EMTP Model for Controlled Switching Simulation by Means of a TACS Routine

R. Rocha
Cia Hidro Elétrica do São Francisco
Rua Delmiro Gouveia, 333, Bongi
Recife - PE 50761 - 901 Brazil

J. L. Távora
Departamento de Eletrônica e Sistema
Universidade Federal de Pernambuco
50.740-530 Recife- PE Brazil

Abstract - **This paper describes a model developed for the EMTP program to simulate controlled switching for the purpose of network studies. The model implements scatter of circuit breakers as well as the imprecision of the optimum time to controller used for switching. By means of this new model it is possible to consider also the pre-strike voltage characteristic of circuit breakers. Its representation by EMTP program was made through TACS (Transient Analysis of Control Systems), which allows to simulate the dielectric characteristic of circuit breakers during closing operations. The new model developed, which includes the gap characteristic and offers the possibility of more precise assessment of the performance of circuit breakers. This shows the benefit brought to the control switching.**

Keywords: Transmission Line, Transient Analysis, Modelling, EMTP, Controlled Switching, Shunt Capacitor Bank.

I. INTRODUCTION

Stress on high voltage installations caused by both transient overvoltages and inrush current from switching operations are today well known and understood. The most common ways known to reduce stress on circuit breakers(CB) and other electrical system equipment are the overvoltage suppression by both zinc oxide arresters and opening/closing of resistors. However, the acceptance of the latter ones by the utilities is decreasing as field experience indicates insufficient reliability[1,2,3].

Theoretically the transients provoked by energizing and de-energizing shunt capacitor banks and no load transmission lines could be suppressed if it were switched at voltage zero across circuit breaker. In practice, some deviation exists due to the optimum point of wave for switching as a result of variations in contact travel time and contact dielectric withstand strength of circuit breaker, and the controller scatter to switch at an instant chosen by algorithm as the switching target as the optimum switching instant.

A very powerful manner to reduce the stress caused by switching operations is closing or opening by point on wave control. Positive experiences in field tests have been registered some years ago with a simple synchronisation device, used for controlling switching shunt capacitor banks in a low high voltage range[4]. The controller is responsible for adjusting the equipment automatically selecting the optimum instant of switching.

The controller is normally an electronic device which is connected to perform the switching operation at optimum point on the wave where there is a minimum switching stress. The operating principle of the controller is generally known as the pattern of signal used as reference to point on wave, which allows the prediction of optimum target for circuit breaker. The precision of this procedure is rather dependent on the accuracy of the signal evaluation, which can been related to the complexity of voltage and the current signal that appears at the breaker location[5,6].

For controlled switching the statistical modelling of the controller and the breaker scatter are essential. The evaluation of the precision of the controller is made by determination of the switching scatter at the instant chosen by a algorithm, when the optimum switching instant occurs.

The circuit breaker itself is characterised by its voltage characteristics of the gap for closing operations as well as for its mechanical accuracy. Thus the voltage withstand characteristic for closing operations ($du/dt|_{CB}$) will preferably have a higher steepness when compared with the network voltage at zero crossing. In reality, the mechanical spread and the actual (du/dt) of the circuit breaker will occur within a pre-strike voltage range where the pre-strike phenomenon will really occur.

The adoption of new solutions which affect the switching surge performance of the network call for a careful analysis of its impact.

In the first instance simulations are preferred as instruments of analysis, due to its simplicity and low associated cost. However, care must be taken to assure that the accuracy of the simulation studies, which depends strongly on the modelling adopted. This paper describes the model developed by EMTP program to simulate the behaviour of the controlled switching(controller + breaker) for network study purposes. The model implements the circuit breaker mechanical scatter as well as the controller imprecision to foresee the target for the switching which are represented by two independent Guassian distributions respectively.

By means of this new model the circuit breaker pre-strike voltage characteristic is also considered. Its representation in EMTP is made by means of TACS routine. The closing switching in that moment occurs only when the voltage across the breaker chamber is higher than the voltage withstand characteristic of the breaker(assumed to be linear for simplicity).

II. CONTROLLED SWITCHING OF CIRCUIT BREAKER DURING CLOSING OPERATION

For illustration, let us consider a three phase shunt capacitor bank with neutral grounded. In order to avoid overvoltage, the energization must be carried out when the voltage is passing through is zero. The dielectric withstand characteristic of the gap of the circuit breaker is supposed to be in straight line defined by Us(t). The withstand tangent(dUs/dt) curve to be preferably equal or higher than voltage tangent($dU/dt\,|_{t=0}$) curve of system at instant zero is a condition for reduce the stress caused by energizing shunt capacitor bank.

As consequence of the scatter cited previously, the withstand curve should be represented within a range of ± DT, i. e., the system voltage may be exceeded between the instants A and B, taking into consideration the dielectric withstand of the circuit breaker gap. In fact, this means that the values of pre-strike voltages (Ua, Ub) may be quite different from each other in subsequent half cycles, as shown in Fig. 1, which may cause severe overvoltage.

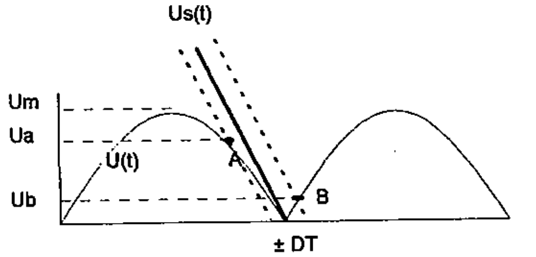


Fig.1: Pre-strike interval A-B caused by influence of mechanical precision of the circuit breaker for closing operations

In order to get equivalent pre-strike voltage in subsequent half cycles, it is necessary to adopt a time delay "td" with respect to the system voltage zerocrossing, as shown in Fig. 2. Considering those assumptions, the maximum pre-strike voltage, which will cause overvoltage, is defined as a fraction(γ) of the peak voltage Um.

Analytically, for reduce overvoltage due energization we should have the following:

A. Condition $dUs/dt \geq dU/dt\,|_{t=0}$

$$\frac{dUs}{dt} = k \cdot \frac{dU}{dt}\bigg|_{t=0} = k \cdot \omega \cdot Um \quad (1)$$

Um is the voltage peak for the pole in question.

From geometric relation between elements of Fig. 2 and equation (1) it is possible to determine which values of td and DT are necessary for the desired value of γ.

Then:

$$\gamma \cdot Um = Umsin(\omega \cdot DT) \quad (2)$$

$$\frac{dUs}{dt} \cdot td = \gamma \cdot Um \quad (3)$$

To obtain the maximum pre-strike γUm given by:

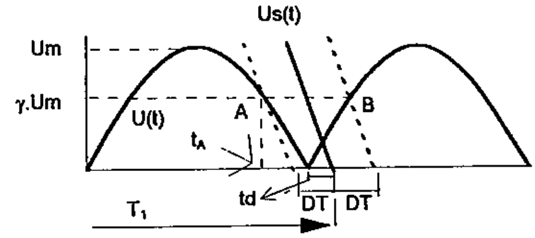


Fig. 2. By controlled switching energizing of a capacitor bank, the pre-arcing voltage is limited to γU_m

$$\gamma \leq sin(\omega \cdot DT) \quad \text{or} \quad DT \leq \frac{arcsen\,\gamma}{\omega} \quad (4)$$

From the above equations, we take the value td

$$td = \frac{\gamma}{\omega \cdot k} \quad (5)$$

B. Condition $dUs/dt < dU/dt\,|_{t=0}$

In this case it is necessary a little more complex solution to obtain the td value. At the correspoding time to point "A"(according Fig. 2), the value t_A may be found by making the withstand tangent curve(dUs/dt) equal to the voltage tangent curve ($dU/dt\,|\,t=t_A$) of system, as shown :

$$t_A = \frac{arccos(k)}{\omega} \quad (6)$$

Since the t_A value is obtained, the value of td may be found by following one of these conditions:

1) Condition $t_A > T1 - DT$

The value of td is given by:

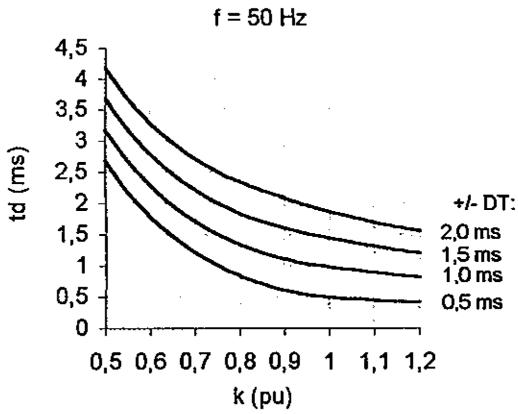
$$td = \frac{\sin(\omega . t_A)}{\omega \cdot k} - t_A + DT \quad (7)$$

2) Condition $t_A < T1 - DT$

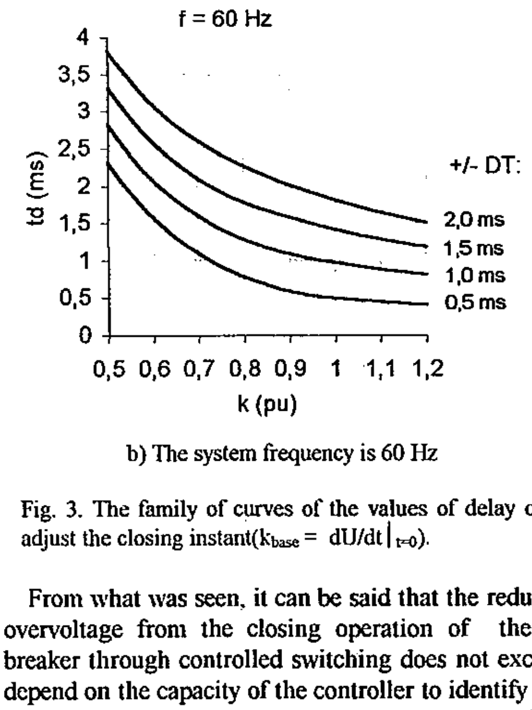
This case the value of td is same as that given by equation (5)

$$td = \frac{\gamma}{\omega \cdot k}$$

The values of delay to adjust the closing instant(td) may be obtained of family of curves as shown in Fig. 3. As can be observed the pre-strike voltage γUm is a function of system frequency, constant *k*, which in turn is a function of the variation rate of closing dielectric withstand of circuit breaker. The delay to adjust the closing instant of circuit breaker is a function of the rated voltage, the number of chamber per pole, the speed of closing and system frequency. Fig. 4 represents a family of curves of the maximum voltage versus the decay rate of dielectric withstand.



(a) The system frequency is 50 Hz



b) The system frequency is 60 Hz

Fig. 3. The family of curves of the values of delay of adjust the closing instant($k_{base} = dU/dt|_{t=0}$).

From what was seen, it can be said that the reduction of overvoltage from the closing operation of the circuit breaker through controlled switching does not exclusively depend on the capacity of the controller to identify all zero crossings of pre-switching voltage. This reduction is also a function of the circuit breaker characteristic.

III. EMTP MODEL FOR CONTROLLED SWITCHING SIMULATION

The simulation of the controlled switching the statistical modelling of the controller and circuit breaker scatter has been curried out in the program EMTP by means of statistical switches, one being "slave" of the other. One is used to represent the scatter of the controller and the other, the main contact of circuit breaker. It is not represented the circuit breaker dielectric characteristic during open and closing operations(statistical model)[6,7].

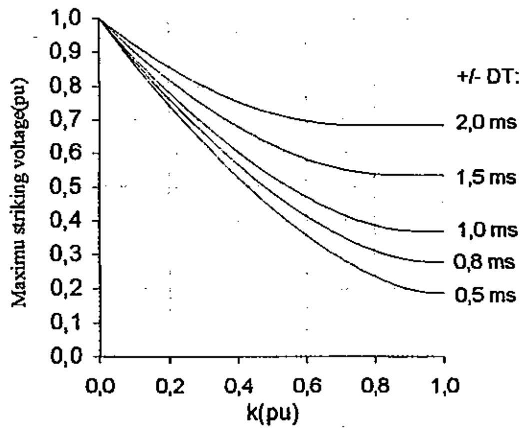


Fig. 4. Maximum striking voltage as a function of decrease of dieletric strength and closing tolerance of circuit breaker[4].

As was mentioned before to carry out simulation of controlled switching it is necessary to reproduce two important aspects: the scatter of optimum instant of switching due to inherent imprecision from operation circuit breaker and the controller, and the withstand dielectric characteristic gap between the contact of circuit breaker during the operation which was developed by TACS. In a specific case under analysis, the developed routine would be applied only to the closing condition. Fig. 5 illustrates the connections for carrying out these simulations(TACS model).

The working principle of this routine is fundamentally associated to the definition of closing instant of the statistical switches whose role is to reproduce the scatter and imprecision in circuit breaker operations and the controller.

To implement the above scatter, it is necessary to define two statistical switches. The switch s_1 is an independent one. It informs the average value of was simulated closing instant of circuit breaker(t_m) and the standard deviation and the switch s_2(dependent). It must only supply the standard deviation referent to the imprecision of the controller. Fig. 6 shows the definitions of closing instants to statistical switching.

The value of t_m is obtained from:

where:

$t_c = DOP \div DUDT$;

DOP: The circuit breaker voltage withstand characteristic considering full open position;

$$t_m = z_0 + td - t_c,$$

DUDT: The slope of voltage withstand of contact gap breaker during closing operations;

td: correction of optimum instant of closing which changes in function of the rated voltage, number of chambers per pole, the closing speed of circuit breaker and the frequency system, according to equation (5);

z_0: instant of system voltage zero-crossing which must be established in simulation carried out previously.

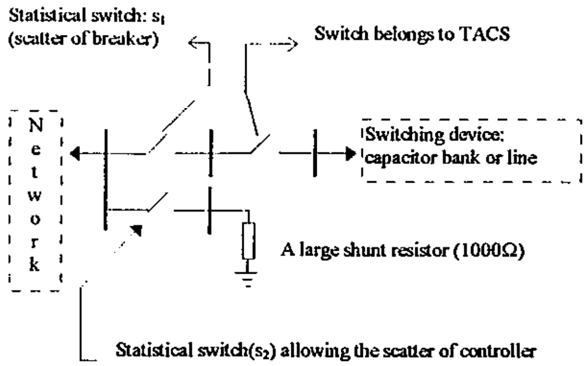


Fig. 5. The connection scheme presents the controlled switching simulated using TACS.

Taking as an example a line out-reclosing on Fig. 7 shows a graph that illustrates the proposed working simulation of controlled operation switching.

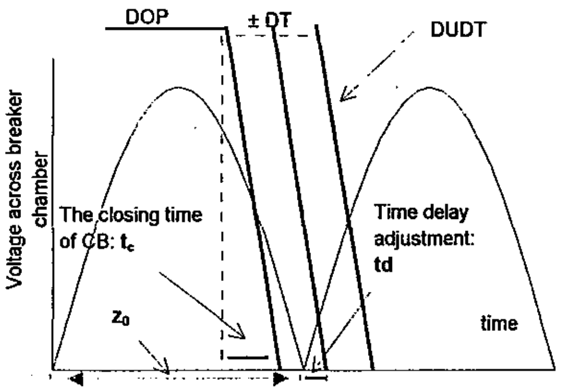


Fig. 6: Influence of mechanical precision on real pre-strike

IV. ANALYSIS OF THE BEHAVIOUR OF THE ROUTINE: EXAMPLE CASES

To estimate the behaviour of the algorithm of the routine two example cases of controlled switching previously simulated were reproduced only with statistical switches: out-reclosing transmission line and shunt capacitor banks.

A. *Out-reclosing transmission line compensated*

For simulation of the out-reclosing transmission line of a radial system of about 700km in 500kV was utilised with two intermediary substations. The line was 70% compensated and it has surge arresters in the terminals. The system frequency is 50Hz.

For this system the following instant were selected: z_0 = 53.7ms to phase R, z_0 = 52.35ms to phase S and z_0 = 51.75ms to phase T. As shown in Fig. 8, these moment correspond to all zero-crossing voltages in three phases through the poles of the circuit breaker in an appropriate condition.

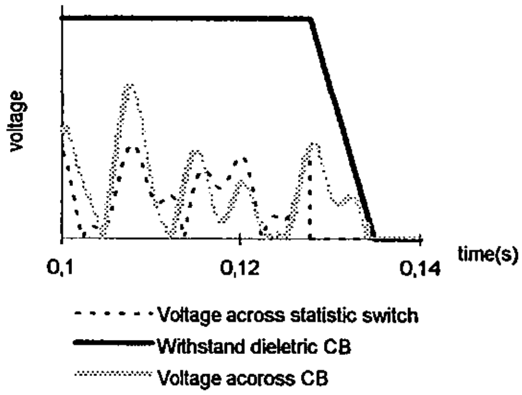


Fig. 7. The out-reclosing line with controlled switching

The circuit breaker of the system has two chambers with the closing speed of 170kV/ms and the standard deviation operation time scatter is 0.35ms(σ_{CB}). The standard deviation adopted for the controller was 0.6ms($\sigma_{Contr.}$) [6]. Then the value of delay to adjust the closing instant (td), obtained through equations of item II is 0.7ms, as can be observed below:

$$DT = (2.5\sigma_{Equivalent})\frac{1}{2} = 0.87ms \quad \text{where,} \qquad (6)$$

$$\sigma_{Equivalent} = \sqrt{\sigma_{CB}^{2} + \sigma_{Contr.}^{2}}$$

From equation of item II, we take the value td

$$td = \frac{Um \cdot sin(\omega \cdot DT)}{dUs/dt} = 0.71ms \qquad (7)$$

In this way, considering 1225kV as dielectric withstand for circuit breaker completely open(DOP), the values of the average instant of closing in three phases are:

phase R:
t_m = 0,05370 + 0,0007 - 1225/170.000 = 0,04729 [s]
phase S:
t_m = 0,05235 + 0,0007 - 1225/170.000 = 0,04584 [s]
phase T:
t_m = 0,05175 + 0,0007 - 1225/170.000 = 0,04524 [s]

It was carried out one hundred line out-reclosing events considering the last segment of the simulated system. The obtained simulation results at the receiving end worked out the following overvoltage: maximum value - 1.8pu; average value - 1.7pu; and the standard deviation - 0.02256pu. Fig. 9 shows the curve of accumulated probability of values expected in receiving end of the line for two types of modellings(TACS and statistical switch). Observe that the values referred to simulations only with statistical switches show slightly lower values(maximum values 1.75pu, average values 1.67pu deviation and the standard deviation 0.06371pu).

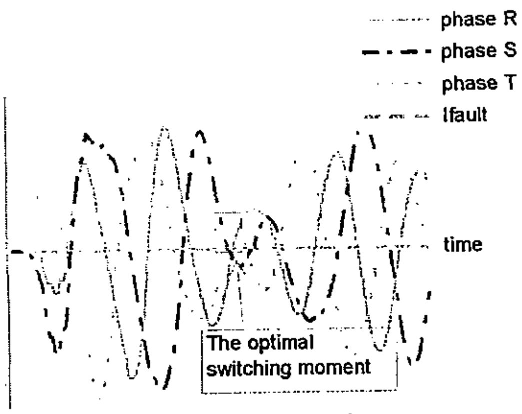


Fig. 8: Voltage across the breaker

The values of obtained overvoltages, measured at 75% from sending end, show a big difference between two types of simulations as can be seen below:

Model	V_{max}(pu)	V_{mean}(pu)	σ(pu)
TACS	2,00	1,80	0,0693
Statistic.	1,75	1,65	0,0146

Fig. 10 shows the curve of accumulated probability of expected overvoltage for two types of modelling, namely, TACS and statistical switch ones. Note that the measured point was located at 75% from the sending end.

In simulation with the TACS model, the closing instants are defined by comparison between the dielectric withstand gap and the voltage across the circuit breaker contacts. On the other hand, in the statistical simulation the closing instants are defined by the scatter of both circuit breaker and controller operations. The latter occurs independent of what happens after closing of the first circuit breaker pole. In the TACS model the closing of second and third pole vary in function of the behaviour of its respective voltages.

To evaluate the difference between utilised modellings, in Table 1 a comparison is shown among the closing instants of each modelling(100 events). Fig. 11 shows a graph of the line out-reclosing.

It can be observed that for two simulations that phase T closes first, but with an average closing instant higher than 0.604ms which represents the value voltage through circuit breaker nearly 8 times above in relation to simulation with statistical switches only, however for statistical simulations the average closing instant corresponds to 9.4kV(2.5% in base of 550 x √2/√3kV) and for simulation with the TACS corresponds to 75.6kV(16.8% in base of 500 x √2/√3kV).

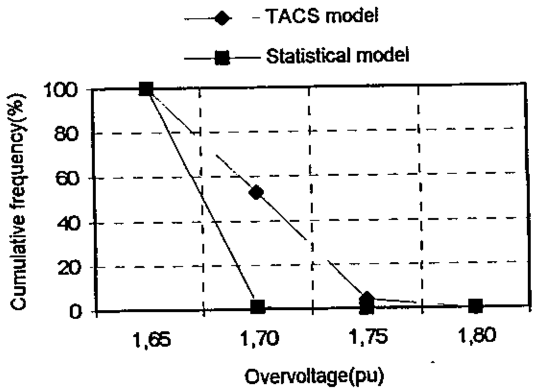


Fig. 9: The out-reclosing line(receiving end)

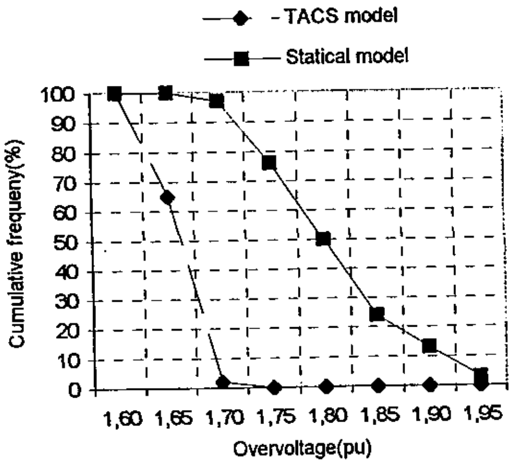


Fig. 10: The out-reclosing line(75% from sending end)

Model	Phase	Instants of closing(ms)			
		Minimum	Maximum	Mean	σ
TACS	R	53.30	56.80	54.61	0.707
	S	51.60	54.90	53.21	0.679
	T	50.70	54.20	52.43	0.690
Statistic.	R	50.75	56.02	53.78	0.972
	S	49.77	54.58	52.17	0.838
	T	49.28	54.28	51.83	0.919

Table 1: The out-reclosing lines instants closing

If a comparison were made with the results of overvoltages, it can be concluded that for out-reclosing of compensated line the statistical simulation shows optimistic values in relation to the simulation of TACS routine.

B. Energization of shunt capacitor bank

The case analysed refers to a shunt capacitor bank of 50.5MVAr in 230KV with grounded neutral and the system frequency is 60Hz. Considering the same procedure for previous simulations and considering that circuit breaker to be used is one that has a chamber with the same considered characteristic in case of line out-reclosing and the standard deviation of the scatter of controller is 0.15ms. Taking the optimum instants closing as indicated below, it can be seen:

phase R:
$t_m = 0{,}0125 + 0{,}0004 - 375.5/88{,}35 = 0{,}008649$ [s]
phase S:
$t_m = 0{,}00972 + 0{,}0004 - 375.5/88{,}35 = 0{,}005874$ [s]
phase T:
$t_m = 0{,}006945 + 0{,}0004 - 375.5/88{,}35 = 0{,}003099$ [s]
Fig. 11: The line out-reclosing

The resulting overvoltages from two controlled switching model by TACS routine and statistical switch are as near as can be seen in registered values below: Fig. 12 shows a graph the shunt capacitor bank energization.

Model	V_{max} (pu)*	V_{mean}(pu)*	σ(pu)*
TACS	1.40	1.19	0.0697
Statistic. switch	1.45	1.27	0.0714

* -The base voltage: $230 \times \sqrt{2}/\sqrt{3}$kV

V CONCLUSIONS

The new developed model which includes the gap dielectric characteristic offers the possibility of assessing the performance in a more precise way, this results in additional benefits for circuit breaker analysis using controlled switching techniques

Concern the results obtained it is possible to conclude that the controlled switching simulation from statistical switch to line out-reclosing introduce optimistic values in comparison with modelling from that developed by TACS routine. This occurs because on the statistical modelling the closing instant is previously defined, which not happen in TACS modelling. This difference in relation to subsequent closing of phase does not exit during simulated energization of shunt capacitor bank with grounded neutral.

These conclusions need a higher number of applications to be consolidated as well as to reproduce the tested conditions in the TNA(Transient Network Analyser), with presence of a controller or even values obtained from field tests.

This routine was developed to control switching of closing, but to make it applicable for the opening operations small adaptations are needed.

It is important to note that the TACS modelling will be enhanced, i. e. performed in a more realistic way, as the variation of the circuit breaker dielectric withstand, with respect to its scatter, being implemented.

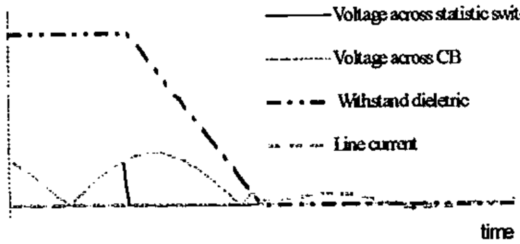


Fig. 11. The line out-reclosing

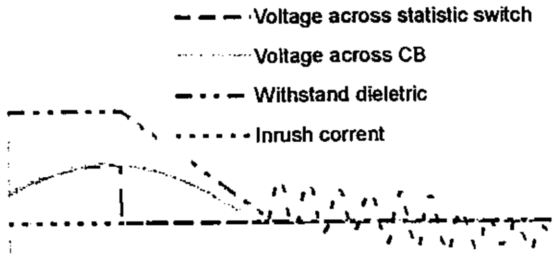


Fig. 12. Capacitor bank energization

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