Qualitative Circuit Models for ECAD Analysis and Support Tools

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Abstract: In ECAD application areas, there is a real need for electrical circuit modelling and analysis tools at an intermediate level between analogue and state-based simulators. Numerical tools do not capture the abstractions valued by engineers and logical/functional models do not maintain sufficient affinities with the electrical properties of a system. This paper examines the nature of this problem and then describes MCIRQ, a qualitative modelling technique that offers a solution. We believe qualitative and quantitative methods can be combined to gain considerable benefits in future integrated ECAD environments.

Key words: Circuit analysis, Qualitative models, ECAD Tools, Design, Diagnosis.

1 The Significance of Qualitative Concepts in Electrical Circuit Analysis

In engineering, ECAD simulation packages are ubiquitous and highly successful tools for detailed numerical analysis of circuits and systems. However, it has long been appreciated that purely numerical methods are difficult to work with, often obscure salient features of the application, and seem to have little affinity with engineers' preferred reasoning processes. Other methods have been developed to capture the non-electrical aspects of circuits, for example logic and gate-level simulators and state modelling systems. But there still remains a need for an intermediate modelling level which captures electrical circuit properties in a qualitative way, without the numeric verbosity of detail of quantitative methods.

Thus, while it is possible to model authentically all behavioural aspects of a circuit on an analogue simulator this often does not capture the distinct qualitative states that characterise important abstractions valued by engineers. This problem is confirmed by reports from ECAD researchers who have access to considerable data on engineers' experience, e.g.

> "Graphical interfaces can present simulation data in more convenient forms, but they do not interpret their meaning nor do they reduce the number of simulations required in order to gain a feel about some circuit performance. It has thus become clear that numerical descriptions of circuit behaviour do not convey understanding about the operation of a circuit. In fact, the use of such numerical-only systems can impose a barrier to the development of insight." [9]

There is a pressing need to overcome these problems and provide an intermediate level model to fill the important gap between voluminous numerical detail and the sparseness of non-electrical representations. There have been various attacks on this problem and we illustrate two approaches here.

1.1 The switch-level modelling approach

Investigations by Hayes and others in the 1980s aimed to build circuit models intermediate between gate-level simulators and analogue electrical models [3]. This "switch-level modelling" work was built from many-valued logic and hence had a symbolic rather than a numeric grounding. The variables, known as "magnitude classes", were value pairs consisting of a 4-valued voltage level and an n-valued current value.

The voltage values were essentially qualitative, being taken from [+, −, 0,U] which represented the two supply potentials, an intermediate potential, and an open circuit, respectively. Resistance values were taken from a finite set consisting of 0, ∞ and $n-2$ intermediate levels, and where $R_{i+1} > R_i$. With a fixed voltage, Ohm's law gives a range of current levels corresponding to the finite resistance levels.

After a great deal of development, Hayes's final paper in 1992 described the severe accuracy limitations that prevented any further development of switch-level models [2]

> "A major conclusion from our work is that switch-level simulators which use many signal strength classes may have no better accuracy than simulators in which only two or three strengths are used to distinguish very large differences in resistance values." [2]

1.2 The qualitative circuit modelling approach

Without any apparent knowledge of the switch-level model experiments, the Qualitative Reasoning (QR) research community have independently developed qualitative electrical models and investigated their application to significant problems in diagnosis, design and analysis.

Software tools are now being developed for such applications and embody qualitative models in contrast to the numerical equation solvers used in most electrical simulation packages. Examples of successful commercial QR applications are seen in diagnosis, e.g. [13], and in our work on analysis, especially FMEA (Failure Mode Effects Analysis). We note that FMEA is *essentially* a qualitative reasoning task. The work described here underpins one of the most advanced commercial systems in regular use for electrical FMEA in the automotive industry [10].

2 Requirements for an Intermediate Representation

Considering typical reasoning tasks as carried out by engineers gives insight into their needs and goals. Examples show how reasoning can be summarised in terms of questions:

Explore system structure What are the distinguishing states that define the main features of a system?

Explore designs How does this device work? What happens when these inputs/parameters change?

Design modifications What happens if this item is removed? How does this circuit relate to other apparently similar circuits?

Diagnose designs Why is this system not meeting the specification? What changes in components/values could be responsible for the error?

Analyse failure modes In what way can this system fail? How serious are failures and how can they be grouped or ranked?

Assess safety What unintended operations may occur? How can these be reduced in likelihood or severity?

In engineering generally, there are many reasoning activities like these and, in humans at least, it seems that they are most beneficially performed on abstract or simplified intermediate representations, without losing the essential structure of the problem.

Previously, we have investigated modelling requirements [5] and identified several important issues:

Vivid models Some forms of model seem to exhibit a closeness with our conceptual basis of the real world. Thus, diagrams are much easier to comprehend than, say, equations. This simplicity and directness of representation has been called vividness [8] and is a way of providing accessible conceptual structures. This seems important for human cognitive processes and helps maintain affinity with engineering concepts. Engineers often seem to use minimal models that allow them to: gain insight, predict behaviour, and reason rapidly.

Simplification and Approximation The mental models used by engineers appear to be simplified, in that various detail is removed, and approximate, in that granularity is high. In our work the QR models are simplified by using only resistance values to represent all components and are approximate by using the coarse granularity of qualitative values rather than numerical precision.

Structural and non-structural changes Many simulation models support extensive analysis of the effects of parameter changes, but are less easy to use for exploring structural change. On the other hand, QR models specialise in structural analysis while some changes in value are often impossible to represent or detect. Both structural and non-structural analysis should be supported in future ECAD tools.

Generality Analogue methods have no problems with generality but some topological forms have proved difficult for some qualitative techniques. Series/parallel reducible circuits (SP) are those those that can be reduced into a single equivalent value by repeated application of standard series parallel reduction rules, [1]. Non SP reducible circuits may contain star/delta configurations and/or bridges that may or may not be balanced. Any useful method must be general enough to cover all these cases.

3 MCIRQ — a Many-Valued Qualitative Model

We now describe our qualitative circuit analysis method. We assume all electrical components can be replaced by suitable configurations of resistance, then all circuits become a resistive mesh represented by a graph E(T, R) containing T nodes and R weighted edges. We also assume two of the nodes are defined as the supply terminals. Only the 2 supply voltage values are used.

The user is then asked to select a set of names for the *distinctive* resistance levels relevant for the circuit under consideration. The extreme values are always 0 and ∞. For illustration we let $n = 5$ and give a quantity space for resistance as: $[0, lo, med, hi, \infty]$. The only constraint is that the values are ordered: $0 < lo < med < hi < \infty$. This means any number of *med* edges in series will always be considered lower in value than a single *hi* edge, and similarly with other pairs in the ordering.

Resistances values from the n-valued set are then assigned to the graph edges. The physics of series and parallel circuit reduction require the numeric summation of their resistances or their conductances respectively. Our system uses Max and Min as the series and parallel reduction rules respectively, see [4] for more detail.

We define a chain as a path between two nodes (both of degree $\neq 2$), where all intermediate nodes have degree 2, and a segment is an SP reducible portion of a circuit. The analysis algorithm has three main parts:

SP reduction We locate all chains, calculate their equivalent resistance (using Max), replace them with a single edge and enter their details in a segment table. Next all parallel edges are located, replaced with their equivalent single edges (using Min) and entered in the segment table. This process is repeated for series/parallel in turn until either a single resistance or a non-SP reducible circuit remains.

Current determination We now find the current in the reduced circuit. If this is a single equivalent resistance then the total current flow in the circuit, I, (i.e. at the main terminals) will be inversely proportional to this resistance value, R'. As we have a finite set of resistance values and a single fixed voltage source, we can define current in terms of the flow that would be produced by a given resistance:

r	0	lo	med	hi	∞
i	∞	hi	med	lo	0

Table 1: Resistance and current have an inverse relation: $i = inv[r]$

In the case that a non SP network remains after SP reduction, this much smaller network is resolved by a graphical method described below.

Current level assignment Finally, the qualitative values assigned to the reduced graph are referred back to the segment table and values are calculated and assigned for each of the composite chains and branches in the original circuit. The segment table is used to expand the SP reduced circuit back to its original form with the current levels being carried through the process.

The final result is that each edge is returned a value, $i = inv[r]$, that indicates its level of current (or activity). Thus, a circuit edge of resistance lo might be shown to be carrying a current corresponding to a hi level of resistance (i.e. $i = inv[hi]$). This might indicate to an engineer that a power circuit is carrying a signal level current. We find it useful to use a colour code for the different current values. Each edge is then clearly labelled in circuit displays.

3.1 Non SP circuit resolution

MCIRQ uses a two stage process; first flow directions are found using a graph-theoretic procedure, and then a path analysis process resolves any remaining bridges or other difficult edges.

First a spanning tree is used to find a set of *fundamental circuits* of the non SP system. This also has the effect of eliminating any dead branches. The steps involved are as follows:

1. For the final circuit produced from SP reduction, K, generate a spanning tree T rooted at the positive supply node. During this process create a co-tree CT (containing those edges missing from the spanning tree). Note that an artificial edge between the two power supply nodes is included in the co-tree.
2. Take each edge in turn from the co-tree, add to the spanning tree and find the cyclic path that is produced. These *fundamental circuits* are saved and form the basis of the circuit space of K. Note that (a) any dead-end branches have now been eliminated and (b) just one fundamental circuit will have a path between the supply nodes.
3. From the set of fundamental circuits generate all combinations of circuit paths using the ring-sum operator $\oplus$. The ring-sum of two graphs contains all the nodes from both and the edges which are in either graph but not both. Only circuit paths involving both supply terminal nodes are saved.
4. For each generated path, beginning at the positive supply node, perform a traversal to the negative node. During the traversal, the edges between the supply nodes are assigned directions of flow (using the convention that flow is from positive to negative) and the path resistances are computed.
5. The edge directions from each circuit path are entered into a **route matrix**. Each edge will end up labelled either consistently with one direction of flow, inconsistently (i.e. ambiguous) or unlabelled (dead branch).

The fundamental circuits represent the loops given by Kirchhoff's voltage law and define the circuit basis. An example is shown in figure 1. In this case the circuit basis contains five fundamental circuits and this gives rise to 31 possible combinations of circuit routes, of which 16 were tested (i.e those containing both supply nodes). 12 valid circuit paths were found, shown in figure 2, and these gave unambiguous flow directions in 6 of the 10 edges in the original circuit. Notice that the dead-end branches, k and l, are eliminated from the fundamental circuits. The route matrix is shown in table 2. In relation to figure 1, a

Path Number	Circuit Basis	Flow directions (A = ambiguous) a	b	c	d	e	f	g	h	i	j	k	l	Path Resistance R	Rank
1	1								→		→			hi,med	7
2	1⊕3	→	→			→		→			→			hi,2med,2lo	10
3	1⊕4	→		→			→				→			hi,2med,lo	9
4	1⊕5							←	→	→				med,2lo	1
5	1⊕3⊕2	→		→	←	→		→			→			hi,3med,2lo	11
6	1⊕3⊕5	→	→			→				→				2med,2lo	3
7	1⊕4⊕2	→	→		→		→				→			hi,med,3lo	8
8	1⊕4⊕5	→		→			→	←		→				2med,3lo	4
9	1⊕3⊕2⊕5	→		→	←	→				→				3med,2lo	5
10	1⊕4⊕2⊕5	→	→		→		→	←		→				med,5lo	2
11	1⊕3⊕5⊕4		→	←		→	←		→	→				3med,3lo	6
12	1⊕2⊕3⊕4⊕5				←	→	←		→	→				2med,3lo	4
Resultant flow		→	→	A	A	→	A	A	→	→	→	0	0		

Table 2: Route matrix for figure 2.

right arrow indicates flow down or to the right and a left arrow indicates flow up or to the left. The symbol, A, indicates an ambiguous edge and 0 indicates a dead edge (no flow). The ranking is in order of minimum path resistance.

The second stage is to examine all the remaining edges labelled "ambiguous" making use of a qualitative version of Thevenin's theorem. Thevenin's theorem states that any linear two-terminal network containing various voltage sources can be replaced by a single resistance, R_{th}, in series with a single voltage source, V_{th}. (The value of V_{th} is given by the open-circuit voltage experienced at the terminals and R_{th} can be found from $R_{th} = V_{th}/I_{short-circuit}$.)

This means that an edge can be *removed* when determining its end potentials as *its resistance value can have no effect on the direction of flow.* If an order-of-magnitude difference between the end nodes is in evidence then the flow direction can be determined, otherwise the edge must remain labeled "ambiguous".

For each ambiguous edge in the route matrix

1. Remove the edge from the circuit (or set its value to ∞) and then generate forward and reverse resistance labels (f/r) for all circuit nodes.
2. The labelling process is based on that given in [6] but is modified to deliver increased information. Instead of recording the minimum resistance to the supply terminals, a full list of the number of resistances of each OM value on the path are given for f and r.
3. The two edge nodes are compared using a potential divider rule, on the basis of decreasing OM values. If there exists a clear order-of-magnitude difference in the potentials then the direction of flow is assigned accordingly, otherwise the edge remains "ambiguous". It is possible to grade the degree of ambiguity on the basis of the qualitative results; this allows "likely" flow directions to be assigned with associated confidence levels.

An example of this stage is illustrated in figure 3. Here edge d is being examined and the f/r values at each end are $med, lo/med, lo$ and $med, lo/3lo$. This is an imbalance as the second r is nearer to the negative terminal by an order-of-magnitude and flow can be assigned towards this node. Notice that if the highest value were the same in all four entries then the next lower value could be used for comparison. However, as there would not then be an order-of-magnitude difference the flow could only be indicated tentatively. For example, with f/r values of $med/med, 4lo$ and $med, lo/med, 3lo$ the equal medium values support the balanced case, but next comparing the lo values, the f value has increased in one direction while the r value has reduced. This allows us to label the edge "ambiguous" but also assign a "likely" direction of flow.

4 Discussion

MCIRQ has been implemented in Java and our results show that path activity can be determined for circuits including diodes and bridges [7]. With QR methods bridges can only be resolved when they are unbalanced and our system works for such cases. Our formulation is an efficient way of discerning such cases that are definitely unbalanced.

Further testing has shown that our method works for any circuit in which all nodes in the graph representing the SP reduced circuit are on at least one path with no edges whose flow is marked as ambiguous in the route matrix. In other words, those circuits where any bridges can be SP reduced to a single segment.

Work is currently being done on a refinement of the method in which the use of f/r values to find the direction of flow through a bridge is replaced by a method in which the flow through an ambiguous edge is determined by the significance of the paths

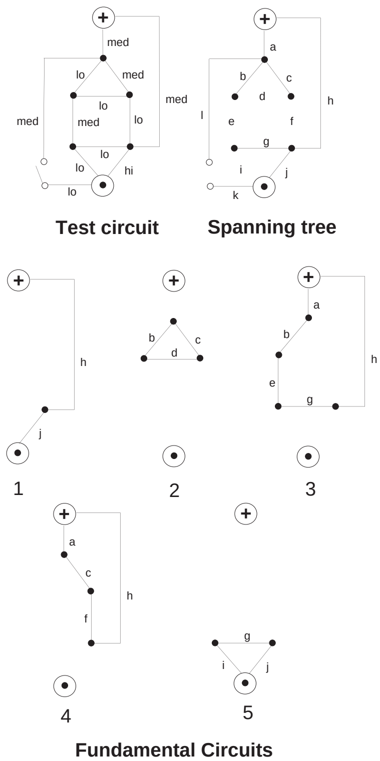

Figure 1: An example circuit, its spanning tree and resulting circuit space

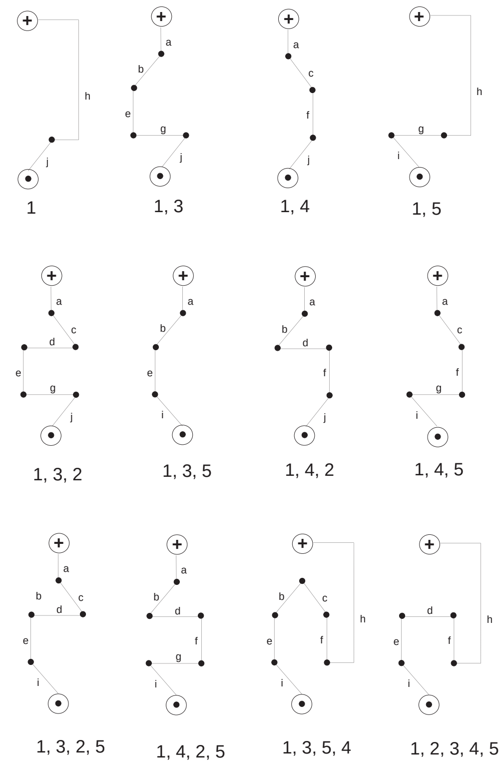

Figure 2: Generated paths give directions of flow

through that edge. Because this method evaluates paths rather than segments it is expected that it will be more capable of giving consistent results in the rare cases where a circuit includes a mesh of edges of possibly ambiguous direction of flow.

The interpretations given to the resistance values is a key feature of the method and these are determined by the application domain. For example, the semantics of *hi* might represent: reverse diode leakage current, high impedance signal currents, or the increased impedance of an unloaded motor. Conversely, *lo* might be used to capture the very low resistance of power cables where voltage-drops have particular significance.

4.1 Benefits of the QR approach

There are several advantages when using qualitative models:

Closer affinities with real system. Resistance values like *hi* and 0 are more natural for simplified reasoning.

Non-exact data can be used. In early designs full detail is often not available but qualitative values can cover a range of numerical data.

Partial models still useful. A great deal of valuable reasoning can be performed with very little data, e.g. see [12] for a powerful example of this.

Other benefits include: low complexity; component re-use options; ease of generating explanations; model re-use.

The main disadvantages are the loss of exact data and the ordering constraint on resistance values.

5 Conclusions

We have presented a new qualitative circuit analysis method. The model has retained a high level of vividness with respect to the real world system; a feature considered important for acceptance and affinity with practicing engineers.

The model illustrates how quantity spaces for resistance can effectively label circuit nodes with application specific classes for different types of current flow. We have used 5 values of resistance but increasing the quantity space set will deliver even more flow classes, representing increasingly finer resolution. We see our method as a way of classifying the branches of a circuit, and the significance of the resulting branch labels will depend upon the initial application semantics given to the resistance value set.

By not attempting the calculation of any current values we have avoided the combinatorial and accuracy problems that arise from arithmetic on several multi-valued qualitative variables as experienced in

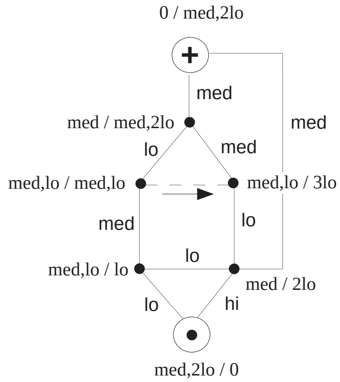

Figure 3: An example of node analysis

the switch-level models of [3]. (Note that interval arithmetic also suffers from these difficulties.)

The method relies on an orders-of-magnitude resistance relation [11]. Thus a circuit might have an equivalent resistance of hi and, when connected to the supply, we would expect a current in the region of $inv[hi]$ to be drawn. As the circuit changes, in either structure or component values, so the active paths will change to reflect how the power, signal, leakage, or other levels, have altered as a consequence. Our Java implementation displays each current level as a different colour, thus highlighting their status and aiding their interpretation. We believe this scenario illustrates the advantages of QR methods and their complementarity with more traditional numeric circuit techniques.

The method is computationally efficient and is also general in that all topologies can be processed. The mapping between the reduced and original circuits is readily accessible from the segment tables and star/delta transformation rules are not required.

In summary, the method is intuitive, general, robust and efficient. It is flexible in that the qualitative value range is tailored to individual applications. The main limitation is that all qualitative values must be constrained by an orders-of-magnitude relation.

We believe that qualitative and quantitative tools should be combined using parallel operation to gain their mutual benefits in an integrated and coherent modelling environment for future engineering application tools.

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