INTELLIGENT FAULTS INTERRUPTION

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Abstract **- The paper focuses on the relative new technology in power systems – controlled switching of high voltage circuit breakers and especially on the authors' so called *intelligent switching*. The concept of intelligent switching means extending the existing controlled switching characteristics to new situations from which the case of faults is the most important. It includes also the extreme cases when the zero cross missing of fault currents are experienced in a given network zone.**

The first part of the article is dedicated to the controlled switching state of art review and its perspectives according to the last theoretical and technological developments. The second one present the specific aspects related to the intelligent switching in case of faults.

Keywords: *controlled switching, circuit-breakers, fault detection, short-circuit current displacement.*

1. INTRODUCTION

The benefits of applying controlled switching, in case of normal conditions, are technical and economical. Technical benefits include the switching transients severity reduction as well as their effects on equipment and power systems components life cycle and performance. Economic benefit assessment may be qualitative or quantitative.

The main benefits on the controlled circuit-breaker are the extension of its life, the increase in time intervals between breaker maintenance or retrofit and added value associated with breaker performance enhancement during current interruption in thermal or dielectric zone.

The benefits for the power system and the equipment can be evaluated considering the probabilistic nature of the transient magnitudes which can be obtained following a probability distribution. In this sense, controlled switching is similar to other methods such pre-insertion resistors, pre-insertion inductors and permanent inductors. Other methods are stochastic due to changes in pole spread, random closing instants and associated initial conditions imposed on the transients. Controlled switching yields a probability distribution of operations affected by breaker characteristics such as mechanical scatter, electrical scatter and deviations of timing due to interval between subsequent operations. Deviations in the adjustments made for control voltage and temperature compensation also come into play. The result is a distribution of controlled operations around a target point on the voltage or current wave. According to fig.1, such characteristic can be translated into a probability distribution of currents and /or overvoltages [1].

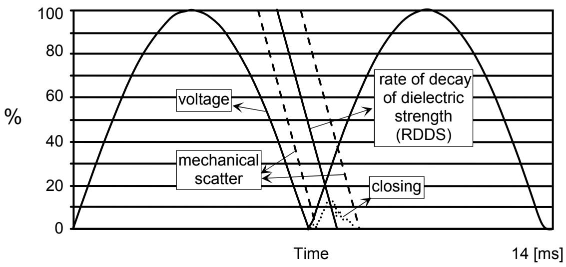

Fig. 1: *Probability* distribution of controlled closing operations around the target for a shunt capacitor bank application

2. SYSTEM COMPONENTS AND THE EFFECTS OF THEIR USUAL SWITCHING

Capacitor banks energisation at a system voltage peak determines excessive inrush currents and overvoltages reaching multiples of the rated values.

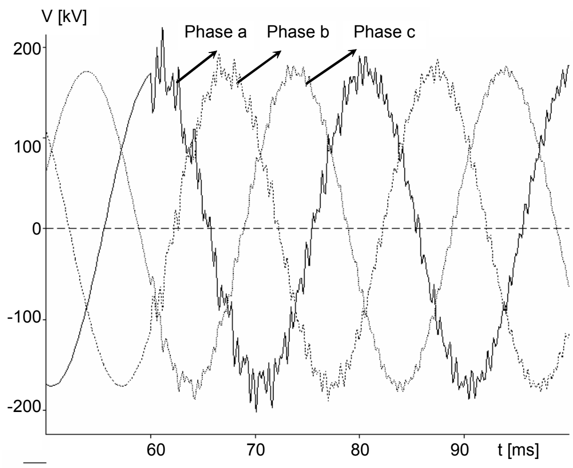

Fig. 2: The transient voltage following uncontrolled closing of a 220 kV unloaded overhead line

The corresponding mechanical and dielectric stresses cause degradation and pronounced ageing of the capacitors.

Under very adverse conditions the capacitors might even be damaged or destroyed.

For unloaded lines, such a *closing* operations leads to severe overvoltages since a voltage wave travels down the line and is reflected at the far end, as shown in fig.2 [2].

Deenergizing capacitive loads might also induce transients which stress the equipment likewise.

Energizing of shunt reactors or transformers at a point on the wave where the voltage is close to zero, causes a large DC component of the current like in fig.3 [2].

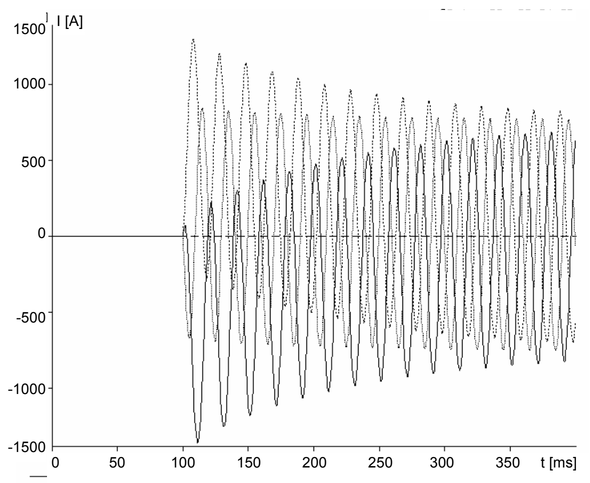

Fig. 3: The inrush currents of a 220/110 kV power transformer due to an uncontrolled switching of the circuit-breaker

The elevated flux density will turn saturate the iron core causing an inrush current which stresses these components.

When breaking inductive loads such as shunt reactors or transformers, the current might be interrupted before the natural zero of the power frequency current. This phenomenon known as current chopping causes overvoltages at the load. The voltage surge might lead to a breakdown of the circuit-breaker's contact gap if the distance between the contacts is not large enough to withstand the dielectric stresses. The subsequent flashover and interruption inevitably causes even larger overvoltages, severely stressing the load.

Table 1 includes the main stresses to be avoided by controlled switching.

As conclusions, there are more useful effects of controlled switching of circuit-breakers from the most important are:

a) technical:

- reduced thermal and electrodynamic stresses of the switched components;
- avoid nuisance relay tripping;
- increase the power quality;
- reduced restrike probability;
- reduced reignition probability, etc.

Load	Operation	Controlled switching	Stress avoided
Inductive	Closing	Closing at voltage peak	Inrush
Capacitive	Closing	Closing at the voltage zero crossing	Inrush
Inductive Capacitive	Opening	Setting of the optimal arcing time	Overvoltage re-strike

Table 1: Specific controlled switching and avoided stresses for different switched components

b) economical:

- increase of switched component life expectancy;
- reduced failure risk;
- reduced maintenance;
- saves closing resistors;
- de-rating of surge arrestors, etc.

3. FROM THEORY TO INDUSTRIAL APPLICATIONS

The above mentioned applications of controlled switching are already transferred to commercially available specific devices [3], [4], and [5]. They are working in power installations in many countries as it is presented in table 2 [6].

Country	1987	1988	1989	1990	1991	1992	1993
Austria	15	1			13	10	
Belgium						2	4
Brazil				1		3	5
Canada			2	1	2		
Denmark		2			13		
Finland		5					
Germany			1		2		
Japan					5	6	
New Zeeland				13			
Norway						2	
Spain			2			4	4
Sweden	4		6	15	25	25	2
Suisse			102	4	4	4	
England					2		
USA						1	
Total	**19**	**8**	**113**	**34**	**66**	**57**	**15**

Table 2: Devices for controlled switching installed in different countries

Most devices are used with dedicated circuit-breakers but the tendency is to use such devices capable to be attached to usual breakers.

3.1. The limits of actual devices for controlled switching and main features of future devices

The devices for controlled switching of circuit-breakers are versatile and their implemented functions consider many parameters influence as presented in table 3 [6].

Parameters	Air blast breakers		SF_6 breakers			
	Open	Close	Hydraulic		Spring	
			Open	Close	Open	Close
Control temperature between -40^0C $+40^0C$	50 $\mu s/^0C$	75 $\mu s/^0C$	30 $\mu s/^0C$	70 $\mu s/^0C$	30 $\mu s/^0C$	70 $\mu s/^0C$
Voltage control between -15% +10%	NA	NA	±0.5 ms	±1.5 ms	±0.5 ms	±0.5 ms
Stored energy available between ±5%	NA	NA	±0.5 ms	-3ms + 2.5 ms	±0.5 ms	-3ms + 2.5 ms
No. of operations	±1 ms	+1.5 ms	±1 ms	±2.5 ms	±1.5 ms	+2.5 ms
Infrequent operation over 10 years life	±1 ms	±1.5 ms	NA	±10 ms	NA	±10 ms

Table 3: Influence of various control and ambient conditions on operating time accuracy

The actual controlled switching devices operate with high voltage circuit breakers *but only* in normal cases: usual manual switching of network components like power transformers, lines, loads, etc. So, the switching over currents and over voltages have minimal values. The influence of the main contacts wearing, environment parameters are considered from mechanical values point of view: switching durations and the corresponding spread.
This kind of devices offer a good opportunity for controlled switching of high voltage single phase operated breakers. For medium voltage the three phases operated breakers need a mechanical delay of them in the case of usual situation when it is necessary to control the capacitor banks switching for transients mitigation.

A new generation of devices for *intelligent switching* of circuit-breakers essentially means:

- intelligent switching of circuit breaker also in the case of network faults;
- a multifunction device for single and three phase operated breakers and for different kind of switched network components like lines, transformers, loads;
- increased artificial bundled intelligence to solve special situations like zero crossing missing inclusively;
- implementation of a fuzzy logic and of an inference engine to allow for a correct operation of the device because, in the normal or fault cases, the switch is governed and influenced by many random variables.

4. INTELLIGENT FAULTS INTERRUPTION

Controlled switching of the circuit-breaker in case of faults is different from the normal situations [6].

4.1. Objectives of controlled switching in case of faults

The concept of using controlled switching for fault current interruption has considerable appeal. The control objective would be to control contact parting time so as to cause a current zero to occur at the beginning of the extinguishing window, such that arcing time and hence the energy generated during arcing is minimized. This could prolong the electrical life of the switching device, possibly increase the interrupting capacity of the switching device, and minimize the thermal requirements for the interrupting chamber and the mechanical requirements for the operating mechanism.
The ultimate objective would be to use an operating mechanism so as to produce an extremely high contact parting velocity such that the contacts can be parted only a few microseconds before a current zero, and clearing occurs at this first current zero. This could permit a very high interrupting capability for a given design.
A high speed operating mechanism to produce the desired contact velocity, and a control scheme such as to control contact parting within microseconds, however, would be a formidable challenge.
A more realizable objective would be to minimize arcing time upon opening, and thereby to extend contacts life, thereby prolonging the inspection periods or reducing the maintenance required following fault current interruption.
Control on closing, might also be desirable to minimize the pre-arcing period such as to reduce contact erosion and damage. To achieve this objective, it would be necessary to control the closing point to a system voltage zero. Unfortunately this would result in

an asymmetrical current when closing into a fault which would be disadvantageous from the standpoint of electromechanical stresses on the switching device and the connected system. It may well be that the problems associated with closing at a time such as to produce asymmetrical currents may out weight the advantages of minimizing contact erosion. It may prove to be of greater advantage to minimize the degree of fault current asymmetry and system stress by closing at or near a voltage maximum recognizing that the typical circuit-breaker will be fault closing as a regular practice, based on typical reclosing sequence utilized by most circuit-breakers.

4.2. Intelligent opening to clear the faults

The general situation of a fault current with zero crossing missing is presented in fig. 4.

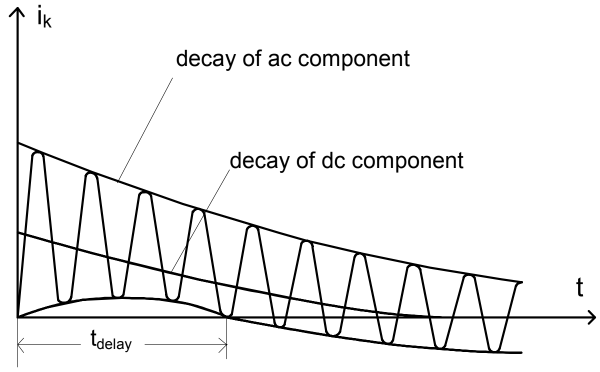

Fig. 4: Typical situation of the short-circuit current displacement

$$i_R=\{[\frac{E_{q0}}{x_d}+(\frac{E'_{q0}}{x'_d}-\frac{E_{q0}}{x_d})\cdot e^{-\frac{t}{T'_d}}+(\frac{E''_{q0}}{x''_d}-\frac{E'_{q0}}{x'_d})\cdot e^{-\frac{t}{T''_d}}]\cdot\cos(t+\theta_0)-[\frac{U_{d0}}{x_q}+(\frac{E''_{d0}}{x''_q}-\frac{U_{d0}}{x_q})\cdot e^{-\frac{t}{T''_q}}]\cdot\sin(t+\theta_0)\}-\frac{x''_d+x''_q}{2\cdot x''_d\cdot x''_q}(U_{d0}\sin\theta_0+U_{q0}\cos\theta_0)\cdot e^{-\frac{t}{T_a}}+\frac{x''_q-x''_d}{2\cdot x''_d\cdot x''_q}[U_{d0}\sin(2t+\theta_0)-U_{q0}\cos(2t+\theta_0)]\cdot e^{-\frac{t}{T_a}} \quad (1)$$

The current displacement is not an usual phenomenon in power systems but there are three cases where it can appear:

a) a finite power source (synchronous generator) having the three phase short-circuit current given by eq. 1 [7] where the a.c. time constant from the subtransient to transient value can be smaller than that of the d.c. time constant; in eq. 1, for the two quadrature axis synchronous generator model, the notations are given in detail in [8] and not on this paper due to the fact they are exceeding its main content;

b) in the case of series compensated power lines;

c) the initial d.c. component amplitude is greater than the ac component, depending on the synchronous machine load before the fault; this is the case of high power generator circuit-breakers.

From the controlled switching point of view, a more detailed analysis has to consider many parameters as it is presented in fig. 5.

An essential condition for a successful intelligent fault interruption is an accurate anticipation of the first zero crossing of the short-circuit current which means mainly to consider the mechanical scatter of the breaker.

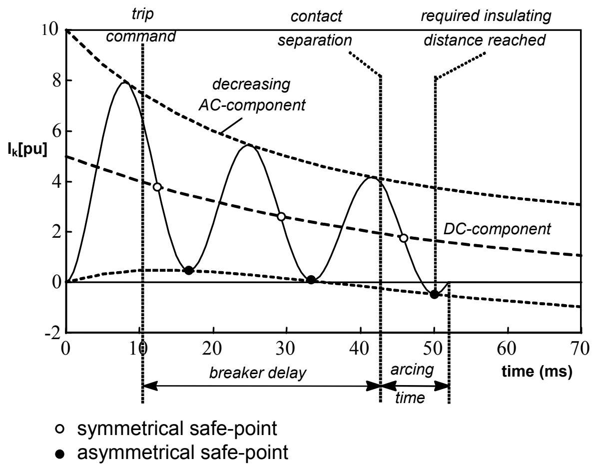

Fig. 5: The main parameters considered in case of intelligent fault interruption

One of the most important problems related to the fault current first zero crossing anticipation is to evaluate the number of measurements on the total fault current wave to optimize the duration – accuracy ratio and, consequently, to be in time with switching command. Theoretical author's studies [7] conducted to the correct answer and conclusions. According to the notations in fig 6, the key elements of the method to solve the above mentioned problems are:

- Δtd, time interval for mechanical breaker opening;

- tn, necessary time interval for data acquisition related to the c.c. fault component with a view to accurately anticipate his evolution for intelligent switch;

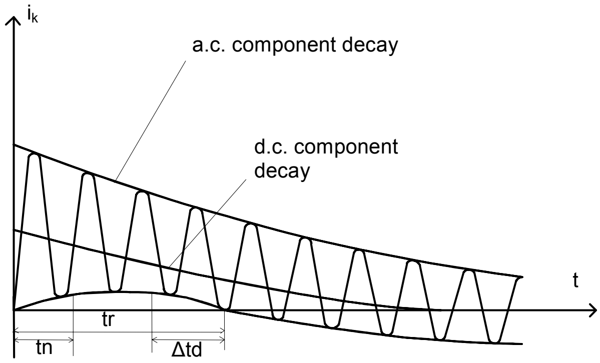

Fig. 6: The key elements to accurately anticipate the first zero crossing in the case of the intelligent fault interruption

- tr, real time estimated for the fault current first zero crossing on that phase;
Zero time is the fault initiation moment.
According to fig.6, the restriction for intelligent breaker switching, neglecting the time for fault initiation detection is:

$$tn + \Delta td \leq tr \tag{2}$$

Considering the possible necessary time interval for fault initiation detection, equation (2) becomes:

$$ti + tn + \Delta td \leq tr$$

Continuous fault current component evolution anticipation and the time of the first time zero crossing of the total fault current are based on the calculation of the parameters of the d.c. component, given by

$$i_a = a \cdot e^{kt}; k < 0 \tag{3}$$

The normal equations system to calculate a and **k** parameters is:

$$\begin{cases} \sum_{i=1}^{n} \log i_{ai} = 0.4343 \sum_{i=1}^{n} t_i \\ \sum_{i=1}^{n} t_i \log i_{ai} = 0.4343 \sum_{i=1}^{n} t_i^2 + (\sum_{i=1}^{n} t_i) \log a \end{cases} \tag{4}$$

Solving equation (4) can be done in an accurate and rapid manner so, the minimum measurements number (n) for a sufficient given accuracy has to be established to calculate **a** and **k**.

A numerical example like in equation (5) was considered to perform a method error analysis.
If we take

$$a = 2.95$$

and

$$k = 38.4615,$$

the c.c. component is given by

$$i_a = 2.95 e^{-100\frac{t}{2.6}} \tag{5}$$

Supposing 1 millisecond as the data acquisition time interval starting with $t_1 = 0.001$ then $t_2 = 0.002$... $t_7 = 0.007$ and using the system given by (4), the c.c. component can be rebuild. Compared to the real component, the errors are presented in table 4.

Number of data acquisitions	Predetermined parameter values		Method errors	
	a	K	a [%]	k [%]
2	3.0380	-58.076	2.955	50.997
3	2.9757	-42.795	0.871	11.267
4	2.9555	-39.2193	0.169	1.970
5	2.9579	-39.3648	0.267	2.348
6	2.9539	-38.6389	0.132	0.461
7	2.9508	-38.5476	0.027	0.424

Table 4: The method errors as a function of the number of measurements

Accepting that the random errors affecting t_i values are negligible with respect of those affecting a_i values, the average error influencing the c.c. component can be evaluated.
For the case given in table 1, the average error is between – 2.576% for two measurements and 0.01% for seven measurements. Generally, the anticipated calculated c.c. component has its first zero crossing in advance that the real one so, the result is conservative.

5. FUTURE WORK AND CONCLUSIONS

For an intelligent opening of circuit-breakers to clear the faults an accurate method to anticipate the first zero crossing of the short-circuit current was presented. The *necessary time* and *prediction accuracy* were balanced and the decision can be made for every given situation.
More details are necessary to be considered specially to make the difference between the faults type. So, the future work should be dedicated to find an extremely rapid detection method of the fault type with a view to select the suitable routine of the intelligent device allowing for a correct fault clearing.
The main conclusions are as it follows:

- controlled switching systems can provide a very effective control of switching surges for different applications;
- actual industrial devices are not designed for fault interruption even they have implemented suitable software to consider the influence of many circuit-breaker, power system node and environment parameters;
- the new generation of the devices for intelligent switching in case of faults has to include:
- increased artificial bundled intelligence to solve special situations like zero crossing missing inclusively;
- a fuzzy logic and of an inference engine to allow for a correct operation of the device because, in the case of faults, the switch is governed and influenced by more random variables.

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