Synthesis Of Circuit Breaker Mechanisms Based On Mechanical Logic Gates

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ABSTRACT

A circuit breaker protects electrical systems from overloads. Once the fault is rectified the circuit breaker permits restoration of power through a command, unlike a fuse that blows and has to be replaced. Of the several types of circuit breakers in operation the spring actuated ones are those that are widely used since they are relatively inexpensive. An attempt to describe the functioning of these devices to novice students lead the authors to examine the possibility of using binary mechanical systems to enumerate structures of mechanisms for use in circuit breakers, and the results of these attempts are discussed here. The procedure enables one to identify the structure of the primary mechanism and also provides an insight into the operating principles.

NOMENCLATURE

CS – Closing Spring. TS – Tripping Spring. MC –	Moving Contact.
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INTRODUCTION

The function of a contact breaker is to protect electric circuits and power distribution systems. The simplest circuit breaker consists of two springs, the closing spring (CS) and the tripping spring (TS) both of which are initially charged by some means. A suitable mechanism links these springs to the moving electrical contact. When the closing spring (CS) is released it drives the moving contact (MC) forward towards the fixed contact thereby closing the circuit. An electrical fault results in the actuation of a solenoid that unlatches the TS and as TS moves from a charged to a discharged state the electrical contact is open. All mechanisms in commercial breakers, possess these basic features apart from a few additional ones for meeting customer requirements [1].

CIRCUIT BREAKERS – BINARY SYSTEMS.

The operation of a typical contact breaker is binary in nature. The three elements CS, TS and MC occupy two positions of interest during the operation of the breaker. CS and TS are either charged or discharged, while the MC might be in either a "closed" or "open" position. By treating the finitely separated positions of these elements as Boolean variables the positions of interest of each element could be assigned a value "0" or "1" in accordance with a predefined convention. As there are two binary inputs (CS and TS) and a single binary output we require a 2 DoF mechanical system to obtain the requisite operational features. It is to be emphasized that our interest is only in the two finitely separated end positions (2 FSP) of the output (MC) as well as the two input links driven by the two springs CS and TS. The structures of such devices can hence be determined by studying them as mechanical logic gates. The procedure outlined further on could be treated as a form of "Type Synthesis".

Mechanical logic gates have been proposed by several authors, and we now explore the possibility of utilizing some of these as the basis for synthesis of circuit breaker mechanisms. Devices to realize the logical functions AND, OR, NOR, and NAND have been synthesized and are either exact devices (force closed) as proposed by Dewey and Soni [2] and Szekely and Traista [3] or approximate devices (from closed) as proposed by Amarnath [4]. In what follows we limit ourselves to the illustration of the synthesis a few basic devices only, specifically those based on the AND gate. The construction of the AND gate is described first [5], before utilizing the same to obtain circuit breaker mechanisms.

AND Gate.

Figure 1 (a) shows a seven-link mechanism with two sliders A and B as inputs. These inputs occupy two positions "0" and "1". Points C1, C2, C3 and C4 are the positions of the joint C for the four possible input combinations (A,B) = (0,0), (0,1), (1,0) and (1,1) respectively. The pivot R on output slider Z is the center of a circle passing through C1, C2 and C3. With pivot R so chosen, output slider Z occupies position "1" only when both inputs A and B are "1", otherwise slider Z is at position "0". The companion Figure 1 (b) shows the same gate, but with rotary inputs and outputs, the synthesis procedure being similar to the earlier.

A NAND gate can be obtained from the AND gate of Figure 1(b), simply by locating the fixed pivot Q of the output link at Q' as shown in Figure 1 (b). Hence an input which causes a clockwise rotation of the output link of the AND gate, will result in an anticlockwise rotation of the output link of the NAND gate.

The devices in Fig. 1 are built using lower pairs and are approximate devices, in the sense that a transition from (A,B) = (0,0) to (A,B) = (0,1) or (1,0) results in a slight

motion of output link Z. This structural error however is an insignificant percentage of the net stroke and it is observed that in most applications the clearance or compliance in the system accommodates this error. "Contact springs" are used in circuit breakers to retain contact between the fixed and moving contacts and these would serve to accommodate this error.



Fig. 1. Mechanical AND Gate

EXPLORING THE AND GATE AS THE BASIS FOR SYNTHESIS

We use the convention that the output link Z in Fig. 1 will carry the moving contact and that the Boolean variable Z = 0 will correspond to "contacts open" and Z = 1 will correspond to "contacts closed". Then based on the closed or open state of the contacts, we assign "charged" or "discharged" status to the different springs involved, namely CS and TS. We do not use "0" and "1" to designate the state of a spring. The values 0 and 1 exclusively indicate the positions of the input (A,B) and output (Z) links and not the charged and discharged state of the springs.

In terms of connectivity of springs to the links we have several possible combinations, but all essentially result in three basic combinations as follows:

a. CS and TS connected to the input links A and B respectively. (The reverse is also possible.)

b. CS connected to output link Z and TS to A (or B).

c. TS connected to output link Z, CS to A (or B).

SYNTHESIS: CS AND TS AT THE INPUTS.

Referring to Fig. 1. let the two springs drive the inputs A and B, with CS connected to input B and TS connected to input A. The moving contact is at Z. When we examine the truth table for an AND gate we notice that Z = 1 only once – when A and B equal 1. For the rest of the combinations of inputs, Z is zero.

We begin by stating that Z=1 corresponds to the "closed" state of the contacts. Since the breaker must be able to protect the circuit it is necessary that as soon as the contacts close the trip spring TS be ready to act. Thus when the contacts are in a closed position, TS should be in a charged condition and ready to trip the contacts. Further the contacts must have reached their closed position upon discharge of the closing spring CS. Thus CS will be in a discharged condition at this instant. We realize that in an AND gate, Z=1when and only when A=B=1. This implies that the discharged condition of CS and the charged condition of TS must correspond to 1 as shown for the state S4 in Table 1.

Proceeding further we notice that during tripping operation the state of TS must change. Hence from Table 1, the tripping operation can be a transition from either S4 to S2 or from S4 to S1. Let us consider these two options in some more detail.

State	А	spring)	B (Closing spring)		Z (Contact)	
	(Tripping					
	Link	Spring	Link	Spring	Link	State
S1	0	Dischar	0	Charged	0	Open
		ged				
S2	0	Dischar	1	Discharged	0	Open
		ged				
S 3	1	Charged	0	Charged	0	Open
S4	1	Charged	Ι	Discharged	Ι	Closed

Table 1: Truth table for "AND operation" with both springs at the inputs.

Transition from S4 to S2.

TS is discharged during this change and the system has reached state S2. We note that at S2, CS is also in a discharged condition. One now has the option of recharging both springs (TS as well as CS) simultaneously by going from S2 to S3 directly.

Another alternative is to go from S2 to S1 and then to S3 thereby charging CS and TS sequentially. The closing operation in either case is a change from S3 to S4.

The third alternative is a transition from S2 to S1 to charge CS. The next transition from S1 to S4 leads to a discharge of CS both to close the contacts as well as charge TS. This requires that the spring CS be fairly strong.

Transition from S4 to S1.

This results in TS tripping the contacts and simultaneously charging CS – and calls for a strong TS. At S1 the tripping spring is in a discharged condition and recharging it requires a move from S1 to S3. Closing operation is a movement from S3 to S4.

All the above have been depicted pictorially in Fig. 2. The mechanism shown is the AND gate of Fig. 1a. We should look upon the device merely as a schematic illustration of the operating principles and the structure of the primary mechanism. The procedure as outlined permits the designer to determine the connectivity of the springs and the sequence required for operation, systematically for all permutations and combinations. Thus what has been outlined is akin to "Type Synthesis".

The truth table is the first step in the synthesis and this is followed by a schematic like the one in Fig. 2. Using the schematic as a guide the designer is free to evolve the actual working mechanism replacing sliders by levers and lower pairs by higher pairs. In Fig. 2 all sliders have equal strokes – which is not necessary in practice. Exact strokes are to be determined from the dimensional synthesis which follows, but one must preserve the generation of the AND function.

In Fig. 2, one notices the use of several latches to hold the links in place. These latches may be actuated through solenoids, or other mechanical means, and often a single degree of freedom system is incorporated to magnify forces. The location of these latches in the actual device is also easily determined from figures such as those in Fig. 2. We shall now continue the exploration to determine other possible topologies and sequences.



Fig. 2. Sequence of operation based on AND gate with CS and TS at the inputs.

SYNTHESIS: CS AT INPUT B AND TS AT OUTPUT Z.

We now examine the case when the TS is connected to the output Z and CS is connected to the input link B. The truth table for this case is shown in Table 2.

State S4 corresponds to the contacts being closed and so TS must be in a charged condition in this state, ready to trip at the trip signal. Hence Z = I indicates TS is charged. Also this state S4 must have been reached by discharge of the CS. So CS must be in its discharged condition in this state. Hence B = 1 pertains to CS in discharged state.

An important point to remember is that the closing operation involves charging of TS and we note that CS must not only close contacts but also charge TS.

State	ate A B (Closing Spring)		Z (Contact and Trip Spring)			
	Link	Link	Spring	Link	Spring	State
1	0	0	Charged	0	Discharged	Open
2	0	1	Discharged	0	Discharged	Open
3	1	0	Charged	0	Discharged	Open
4	1	1	Discharged	1	Charged	Closed

Table 2: Truth Table for AND operation with TS at the output and CS at input.

Transitions from S4 to S1 or from S4 to S3 could be utilized for tripping but these will involve the charging of the closing spring by the tripping spring. Since TS has been charged by CS (CS is to be stronger than the TS) the discharge of TS cannot cause charging of CS. Hence the tripping operation must be a transition from S4 to S2. Subsequent to the S4 to S2 transition, the charging of closing spring occurs during S2 to S1, with A held at 0 (recall that trip spring is connected to Z). This is followed by the reset operation S1 to S3 and the breaker is ready for a closing operation. The springs are neither charged nor do they discharge during a reset operation.

The closing operation occurs as a transition from S3 to S4, and the discharge of CS causes the closing operation as well as charging of tripping spring.

SYNTHESIS: TS AT INPUT A, CS AT OUTPUT Z

We now consider the case when the trip spring TS is connected to A and the closing spring is connected to output link Z.

Following a similar argument as in the previous two cases, we get the charged and discharged states of the springs as shown in Table 3. S4 to S2 is the tripping operation resulting in discharge of TS and the resultant charging of CS, by the discharging TS. (So

TS must be stronger than CS). The reset operation follows and is from S2 to S1. The next move from S1 to S3 results in TS being charged. S3 to S4 results in a closure of contact.

State	A(Tri p	spring)	В	Z (Contact and Closing spring)		
	Link	Spring	Link	Link	Spring	Contact
1	0	Discharged	0	0	Charged	Open
2	0	Discharged	1	0	Charged	Open
3	1	Charged	0	0	Charged	Open
4	1	Charged	1	1	Discharged	Closed

Table 3: Truth Table for AND operation with TS at input and CS at the output.

EXISTING CIRCUIT BREAKERS

In an ongoing study the authors have examined a few circuit breakers [1,7,8], and these studies will be reported later in detail separately. However one point that emerges is that several commercial units use cams and by replacing the higher pairs with two lower pairs the ensuing topologies are similar to those discussed here. Also commercially available devices incorporate a host of secondary mechanisms in addition to the primary device. Several single degree of freedom chains are used to modulate and communicate motion or forcesto the primary operating mechanism. Springs are often charged by motors and transmission systems consisting of unidirectional clutches. Many a moving element is used to actuate the latches. The net result of all the above is a very complex looking device formidable to comprehend. But once the system is recast into a truth table and a schematic as in Fig. 2 is developed, it is relatively easy to grasp the functioning of the device.

The input and output links in the gates in Fig. 1 have identical strokes. This, clearly, is not a necessity. Gates with unequal strokes could be designed to meet the primary requirements, and by replacing a few links and lower pairs by higher ones, one could obtain any desired motion during transitions. The point to emphasize here is that the procedure outlined here permits one to arrive at a topology and sequence. Dimensional synthesis must then follow.

DISCUSSIONS AND CONCLUSIONS

It has been proposed that mechanical logic gates be used as a basis for the "type synthesis" of mechanisms for meeting the primary functional requirement of circuit breakers. The same procedure could also be used to understand the functioning of existing mechanisms that exist in seemingly innumerable varieties, and may be based on functions other than the AND [6]. Through this work the designer has been provided a tool that could be used to systematically lay down several "types" of mechanisms each with its own set of features. The final choice of a specific mechanism is best left to the designer to decide.

Basic devices synthesized from the AND gate have been studied and operational sequences determined for a variety of spring connections. In the devices discussed here charging the closing spring is possible only when the contacts are open. The devices can however trip the breaker upon closing – a feature that is essential to protect a circuit when the fault downstream of the contactor has not been fully rectified.

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