Using Behavior Deviations and an Interval-Based Calculus for Modeling Electronic Circuits

Lothar Hotz, Heiko Milde, Ralf Möller, Bernd Neumann
Labor für Künstliche Intelligenz, Universität Hamburg

Abstract

This paper introduces an approach for modeling and simulating a technical device for diagnostic purposes. A resistive network is used as a component-oriented device model which is automatically transformed into a simulation model that explicitly represents the global topological structure of the circuit. The simulation model is based on qualitative descriptions of behavior deviations and supports an interval-based qualitative calculus for reasoning about deviations.

1 Introduction

Current approaches for developing model-based diagnosis systems differ significantly in their strategy for deriving a simulation model from an initially given component-oriented system model. Many approaches use the initial component model directly as the basis for a simulation system without explicitly representing the global topological structure (see e.g. [Struss and Dressler, 1989]). In order to model causal influence chains for discriminating broken elements, simulation methods often use local propagation constraint solving algorithms that operate directly on the components defined in the initially given schematic diagram. However, with this technique not all circuit topologies can be handled adequately because local propagation is suitable only for acyclic causal influence chains. In many cases, the structure of the whole circuit has to be considered as well. Therefore, another class of approaches transforms the initial model into another model which explicitly represents information about the global topological structure of circuit components (e.g. [Mauss and Neumann, 1996]). The introduction of connectivity variables for ports in [Struss et al., 1995] can also be considered as a kind of model transformation.

Considering a real-world technical diagnosis problem, this paper introduces an extended approach of the second class for deriving a behavior model based on relative descriptions of component behavior. A device is simulated using qualitative descriptions of behavior deviations. With the reasoning method presented in this paper, qualitative reasoning problems about cascading defects can be solved that are either not handled in previous approaches or are handled in a more complex way (e.g. [Tatar, 1996]).

The behavior model of a specific system is used to compute a fault relation which explicitly represents the relationship between faults of single components and corresponding values of voltages and currents at predefined metering points. Model-based reasoning is used in a preprocessing phase to derive a runtime system which defines a predefined serialization of required queries and measurements. In order to find measurements that definitely identify faults and to avoid unneccessary measurements at runtime, no spurious ambiguities in behavior descriptions computed at development-time should be introduced.

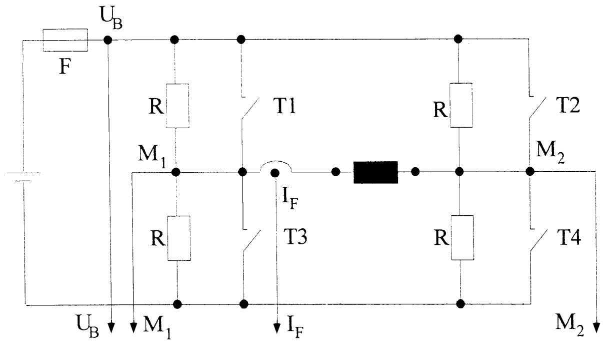

Figure 1. Field regulator (resistors, controlled switches T1 to T4) with field coil (black rectangle), a fuse and predefined metering points for voltages (U_B, M_1, M_2) and currents (I_F). In this figure, the electronic circuit for controlling the switches has been omitted.

1.1 An application scenario

A subcomponent of an electricity-powered motor is the field regulator. We consider a specific field regulator that is used in a certain fork-lift. A schematic diagram of the circuit is presented in Figure 1. The components shown in the figure are already abstractions of the physical components used in the circuit. For instance, the control switches T1 to T4 are implemented with transistors and diodes. We assume that a graphical model editor is used for defining the circuit structure as required for diagnostic purposes. For diagnosis, several operating states have to be examined. For instance, T2 and T3 might be closed, T1 and T4 might be opened and vice versa. In the first operating state the current through the field coil flows from right to left (see the I_F metering point), in the second it flows in the other direction. We assume that operating states are stable states.

We assume that each of the components is taken from a library. The component library defines a set of model fragments (in the spirit of [Falkenhainer et al., 1994]) to be applicable under certain circumstances. In order to compute the fault relation for all single faults, we iterate over the list of circuit components and, for each component, we assume that a fault model fragment holds. As an example we consider a stuck-at-closed fault model for the switch T4. This fault model asserts that T4 has no longer its “normal”, infinite resistance but a “lower” resistance, “too low” but larger than zero. Note that qualitative descriptions like “normal” or “too low” are defined in relation to the operating state of the circuit. In the application domain, qualitative value descriptions

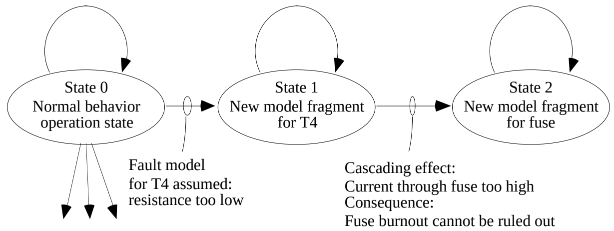

Figure 2. States of the field regulator circuit: normal operation (State 0), short of T4 (State 1) and blow of the fuse (State 2).

like "normal" correspond to intervals in the quantitative domains of the variables. The widths of the intervals are largely unknown, i.e. only qualitative knowledge is applicable because the component models are already coarse-grained abstractions from the concrete physical components.

Inserting a fault model for a single component has a cascading effect on variables of other components. As a result, the set of model fragments valid at a certain time-point might change. If T4 becomes shorted, its resistance will be "too low" and, as a consequence, the fuse might blow because the current through the fuse might be "too high." In our approach, the fuse blow is represented as a discrete state change (see Figure 2).

State 0 represents the normal behavior with no failure. In State 1 we assume that the switch T4 becomes shorted (cf. a stuck-at-closed fault model). State 2 describes the subsequent model fragments which are induced by the current through the fuse being "too high." Note that "too high" means the fuse *might* blow. If this does not happen, the system will remain in State 1 (see the loop edge in Figure 2). For all fault models of each component additional successor states for State 0 are generated. The discrete model of changes over time is comparable to the DME approach presented in [Iwasaki and Low, 1991]. It is important to note that the blow model fragment for the fuse is no fault model. However, there might be a fault model which represents blow behavior due to ageing effects. Although this model will be inserted as one of the fault models for components, in this paper, we only consider the normal behavior blow model which induces another system state (represented as State 2 in Figure 2).

Motivated by the necessary abstractions in the application domain, we need a *qualitative* calculus for *deriving state changes in system behavior* caused by *behavior deviations*. In our application domain, we only need components with *piecewise linear and monotonic* behavior

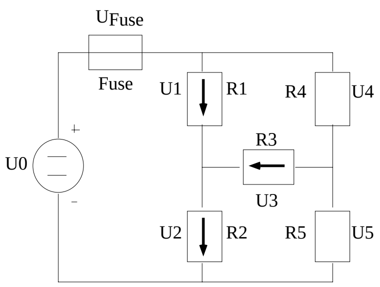

Figure 3. A bridge circuit being used as an abstraction for the field regulator circuit in Figure 1.

descriptions. We assume that for each linear part of a component's characteristic, a different model fragment holds (one model fragment per state). Therefore, all components are described by model fragments that have a resistor-like characteristic. Considering the topology of the field regulator circuit, it becomes clear that the calculus must support reasoning about deviations in *bridge circuits* (see Figure 1), a circuit topology that is not handled well in most qualitative approaches known today. Bridge circuits can also often be found when possible short circuits are explicitly modeled.

1.2 Reasoning about deviations in bridge circuits

The problem with bridge circuits is that the direction of the current through the bridge resistor cannot be derived based on qualitative confluence values, i.e. it depends on the concrete quantitative values of the components' parameters. However, in this paper it will be shown that reasoning about *deviations* in bridge circuits can be modeled with a qualitative theory. The paper also shows that reasoning about deviations is suitable for building the state-space graph for a circuit (see Figure 2). In general, the problem of state space derivation is to rule out impossible behavior deviations. For instance, in our fuse example, it might not be wrong to assume that the fuse might blow. However, if it can be proven at model development time that – according to the model – cascading effects like fuse blows cannot happen at runtime, unnecessary measurements in the final diagnosis system can be avoided.

The qualitative calculus introduced in this paper supports the derivation of effects of model fragment changes for bridge circuits. It will be shown that in our diagnosis application a behavioral model can be derived by propagating qualitative values 0, "too low," "normal," "too high" and ∞ in a transformed model. The combination of these values is defined in accordance with a formal quantitative semantics. Even bridge circuit topologies can be handled adequately.

2 SDSP Model Transformation

Our approach for explicitly representing the topological structure of a circuit uses a series-parallel grouping circuit transformation (so-called sp-analysis, see also [Lee and Ormsby, 1992] and [Mauss and Neumann, 1996]). In order to make this transformation applicable, the well-known star-delta transformation is applied in a preprocessing step (hence the name SDSP model transformation). In Figure 3 the field regulator from Figure 1 has been simplified for presentation purposes. The parallel configuration of resistor and controlled switch is represented as a resistor aggregate. For sp-analysis the star represented by the resistors R1, R2 and R3 is transformed into a delta (see Figure 4). We assume that the current through the bridge resistor is arbitrarily defined to be directed toward the center of the star and the currents through the other resistors are directed as indicated in Figure 3. The following equations describe the correspondences between the original and the delta resistors and their respective currents and voltages.

$$R12 = R1 + R2 + \frac{R1 \cdot R2}{R3} \qquad R1 = \frac{R12 \cdot R13}{R12 + R13 + R32}$$

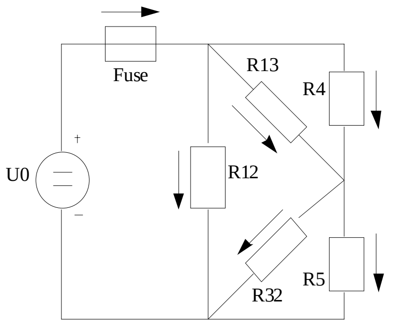

Figure 4. The circuit from Figure 3 after a star-delta transformation.

$$R32 = R2 + R3 + \frac{R2 \cdot R3}{R1} \qquad R2 = \frac{R12 \cdot R32}{R12 + R13 + R32}$$

$$R13 = R3 + R1 + \frac{R3 \cdot R1}{R2} \qquad R3 = \frac{R13 \cdot R32}{R12 + R13 + R32}$$

$$I1 = I12 + I13 \qquad U12 = U1 + U2$$

$$I2 = I12 + I32 \qquad U13 = U1 - U3$$

$$I3 = I32 - I13 \qquad U32 = U2 + U3$$

The equation for I3 indicates that, in a qualitative calculus based on confluences, the backward transformation might be ambiguous (e.g. when two positive currents are subtracted).

For the calculus presented below, the direction of current flow through each component has to be fixed such that all currents and voltages are positive. Assuming the distribution voltage is applied to S10 (the topmost node of the Sp-tree, see Figure 5), the corresponding direction can be propagated downward. By this process the direction of current flow and voltage drop is defined for each resistor in the network (see Figure 4: current flow from "hill" to "valley"). If the directions do not correspond to the directions assumed for the star-delta transformation, the corresponding preceding signs in the equations above have to changed accordingly.

The sp-tree of a network (see Figure 5) can be used to compute the effects of behavior deviations when fault models are inserted for certain resistors. This will be explained in the next section. It is shown that physical

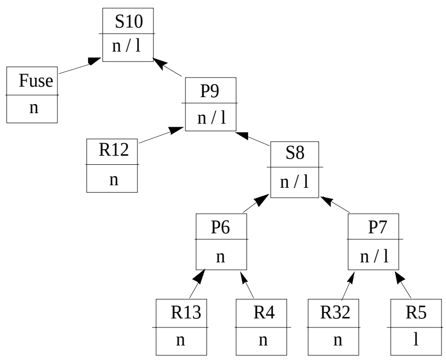

Figure 5. Sp-tree describing the topological structure of the circuit in Figure 4 in terms of serial (S_i) and parallel (P_i) resistor substitutions. See the text for the meaning of the entries in the lower part of the boxes.

knowledge can be represented in such a way that changes in the currents and voltages of other resistors can be computed based on local propagation techniques for qualitative descriptions.

3 A qualitative calculus for reasoning about deviations in resistive networks

In the introduction the use of qualitative domains for component variables has been motivated. The components required for diagnosis are already abstractions from the real physical objects used to implement a component. Thus, we assume that a value "normal" in the qualitative domain denotes an interval in the quantitative domain. The same holds for "too low" and "too high". For presentation purposes we use the notation V_l, V_n and V_h as an abbreviation for "Variable V has value l, n or h" (see the upper part of Figure 6). The two specific qualitative values 0 and ∞ denote the respective quantitative values.

In order to compute the compensation resistance for series groupings (see Figure 5), we must define a qualitative version of the addition operation in such a way that the quantitative semantics is supported. For monotonic functions the quantitative interval calculus reduces interval arithmetic to end-point arithmetic (e.g. $[A_{left}, A_{right}] + [B_{left}, B_{right}] = [A_{left} + B_{left}, A_{right} + B_{right}]$).

The value "normal" characterizes the faultless behavior, i.e. for a series grouping of resistors the compensation resistor must be "normal" when both resistors are "normal". Therefore, in our calculus we define that "normal" + "normal" = "normal" but with a longer "normal" interval for the result. What about adding a value that is "too low" and a "normal" value (see the lower part of Figure 6: $[C_{left}, C_{right}] := A_l + B_n$)? In this case, the result is ambiguous: C will be either "normal" or "too low." This can be shown when the resulting interval boundaries are considered (see Figure 6, the "normal" interval is indicated with subscripts "min" and "max"). C_{left} will be less or equal than C_{min} because $C_{left} = 0 + B_{min}$ and $C_{min} = A_{min} + B_{min}$ with $A_{min} \geq 0$. C_{right} will be between C_{min} and C_{max} because $C_{right} = A_{min} + B_{max} \leq A_{max} + B_{max}$. Thus "normal" + "too low" = ("normal" ∨ "too low"). Similar derivations can be given for each combination of the qualitative values {0, l, n, h, ∞}. In each derivation, a reduction to the quantitative landmark values $\{0, C_{min}, C_{max}, \infty\}$ is possible. Table 1 lists the result for the qualitative addition of these derivation descriptions. A parallel grouping of two resistors can also be replaced by a compensation resistor: P = (R1 · R2) / (R1 + R2). However, as

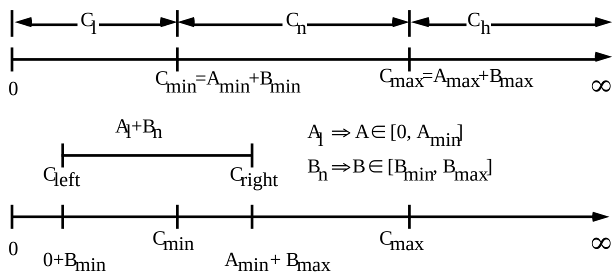

Figure 6. Relationship between qualitative and quantitative values.

has been shown by [Struss, 1990] a naïve application of primitive operations like addition and multiplication on intervals results in solution intervals that are too large. The reason is that the worst-case approach for interval arithmetic does not take into account that an interval variable might be mentioned more than once in a term (e.g., see the previous equation). Thus, each equation must be “optimized” by hand. For a parallel grouping of resistors this would result in a compensation resistor with the following interval for the resistance:

$$Pleft = \left.\frac{R1 \cdot R2}{R1 + R2}\right|_{min} = \frac{R1left \cdot R2left}{R1left + R2left}$$

$$Pright = \left.\frac{R1 \cdot R2}{R1 + R2}\right|_{max} = \frac{R1right \cdot R2right}{R1right + R2right}$$

The partial derivatives wrt. R1 and R2 are each positive and therefore the left and right interval borders are inserted to minimize and maximize the expressions, respectively. The complete set of rules for combining qualitative values is summarized in Table 1 and Table 2.

A + B	0	l	n	h	∞
0	0	l	l / n	l / n / h	∞
l	l	l	l / n	l / n / h	∞
n	l / n	l / n	n	n / h	∞
h	l / n / h	l / n / h	n / h	h	∞
∞	∞	∞	∞	∞	∞

Table 1: Qualitative addition.

R1 | R2	0	l	n	h	∞
0	0	0	0	0	0
l	0	l	l / n	l / n / h	l / n / h
n	0	l / n	n	n / h	n / h
h	0	l / n / h	n / h	h	h
∞	0	l / n / h	n / h	h	∞

Table 2: Parallel Resistors Rule.

3.1 Bottom-up propagation

With the two rules from Table 1 and Table 2 the resistance values for the compensation resistors of the sp-analysis in Figure 4 can be computed. In Figure 5, the lower part of a resistor box contains the possible qualitative values. In the beginning, this is the set {0, l , n, h, ∞}. For the leaves, corresponding constraints for the assumptions are inserted, i.e. the value “too low” for R4 and “normal” for the others. The rules are used as constraints to compute the sets of values for the series and parallel compensations resistors. Restrictions are propagates from leaf resistors to the top compensation resistor using the rules in Table 1 and Table 2 (bottom-up propagation, see also the approach in [Mauss and Neumann, 1996]). The result of the propagation process indicates that the complete compensation resistance (node S10) will be either “too low” or “normal”. The latter value implies that in the whole context, the deviation of R4 is neglectable. Besides the resistances, the currents and voltages must be computed for each resistor. So far, we have only restrictions for the voltage of S10. The voltage drop at S10 is identical to the distribution voltage. Based on this knowledge, restrictions for other voltages and currents in the sp-tree can be derived in a top-down propagation phase.

3.2 Top-down propagation

In this section, it is shown that physical knowledge can be represented in such a way that constraints for derivations of voltages and currents can be derived by local propagation in the sp-tree (top-down and lateral propagation). Once the possibilities for the resistance of S10 are known, the possibilities for the current through S10 can be constrained (Ohm’s Law: I = U / R). In Table 3 the required rules for the qualitative division for our domain {0, l , n, h, ∞} are summarized.

A / B	0	l	n	h	∞
0	?	0	0	0	0
l	∞	l / n / h	l / n	l	0
n	∞	n / h	n	l / n	0
h	∞	h	n / h	l / n / h	0
∞	∞	∞	∞	∞	?

Table 3: Qualitative division (required for Ohm’s Law).

Thus, I10 is either “normal” or “too high” (see the augmented sp-tree in Figure 7). Restrictions for the voltage drop (U = R · I) can be computed with a qualitative multiplication (see Table 4).

A · B	0	l	n	h	∞
0	0	0	0	0	?
l	0	l	l / n	l / n / h	∞
n	0	l / n	n	n / h	∞
h	0	l / n / h	n / h	h	∞
∞	?	∞	∞	∞	∞

Table 4: Qualitative multiplication (required for Ohm’s Law).

Other physical laws are exploited to derive further inferences. For instance, the voltage drops at each resistor of a parallel grouping are the same. The same rule holds for currents in series groupings. Furthermore, we have the Voltage Divider Equation for series groupings and, as a dual, the Current Divider Equation for parallel groupings of resistors.

The Voltage Divider Rule is discussed here as an example. If we have two resistors R1 and R2 in a series grouping with voltage drop U3 for the compensation resistor, then the following equations hold:

$$U1left = \left.\frac{R1}{R1 + R2} \cdot U3\right|_{min} = \frac{R1left}{R1left + R2right} \cdot U3left$$

$$U1right = \left.\frac{R1}{R1 + R2} \cdot U3\right|_{max} = \frac{R1right}{R1right + R2left} \cdot U3right$$

R1\R2 or R2\R1	0	l	n	h	∞	U3 or I3
0	?	0	0	0	0	l
	?	0	0	0	0	n
	?	0	0	0	0	h
l	l / n / h	l / n / h	l / n	l	0	l
	n / h	l / n / h	l / n	l / n	0	n
	h	l / n / h	l / n / h	l / n / h	0	h
n	l / n / h	l / n / h	l / n	l / n	0	l
	n / h	n / h	n	l / n	0	n
	h	n / h	n / h	l / n / h	0	h
h	l / n / h	l / n / h	l / n / h	l / n / h	0	l
	n / h	n / h	n / h	l / n / h	0	n
	h	h	n / h	l / n / h	0	h
∞	l / n / h	l / n / h	l / n / h	l / n / h	?	l
	n / h	n / h	n / h	n / h	?	n
	h	h	h	h	?	h

Table 5: Voltage Divider and Current Divider Rules.

The respective minimum and maximum is given to the right in terms of interval end-points. For instance, U1 can be minimized ($U1_{left}$) by using the maximum value of R2 (R2 is in the denominator) and the minimum of U3. U1 will also be minimized if the minimum of R1 is inserted (the partial derivative wrt. R1 is positive). Other proofs are similar. Table 5 shows the complete composition table for all qualitative values. The Current Divider Rule is given below:

$$I1 \in \left[\frac{R2left}{R1right + R2left} \cdot I3left, \frac{R2right}{R1left + R2right} \cdot I3right \right]$$

Note that for the Current Divider Rule R1 and R2 must be reversed in the composition table (see Table 5).

With these additional rules, further constraints can be derived for the voltages and currents of other resistors. Figure 7 shows the result after all rules have been applied. It is important to note that sometimes the rules for Ohm's Law and sometimes the Current and Voltage Divider Rules impose more restrictive constraints. For instance, for the node R12 in Figure 7 the Current Divider Rule imposes the constraint l / n / h on I12. The qualitative division (I12 = U12 / R12) even rules out the h. For node P6 the Voltage Divider Rule constrains U6 to be one of l / n / h whereas the qualitative multiplication (U6 = R6 · I6) also eliminates the l in this node. If only the multiplication rule were applied at node P7, the voltage would only have been restricted to l / n / h. However, with the Voltage Divider Rule, U7 is restricted to l / n.

Therefore, all rules must be applied for each node in the tree. The sp-tree in Figure 7 describes all resistances, voltages and currents for the circuit from Figure 4. Now, the star-delta transformation can be reversed. The star-delta transformation equations from above indicate that we also need a qualitative subtraction: I3 = I32 - I13. It is not guaranteed that the result of the subtraction of two intervals is always a positive interval. We introduce a new set of variables {"too Low" (L), "Normal" (N), "too High" (H)}. These values do not represent any information about signs, and therefore, they cannot be combined with the other values introduces above. The qualitative subtraction rules are given here as Table 6.

A – B	0	l	n	h
0	L/N/H	L/N/H	L/N	L
l	L/N/H	L/N/H	L/N	L
n	N/H	N/H	N	L/N
h	H	H	N/H	L/N/H

Table 6: Qualitative subtraction (for star-delta transformation).

The interpretation of the subtraction results is discussed with an example. Since I32 = l / n and I13 = n / h (see Figure 7), I3 = L / N. Thus, the current through the bridge resistor is either "too Low" (L) or "Normal" (N). However, being "too Low" can even mean that the absolute value is higher because the direction is reversed. The values of subtractions are only interpreted wrt. required measurements.

3.3 Interpretation of propagation results

The values computed by the propagation process are used (i) for defining fault-discriminating measurements and (ii) for deriving possible state changes. On the one hand, the fault model for R5 influences the field current and, therefore, one candidate measurement to detect that R5 is too low is the field current at metering point I_F (see Figure 1). On the other hand, the sp-tree node for the fuse indicates that the current through the fuse will be "normal" or "too high." This means that it cannot be ruled out that the fuse might blow. This behavior is anticipated with State 2. In this state, another model fragment for the fuse with R = ∞ is used. Figure 8 summarizes the results of the constraint propagation process in the corresponding sp-tree.

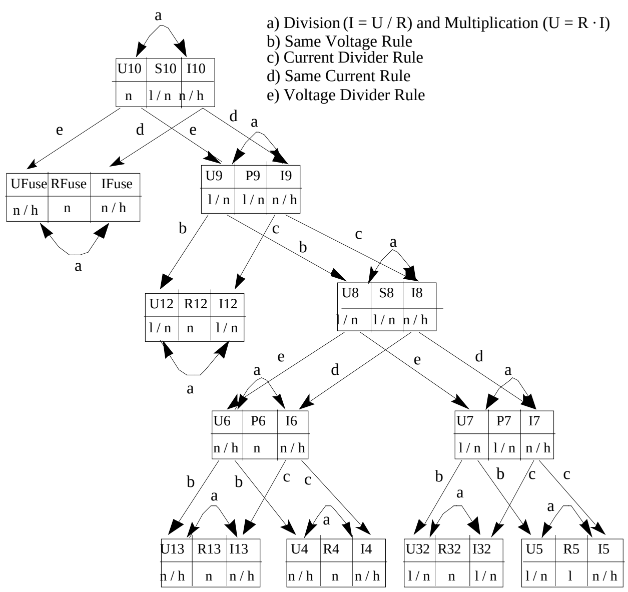

Figure 7. Sp-tree, augmented with voltages and currents.

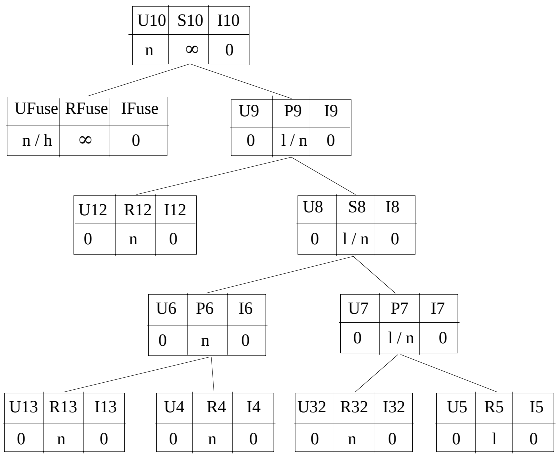

Figure 8. Sp-tree for State 2.

The figure indicates that in State 2 all currents will be zero. The voltage drop at the fuse will be normal or higher (R5 is still lower in this state).

Metering Point Fault Model	U_B or U9	M_1 or U2	I_F or I3	M_2 or U5	State
...	...	...	...	...	...
R5 too low	l / n	l / n	L/N	l / n	1
R5 too low	0	0	L/N/H	0	2
...	...	...	...	...	...

Table 7: Fault relation (U2 = I2 * R2 = (I12 + I32) * R2).

With an additional set of rules, the sp-tree can be used to derive the fault relation of the whole system. Due to space limitations, in this paper we discuss only a sketch of the fault relation which is presented here in Table 7. As an interpretation of the fault relation, a measurement at metering point U_B (see also Figure 1) might be used to discriminate State 2 in the final runtime system etc.

As we have seen, in this example we have two deviations from normal behavior (the fuse and the resistor R5). The question is whether the calculus presented above always computes the most restrictive value sets for domain variables and under what circumstances. This leads us to an evaluation of the approach.

3.4 Evaluation of the approach

The problem of computing deviations in resistive networks is solved by an algorithm that restricts the set of possible values for component variables by applying a set of predefined rules. The initial model must be transformed (into the sp-tree data structures) in order to make the rules applicable.

The algorithm terminates because at each propagation step the set of possible values for a variable is reduced. It can be easily seen that the complexity of the algorithm is linear. The algorithm is sound, i.e. the constraints imposed on component variables by the propagation rules described above are not too restrictive. This can be shown by induction on all operations presented in the tables. We have sketched the proofs with some examples above (for details see [Milde, 1997]). The algorithm is complete, i.e. the computed value sets for component variables (e.g. l / n / h) are restricted as much as possible, when only one component variable shows non-normal behavior and no fault model with “resistance too low” or “resistance too high” is assumed for the bridge resistor (for the proof see [Milde, 1997]). Note that our notions of soundness and completeness differ from those defined in [Struss, 1990].

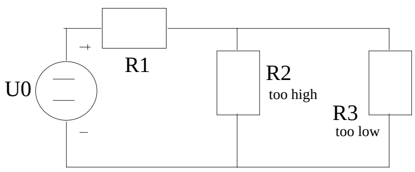

Figure 9. Example circuit with two non-normal resistors.

In the example circuit shown in Figure 9 with R2 being “too high” and R3 being “too low”, the calculus computes l / n / h for the voltages and currents of R2 and R3. However, in this special constellation, it can be proven that e.g. the current through R2 will be “too low” or “normal” and the current through R3 will be “normal” or “too high”. In our scenario (with the single fault assumption), a similar situation can only occur when the bridge resistor is faulty (more than one star-delta substitution resistor has non-normal behavior). Simple situations like these can be detected with special model fragments that impose additional constraints on component variables when the components are used in certain component constellations and operating conditions.

4 Conclusion

The calculus for model-based reasoning about behavior deviations in resistive networks supports the generation of a fault relation as an off-line preprocessing step to the generation of a complete diagnosis system (runtime system). In constrast to [de Kleer and Raiman, 1995] who propose a runtime strategy called “computing and probing” to reduce computational costs, our calculus ensures that behavior ambiguities are avoided for single faults and, therefore, it is possible to simulate devices at development-time (preprocessing step) with a linear algorithm. The deviation calculus presented in this paper is more powerful than the approach presented in [Mauss and Neumann, 1996] because the changes can be interpreted to suggest measurements in bridge circuit topologies even with qualitative values for component variables. In contrast to [Neitzke and Neumann, 1994] the normal behavior is represented by an interval rather than a point. This is important because in practice differential deviations are always present in concrete technical devices.

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