-directional in voltage  
**Then** : the static characteristic has 3 branches

Figure 12.a: static characteristic of switch  $K_1$

Switch  $K_1$  is a transistor with a diode placed in anti-parallel because of:  
**rule (function-4)**  
 which states:  
**If** : the static characteristic of a switch has 3 branches  
**And If** : there is a controlled turn-on  
**And If** : there is a controlled turn-off  
**And If** : there is a spontaneous turn-on  
**And If** : there is a spontaneous turn-off  
**Then** : the switch is a transistor with a diode placed in anti-parallel

Figure 12.b: synthesis of  $K_1$

## VII- CONCLUSION

A first application of knowledge based systems to the design in power electronic is presented. Its aim is to help in the design of direct static converters.

This module tries to reproduce a model of the process of a human designer. Its application domains are both research and education. As a design tool, it is able to apply automatically and without a priori a set

About the reasoning of the system, Fig. 11 shows the part of the inference tree which corresponds at a given time to the determination of the states and of the electrical quantities of two switches associated in a cell: in node (a), the state of  $K_1$  is known (the value of this slot is defined); after the rule *state-2* has been fired, its voltage is determined (node (b)); the rule *KVL-1* gives the voltage across  $K_2$  (associated with  $K_1$  in a cell) (node (c)); firing the rule *state-3* leads to the definition of the state of  $K_2$  (node (d)); the rule *state-1* gives the current in  $K_2$  (node (e)).

Any step of the reasoning (associated with a node in the tree) corresponds to the firing of a rule; an explanation module is able to determine which rule has been used to obtain the value of a given slot and to present (in natural language) the comments of the rule. Figs. 12a and 12b show the inferences which led to the synthesis of switch  $K_1$ .

of general rules in any case where a direct converter is able to fulfil the specifications.

In the educational domain, as it manipulates elementary rules and proposes a rigorous approach for the synthesis of a converter it encourages the assimilation of an improved method of design.

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