FROM CONTROLLED SWITCHING TO INTELLIGENT SWITCHING

Florin MUNTEANU[1], Dumitru IVAS, Ciprian NEMES
„Gheorghe Asachi" Iasi University of Technology, Romania

1. INTRODUCTION

Synchronous, or controlled, switching of circuit-breakers allows for a higher power quality as well as for reduced re-ignition probability, reduced transients, increased life expectancy or reduced failure risk.

Compared to the actual well known synchronous switching the proposed solution includes a new supplementary and important feature of the corresponding devices: intelligent switching in case of faults by differential detection not only in usual situations but in special cases also like power generator circuit-breakers and the very special case of the longitudinal compensated power lines. In these two situations, the fault current displacement or zero passing missing is possible and the results mean higher stresses for circuit-breaker and network components.

One of the main aspect is related to modern high speed circuit-breakers which are opening before the d.c. component of the short-circuit current is closed to zero. Consequently, the intelligent device attached has to be capable to control the breaker in case of closed located faults, to detect rapidly the fault initiation and its type and, to anticipate, if it will be the case, the fault current first zero crossing.

With a view to assure not only the initial fast detection but also the necessary high accuracy in anticipating the right switching moment for every phase, the intelligent device uses digital and analogues modules respectively.

2. THE LIMITS OF ACTUAL DEVICES FOR CONTROLLED SWITCHING AND MAIN FEATURES OF FUTURE INTELLIGENT DEVICES

The devices for controlled switching of circuit-breakers are versatile and their implemented functions consider many parameters influence as presented in table 1 [1]. 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.

---

[1] *"Gheorghe Asachi" Iasi University of Technology, Faculty of Electrical Engineering,*
Department of Power Engineering
B-dul D. Mangeron no. 51-53, Iasi, code 700050, Romania
Phone: 40 232 278683 ext. 1166
Fax: 40 232 237627
E-mail: flmunt@ee.tuiasi.ro or flmunt@ieee.org

Table 1 Influence of various control and ambient conditions on operating time accuracy [1]

Parameters	Air blast breakers		SF_6 breakers			
	Open	Close	Hydraulic		Spring	
			Open	Close	Open	Close
Control temperature between $-40^{0}C$ $+40^{0}C$	50 $\mu s/^{0}C$	75 $\mu s/^{0}C$	30 $\mu s/^{0}C$	70 $\mu s/^{0}C$	30 $\mu s/^{0}C$	70 $\mu s/^{0}C$
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

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.

3. INTELLIGENT FAULTS INTERRUPTION

Controlled switching of the circuit-breaker in case of faults is different from the normal situations [1].

3.1 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 de 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.

3.2 Intelligent opening to clear the faults

The general situation of a fault current with zero crossing missing is presented in fig. 1.

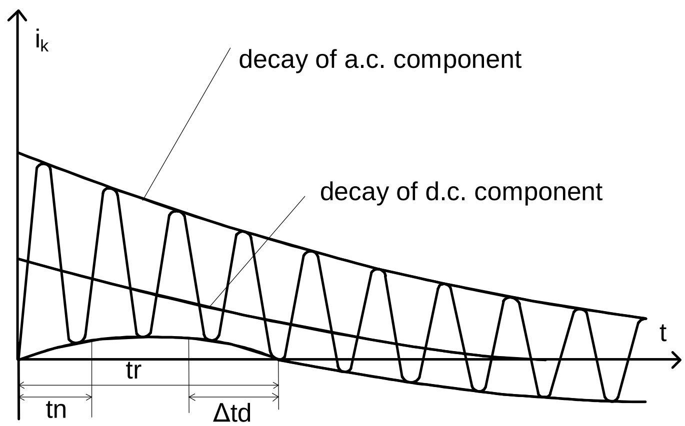

Fig.1 Typical situation of the short-circuit current displacement

3.2.1 The typical situations for fault current displacement

There are following situations

A) The case of a finite power source for which the three phase short circuit on phase a is given by equation (1) according to [2] for a synchronous generator with damping wiring when the time constant of the a.c. fundamental component from the subtransient value to transient and, finally, to new steady state synchronous value can be smaller compared to the time constant of the d.c. component of the short-circuit current.

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

The restriction of A) is expressed by

$$T''_d + T'_d < T_a \tag{2}$$

In [3] is demonstrated that the maxim value of T_a is

$$T_{\max} = \frac{T''_d T_a}{T'_d - T_a} \ln(\frac{x'_d}{x''_d} \cdot \frac{U_0}{U_{q0} + x'_d i_{d0}}) \tag{3}$$

Equation (3) proves that T_{amax} is strongly influenced by the generator operating point before the short-circuit established through the u_{q0} and i_{d0} values of the initial transversal voltage component and the longitudinal current component respectively (the theory of the quadrature axis of the synchronous machine).

The current displacement is severe when the generator operating point before the short-circuit corresponds to a high internal machine angle or to a low value of its magnetic field.

B) In the case of longitudinal compensated power lines [4].

C) The initial d.c. component amplitude of the short-circuit current can exceed the a.c. fundamental component amplitude depending on the generator load before the fault.

The case C) is detailed in the followings.

3.2.2 The differential faults diagnosis

A simplified power circuit like in fig.2 is considered with a view to find out the situations when the initial d.c. component of the fault current is greater then the a.c. component.

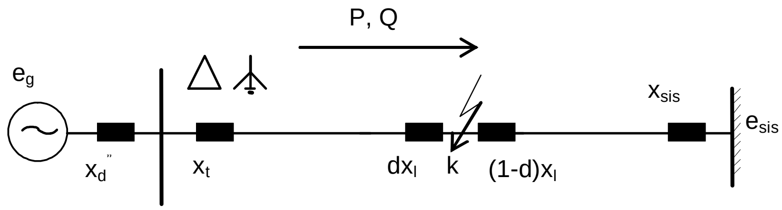

Fig.2 The simplified circuit for fault current displacement analysis

In fig.2 e_g is the machine internal voltage, x_d'' is the machine subtransient direct axis reactance, x_t is the power transformer reactance, d is the fault distance from the source and x_{sis} is the equivalent network reactance.

It was considered also:

$$x_g = x_d'' + x_t + dx_l \tag{4}$$

$$x_s = (1-d)x_l + x_{sis} \tag{5}$$

- the resistances where neglected;
- the voltage at the fault location and before it is 1 pu;
- the fault moment, given by θ, corresponds to the maximum value of the short-current displacement.

For an accurate and fast fault type detection the followings where considered:

- the detection based on a qualitative analysis rather then a quantitative one based on the d.c. components of every phase;
- full independence by the fault moment initiation;
- the primary information taken from the high current transformers (Rogowski coils) [5];

Consequently, the initial values of the d.c. phase fault currents are as presented in table 2 as well as the qualitative conditions for fault current displacements.

Three phase fault

$$i_{dca} = \frac{1}{x_g}\cos\theta \qquad i_{dcb} = \frac{1}{x_g}\cos(\theta - \frac{2\pi}{3}) \qquad i_{dcc} = \frac{1}{x_g}\cos(\theta + \frac{2\pi}{3}) \tag{6}$$

means

$$i_{dcs} + i_{dcb} + i_{dcc} = 0 \tag{7}$$

The line b to line c fault

$$i_{dca} = 0 \qquad i_{dcb} = \frac{\sqrt{3}}{2x_g}\sin\theta \qquad i_{dcc} = -\frac{\sqrt{3}}{2x_g}\sin\theta \tag{8}$$

is defined by the qualitative relations

$$i_{dca} = 0 \quad and \quad i_{dcb} + i_{dcc} = 0 \tag{9}$$

The line a to ground fault type has the initial d.c. phase components as given by eq. (10):

$$i_{dca} = (2KY_g + K_0 Y_g)\cos\theta \qquad i_{dcb} = (K_0 Y_g - KY_g)\cos\theta \qquad i_{dcc} = (K_0 Y_g - KY_g)\cos\theta \tag{10}$$

and is defined by

$$i_{dcb} = i_{dcc} \tag{11}$$

The line b to line c to ground fault has the initial d.c. phase currents:

$$i_{dcs} = (KY_{gg} - K_0 Y_{gg})\cos\theta \quad i_{dcb} = -Y_{gg}(K_0 + \frac{K}{2})\cos\theta + \frac{3}{2}KY\sin\theta$$
$$i_{dcc} = -Y_{gg}(K_0 + \frac{K}{2})\cos\theta - \frac{3}{2}KY\sin\theta \tag{12}$$

and is defined by the qualitative condition

$$i_{dca} \neq i_{dcb} \neq i_{dcc} \tag{13}$$

Table 2 The basis of a qualitative method for fault type detection

	Fault type	The qualitative condition at the fault moment allowing that d.c. component to be greater than the a.c. component		
		Phase a	Phase b	Phase c
1	Three phase	$P^2 + (Q - \frac{1}{x_g})^2 << \frac{1}{x_g}$	$P^2 + (Q - \frac{1}{x_g})^2 << \frac{1}{x_g}$	$P^2 + (Q - \frac{1}{x_g})^2 << \frac{1}{x_g}$
2	Line b to line c	No current displacement	$(P + \frac{\sqrt{3}}{4x_g})^2 + (Q + \frac{3}{4}x_g)^2 < \frac{3}{4}x_g^2$	$(P - \frac{\sqrt{3}}{4x_g})^2 + (Q + \frac{3}{4}x_g)^2 < \frac{3}{4x_g{}^2}$
3	Line a to ground	$P^2 + [Q + Y_g(2K + K_0)]^2 < Y_g^2(2K + K_0)^2$	$[P + \frac{\sqrt{3}}{2}Y_g(K_0 - K)]^2 + [Q - \frac{1}{2}Y_g(K_0 -- K)]^2 < Y_g^2(K_0 - K)^2$	$[P - \frac{\sqrt{3}}{2}Y_g(K - K_0)]^2 + [Q - \frac{1}{2}Y_g(K_0 - K)]^2 < Y_g^2(K_0 - K)^2$
4	Line b to line c to ground	$P^2 + [Q - Y_{gg}\cdot(K_0 - K)]^2 < Y_{gg}^2\cdot(K_0 - K)^2$	$\{P + \frac{\sqrt{3}}{4}KY - (2K_0 + K)Y_{gg}]\}^2 + \{Q + \frac{1}{4}[3KY - (2K_0 + K)Y_{gg}]\}^2 < \frac{3}{4}[K^2Y^2 + (2K_0 + K)^2 Y_{gg}^2]$	$\{P - \frac{\sqrt{3}}{4}[KY - (2K_0 + K)Y_{gg}]\}^2 + \{Q + \frac{1}{4}3KY - (2K_0 + K)Y_{gg}]\}^2 < \frac{3}{4}[K^2Y^2 + (2K_0 + K)^2 Y_{gg}^2$

The notation in the above equations are

$K = x/x_g$; $x = x_g x_s/(x_g + x_s)$; $Y_g = 1/(2x + x_0)$; $x_0 = x_{g0} x_{s0}/(x_{g0} + x_{s0})$; $K_0 = x_0/x_{g0}$

The 0 means the zero sequence.

The equations (7), (9), (11) and (13) allows for a differential diagnosis of faults by qualitative relationship.

There are some ambiguous cases due to the initial voltage phase given by θ. All these are presented in table 3.

Table 3 The initial d.c. component values for some particular θ

		Three phase fault	**Phase b to ground**	**Phase a to ground**	**Phase b to phase c to ground**
θ=0	Phase a	$1/x_g$	0	$Y_g(2K+K_0)$	$Y_{gg}(K-K_0)$
	Phase b	$-1/2x_g$	0	$Y_g(K_0-K)$	$-Y_{gg}(K_0+K/2)$
	Phase c	$-1/2x_g$	0	$Y_g(K_0-K)$	$-Y_{gg}(K_0+K/2)$
θ=π/2	Phase a	0	0	0	0
	Phase b	$3/2x_g$	$3/2x_g$	0	$3/2x_g$
	Phase c	$-3/2x_g$	$-3/2x_g$	0	$-3/2x_g$
θ=π	Phase a	$-1/x_g$	0	$-Y_g(2K+K_0)$	$Y_{gg}(K_0-K)$
	Phase b	$1/2x_g$	0	$Y_g(K-K_0)$	$Y_{gg}(K_0+K/2)$
	Phase c	$1/2x_g$	0	$Y_g(K-K_0)$	$Y_{gg}(K_0+K/2)$
θ=3π/2	Phase a	0	0	0	0
	Phase b	$-3/2x_g$	$-3/2x_g$	0	$-3/2x_g$
	Phase c	$3/2x_g$	$3/2x_g$	0	$3/2x_g$

To preserve the method accurate, collecting information about the symmetrical current components is strongly necessary (indices +, - and 0 refers to the positive, negative and zero sequence respectively):

$$I_+ = i_- = i_0 = 0 \quad (14)$$

for the line to ground fault type,

$$i_+ + i_- = 0 \quad (15)$$

for line to line fault type

$$i_0 = 0 \text{ and } i_- = 0 \quad (16)$$

for three phase fault type.

Attaching the conditions expressed by eq. (14), (15) and (16) the above mentioned method can accurately detect the fault type and provide necessary information for the intelligent device to control the circuit breaker with a view to clear the short-circuit.

This original method conducted to a hybrid structured relay presented in fig. 3.

3.2.3 Anticipating the first zero crossing of the fault current

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.

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 conducted to the correct answer and conclusions. According to the notations in fig.1, 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;
- tr, real time estimated for the fault current first zero crossing on that phase;

Zero time is the fault initiation moment.

According to fig.1, the restriction for intelligent breaker switching, neglecting the time for fault initiation detection is:

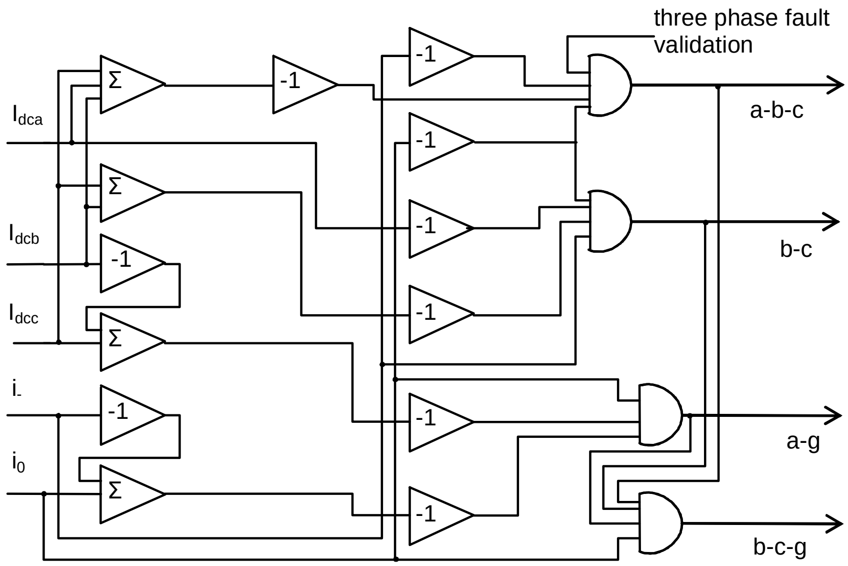

Fig.3 The principle of a hybrid structured relay for fault type detection

$$tn + \Delta td \leq tr \quad (17)$$

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 c.c. component, given by

$$i_a = a \cdot e^{kt}; k < 0 \quad (18)$$

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

$$\begin{cases} \sum_{i=1}^{n} \log i_{ai} = 0.4343 \sum_{i=1}^{n} t_i \\ \sum_{i=1}^{n} t_i \log i_{ai} = 0.4343 \sum_{i=1}^{n} t_i^2 + (\sum_{i=1}^{n} t_i) \log a \end{cases} \quad (19)$$

Solving equation (19) 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 (20) 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

$$i_a = 2.95 e^{-100\frac{t}{2.6}} \quad (20)$$

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 (19), the c.c. component can be rebuild. Compared to the real component, the errors are presented in table 4.

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

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

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 4, 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.

4. CONCLUSIONS

The main conclusions are:
- 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.

Methods for detecting the fault type and to anticipate the first zero crossing of the fault current in every phase were presented.

5. ACKNOWLEDGEMENT

This paper is a part of the work and research developed in the frame of the Phase I of the grant no. 607/2005 financed by Romanian National Authority for Scientific Research.

LIST OF REFERENCES

1. *** CIGRE Task Force 13.00.1 of Study Committee 13 “Controlled switching - A state-of-the-art-survey”. ELECTRA review nr. 163, December 1995, pg. 34-39.
2. Fl. Munteanu, D. Ivas, C. Nemes “Power Plants – Electrical Part. The Short-Circuit Phenomenon Analysis” Ed. SETIS, Iasi, Romania. ISBN 973-86764-6-0, pgs. 104-109 (in Romanian).
3. *** Brown-Bovery Review no.5, May 1974, tome 61, pg. 199.
4. B. Khodabakhchian, S. Breault, E. Portales, H. Huynh, Y. Hotte “ TRV and The Non-Zero Crossing Phenomenon in Hydro-Quebec’s Projected 735 kV Series Compensated System. Proceedings of CIGRE Session, Paris, August-September, 1992.
5. Fl. Munteanu, D. Ivas “Techniques for fault type diagnosis in high voltage networks”. Energetica Review, no. 6-7, 1990 (in Romanian).