Controlled Switching Based on the Injection Method

C.D. Tsirekis, N.D. Hatziargyriou, B.C. Papadias
Electric Energy Systems Laboratory
Department of Electrical and Computer Engineering
National Technical University of Athens, Greece
9 Heroon Polytehniou Str., 15773 Zografou, Athens, Greece
tsirekis@power.ece.ntua.gr, nh@power.ece.ntua.gr

Abstract - **Fundamental requirement for all controlled switching applications is the precise definition of the desired switching times. This can be achieved by exhaustive simulations using for each network transient simulation programs like EMTP/ATP. In this paper a new methodology is proposed, based on the "Injection Method", that eliminates the need for exhaustive simulations by calculating the exact transient voltage or current expressions in parametric form. Circuit-breaker's statistical characteristics, like contact operation time scatter and deviation of the slope of the contact gap voltage withstand characteristic are taken into account in this method.**

Keywords: Controlled Switching, Switching Transients, Optimum Switching Instant, EMTP, Circuit-Breaker.

I. INTRODUCTION

Controlled switching is a technique that automatically adjusts the circuit-breaker mechanism in such a way that switching operation takes place at a point-on-wave which minimizes switching transients, such as the phase-to-earth overvoltage, the inrush current and the transient recovery voltage (TRV) across the breaker poles [3, 8].

One of the most significant requirements for proper controlled switching porformance is to reduce the statistical variations of contact operation times. Circuit-breaker technology has improved these statistical scatters, allowing thus utilities and manufacturers to achieve contact operation times quite close to the preferable ones. This means that a precise definition of the desired switching times is required. This can be achieved by exhaustive simulations using for each network transient simulation programs like EMTP/ATP [3]. This procedure is imposed by the necessity of the investigation of the effects of parameter changes (such as the trapped charge in a capacitor bank or the impedance of a load) and the circuit-breaker characteristics (such as the statistical variations of the contacts operating times and the contacts gap characteristic of dielectric strength) on the optimum switching instant.

In this paper a new methodology is proposed, based on the "Injection Method", that overcomes these problems. The basic principle is the calculation of the exact transient voltage or current expressions in parametric form, as functions of the switching instants and the network parameters. Circuit-breaker characteristics, such as contacts gap voltage withstand characteristic and variations in contacts operating times are considered. With the aid of arithmetic techiques, the extrema of these functions as well as the values of the switching instants and the network parameters for which these extrema occur, can be easily calculated.

A series of study cases has been carried out for the implementation of the method. It includes simple network configurations, for the easy confirmation of the accuracy of the results. In all cases the optimum switching instants are calculated using exchaustive EMTP simulations and the Injection Method and a comparison of the results is carried out.

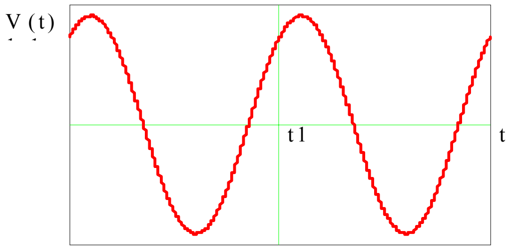
II. THEORETICAL ISSUES

A. Injection Method

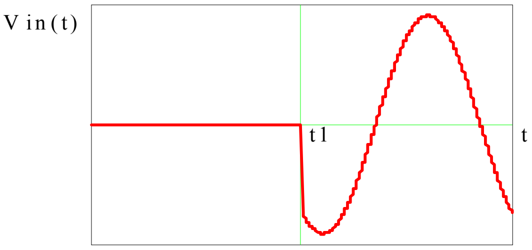
Injection method is the generalization of the already known "Current Injection Method" [1, 2], which is based on superimposition theorem and has been used for the calculation of transient currents and voltages in switch opening cases, especially single-phase ones. The generalized Injection Method is also applicable to switch closing cases. Furthermore, modern computer facilities allow the performance of the necessary calculations in a systematic way, making Injection Method a suitable mean for three-phase calculations, not only for closing or opening cases, but also for more complicated switching scenarios, like auto-reclosing.

In closing cases Injection Method calculates the transient voltages and currents produced when a voltage Vin, with equal magnitude and opposite polarity to the one appearing across the open poles of the switch just before the closing instant, is imposed, resulting in elimination of the voltage across the switch just after the closing instant. With the assumption that the network elements are linear, this elimination can be simulated with the injection of Vin to the switching point at the switching instant. In Fig. 1 it is shown how the actual voltage can be obtained by the superimposition of the voltage Vin to the initial one to be eliminated.

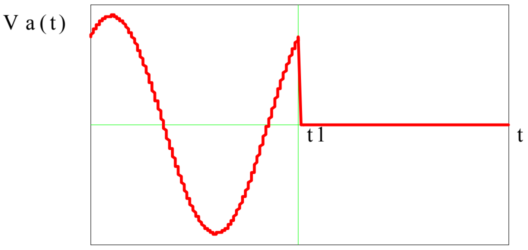
Similarly, in opening cases Injection Method calculates the transient voltages and currents produced when a current Iin, with equal magnitude and opposite polarity to the one flowing through the closed poles of the switch just before the opening instant, is imposed, resulting in elimination of the current through the switch. Assuming again that the network elements are linear, this elimination can be simulated with the injection of Iin to the switching point at the switching instant.



(a) - Initial voltage V(t)



(b) - Injected voltage Vin(t)



(c) - Actual voltage as the result of superimposition of Vin to V

Fig. 1. Diagrams illustrating the Voltage Injection Method in a case of switch closing at the instant t=t1

B. *Optimum Switching Instant.*

The definition of what "Optimum Switching Instant" means in this method is of great importance. The significance of this definition is necessary if it is clear that the switching instant which leads to the minimization of a resulting voltage or current of interest somewhere in the network, may be more or less different from the switching instant which leads to the minimization of interesting voltages and/or currents at the same or at other network locations. Furthermore, the total number of three-phase switching operations in each application, considering the opening or closing of each pole as separate switching operation, is usually not less than three and therefore the optimum switching instant for one switching operation may refer to a different point-on-wave than the optimum switching instant of other operations. Therefore, we have to talk about *optimum switching instant combination* rather than optimum switching instant. This is defined as the combination of instants corresponding to the respective points-on-wave, so that when each switching operation takes place, the following objective function is minimized:

$$A(\mathbf{t_0}) = \sum_i X_i \cdot V_i^2(\mathbf{t_0}) + \sum_j Y_j \cdot I_j^2(\mathbf{t_0}) \qquad (1)$$

where V_i and I_j the interesting p.u. voltages and currents to be controlled, X_i and Y_j the respective user-defined weighting factors which determine the degree of significance of each controlled quantity and $\mathbf{t_0}$ the vector of the switching instants for each operation. The solution of the problem of minimization of the above objective function is achieved arithmetically for a large number of possible switching instants combinations over a user-defined range of values of $\mathbf{t_0}$ elements.

Statistical distribution of controlled circuit-breaker characteristics makes the problem of investigation of optimum switching instants combination much more complicated [3, 8]. The way these statistical characteristics are taken into account in the proposed method for closing or opening cases, is described in the next paragraphs.

1) *Closing*

In most cases the closing switching instant (named *making instant*) does not coincide with the instant of mechanical closing of the circuit-breaker contacts (*target instant*). Making instant is determined by the intersection of the waveform of the voltage across the circuit-breaker contact and the contact gap dielectric strength characteristic, the rate-of-decay of which (RDDS) is infinity only in ideal (and thus non-actual) switches. Statistical deviations of the operating time (the time interval until the initiation of contact movement), the contact velocity and the contact gap dielectric strength affect the target instant and the slope, resulting in a parallel shifting to both sides of the voltage withstand characteristic and a deviation of its slope [3, 4, 7, 8]. Thus, instead of a simple making instant and the respective target instant, it is more realistic to talk about a "window" of making instants and the respective target instants, as illustrated in Fig. 2 [3]:

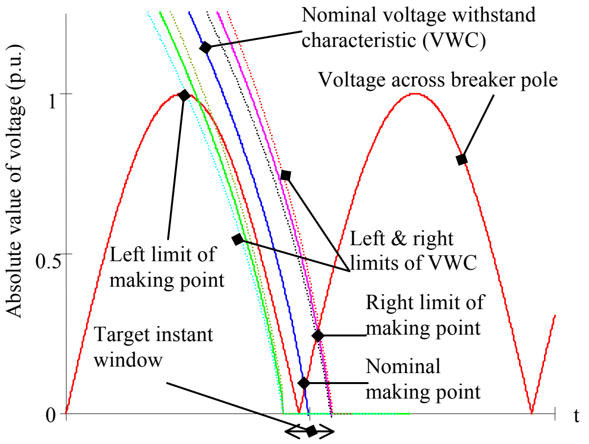


Fig. 2. Diagram illustrating the making instant window for a case where target instant corresponds to zero voltage.

For each target instant window combination for all closing cases (including the individual poles closing of the same circuit-breaker), a maximum value of $A(\mathbf{t_0})$ is obtained, named *Am*. The optimum target instant window combination results arithmetically from the minimum *Am* of all possible target instant window combinations. Note that the procedure is quite complicated because of the possible dependence of waveforms of the voltages across the circuit-breaker poles from the target instants of previously closed poles, as it may occur in systems with ungrounded neutral.

2) Opening

Similarly to closing, the switching instant in opening cases (named breaking instant) does not coincide with the instant of mechanical separation of the circuit-breaker contacts (here this is the target instant). Breaking instant is either the instant of the next physical zero current or the instant of a possible current chopping. Current chopping complicates the problem, because theoretically it may occur at any current level, especially in vacuum circuit-breakers [5, 6]. Assuming for simplification that arc extinguishing at physical zero current is equivalent to a zero current chopping, it is assumed that current chopping will occur in any case.

Current chopping leads to higher overvoltages than those resulting from breaking at a physical zero current. However, bibliography shows [5, 6, 7, 8] that current chopping is rather less severe for dangerous overvoltages than reignitions. Therefore, the basic principle for controlled opening is the avoidance of reignitions.

Reignition will occur whenever the transient recovery voltage (TRV) across the opening circuit-breaker contacts intersects the voltage withstand characteristic of the breaker contact gap. Contrary to the closing cases, the voltage withstand characteristic is absolutely consecutive in opening cases and initiates at the contact separation instant (target instant), as illustrated in Fig. 3 [5, 6]:

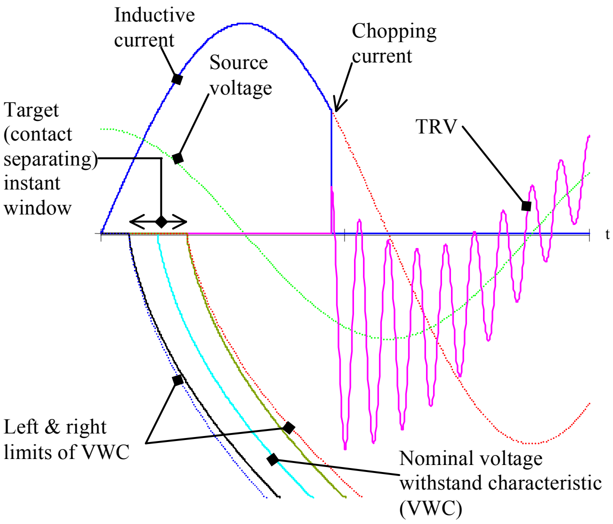


Fig. 3. Diagram illustrating the breaking instant window for a case of successful inductive current interruption.

For each target instant window combination for all opening cases (including the individual poles opening of the same circuit-breaker), a maximum value of $A(\mathbf{t_0})$ is obtained, named *Am*. This maximum value is extracted for all possible chopping currents for each target instant, excluding those which lead to reignition. In the latter case for all possible chopping currents, an extremely large value is set for $A(\mathbf{t_0})$. The optimum target instant window combination results arithmetically from the minimum *Am* of all possible target instant window combinations.

III. ALGORITHM

The algorithm can be summarized in the following steps:

A. Conversion of all voltage sources to current sources.

The conversion is done by means of Norton-Thevenin transformation.

B. Construction of steady-state network conductance matrix.

The initial steady-state conductance matrix $\mathbf{Y}(j\omega)$ is a complex function of frequency.

C. Construction of the steady-state equations.

The system of steady-state equations in matrix form is

$$\begin{aligned}&\mathbf{Y}(j\omega)\cdot\mathbf{E}(j\omega)=\mathbf{J}(j\omega)\\&\mathbf{A}^T\cdot\mathbf{E}(j\omega)=\mathbf{V}(j\omega)\\&\mathbf{A}\cdot\mathbf{I}(j\omega)=\mathbf{0}\end{aligned}\qquad(2)$$

where **E**, **V**, **J**, **I** the node voltage, branch voltage, node current sources and branch current vectors respectively and **A** the network incidence matrix. The solution of (2) is initially expressed in frequency-domain (phasors). Then the expressions are transformed into time-domain.

D. Production of initial voltage and current expressions.

From the results obtained from the previous step, expressions of voltages across the contacts to close (for closing cases) or currents through the contacts to open (for opening cases) at the same switching instant and other currents and voltages of interest as well as the initial conditions for the next switching operation, are derived.

E. Calculation of Vin or Iin.

From the above derived voltage or current expressions, Vin or Iin (for closing and opening cases respectively) is calculated as described in paragraph II. Vin (or Iin) are transformed from time-domain to s-domain via Laplace transformation.

F. Application of Injection Method.

Substitution of voltage and current sources of the original network with short- and open-circuits respectively and connection of a voltage source Vin (for closing cases) or a current source Iin (for opening cases) between the network nodes representing the poles of the switch to close or open respectively, as described in paragraph II.

G. (For closing cases only) Conversion of all Vin voltage sources to current sources.

The conversion is done by means of Norton-Thevenin transformation.

H. Construction of new equivalent network conductance matrix.

The conductance matrix **Ye**(s) of the new equivalent network resulting after the application of the steps F and G, is a function of Laplace variable “s”.

I. Construction of the system of "injection-state" equations.

The system of "injection-state" equations in matrix form is

$$\begin{aligned}&\mathbf{Ye}(s)\cdot\mathbf{Ee}(s)=\mathbf{Je}(s)+\mathbf{We}(s)\\&\mathbf{Ae}^{T}\cdot\mathbf{Ee}(s)=\mathbf{Ve}(s)\\&\mathbf{Ae}\cdot\mathbf{Ie}(s)=\mathbf{0}\end{aligned}\qquad(3)$$

where **Ee**, **Ve**, **Je**, **Ie** the node voltage, branch voltage, node current sources (corresponding to Vin and Iin) and branch current vectors of the equivalent "injection-state" network respectively, **We** a vector including the initial conditions and **Ae** the equivalent "injection-state" network incidence matrix. The solution of (3) is initially expressed in s-domain and then is transformed into time domain.

J. Production of full voltage and current expressions.

Full time-domain expressions of voltages and currents of interest after this operation instant are calculated as a sum of the results obtained from the previous step and the respective results obtained from step C (prior to the switching operation at this instant).

K. If there are more switching operations go to step D, else go to the next step.

The operation of each circuit-breaker contact is considered as individual switching operation.

L. Reading user-defined data.

The user determines specific values or defines the range and the step of the possible values of each parameter, the effect of which to the controlled switching is investigated. The same is done for each switching instant window. Finally, circuit-breaker data (voltage withstand characteristic as a function of target instants, statistical scatters, maximum chopping current level etc.) are defined by the user.

M. Calculation of the optimum switching instant windows combination.

The calculation is executed arithmetically for each combination of the parameters under investigation and is based on the minimization of the objective function *Am* among all possible "switching instant windows" combinations, as described in paragraph II.

N. Calculation of the maximum transient voltages and/or currents obtained by the algorithm.

For each optimum switching instants windows combination resulting in the previous step, the maximum transient voltages and/or currents of interest are calculated.

O. Procedure termination.

The results obtained by the two previous steps (optimum switching instants windows combinations, maximum obtained voltages and currents) for each investigated parameter values combination are stored to be further processed (e.g. curve plotting).

IV. STUDY CASES

The energization of a shunt capacitor bank studied in this paper is a common study case for controlled switching applications due to the substantial reduction of the transient overvoltages and inrush currents that can be achieved [3, 4, 7, 8]. An important parameter which affects the optimum switching instants in these cases is the degree of the trapped charge in the capacitor bank, resulting after the bank de-energization [3]. For this reason, the trapped charge is the variable parameter, the influence of which to the optimum switching instants is investigated in this study.

The single line diagram of the studied network is given in Fig. 4. The frequency of the 150 kV voltage source is 50 Hz. The network series impedance corresponds to a short-circuit power of 5 GVA. The 100 MVAr capacitor bank is wye-connected with grounded neutral.

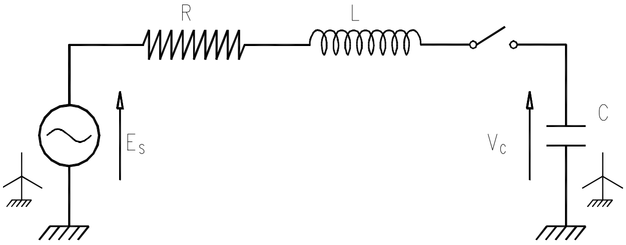


Fig. 4. Single-line diagram considered for the energization of a capacitor bank.

The objective of controlled-switching application to this case is the reduction of the inrush currents (3 functions, one for each phase) and the transient phase-to-ground overvoltages at the capacitor bank side (3 functions, one for each phase). Execution of Injection Method gives the following expressions for these functions for each phase:

$$\begin{aligned}V(t_0)&=e^{-A\cdot(t-t_0)}\cdot\{B\cdot V_0\cdot\cos[\omega\cdot(t-t_0)+\theta_B]\}\\&+D\cdot\cos[\omega_0\cdot(t-t_0)+\theta_D]+F\cdot\cos(\omega\cdot t+\theta_F)\end{aligned}\qquad(4)$$

$$\begin{aligned}I(t_0)&=e^{-G\cdot(t-t_0)}\cdot\{H\cdot V_0\cdot\cos[\omega\cdot(t-t_0)+\theta_H]\}\\&+K\cdot\cos[\omega_0\cdot(t-t_0)+\theta_K]+M\cdot\cos(\omega\cdot t+\theta_M)\end{aligned}\qquad(5)$$

where V_0 the trapped charge, t_0 the making instant in the respective phase, ω_0 the circuit natural frequency and *A, B, D, F, G, H, K, M* coefficients depending on the network elements. Thus, from (1) the following objective function is derived:

$$\begin{aligned}A(\mathbf{t_0})&=X_R\cdot V_R^2(\mathbf{t_0})+X_S\cdot V_S^2(\mathbf{t_0})+X_T\cdot V_T^2(\mathbf{t_0})\\&+Y_R\cdot I_R^2(\mathbf{t_0})+Y_S\cdot I_S^2(\mathbf{t_0})+Y_T\cdot I_T^2(\mathbf{t_0})\end{aligned}\qquad(6)$$

The next important step is the definition of the coefficients X_R, X_S, X_T, Y_R, Y_S, Y_T, which is not obvious, as the p.u. values of inrush currents depend on the value of the system basic power which has been chosen and thus, they may be several tens of times either higher or lower than those of phase-to-ground overvoltages. However, the high frequency of the expected inrush currents (in the order of 1 kHz or even higher) and consequently the relatively low energy which they contain, makes them less dangerous than the transient overvoltages. Therefore, a small value for the current weighing factors Y_j is sufficient just for ensuring the avoidance of extremely high overcurrents. In the present study, the values 1.0 and 0.1 are chosen for the voltage weighting factors X_i and the current weighing factors Y_j respectively.

In every capacitor bank energization case the range of possible values of the trapped charge is by default from 0 (for the case of a fully uncharged bank energization) to 1.0 p.u. (for the energization of a bank shortly after its de-energization). In this study the above range of values of trapped charge is considered, with a step of 0.1 p.u..

Circuit-breaker nominal voltage withstand characteristic is considered straight, with a slope (RDDS) equal to the slope of the phase-to-ground source voltage at zero crossing point, with a deviation of ±20%. The statistical scatter of the target instants is considered ±1%. Both of the above deviations determine the possible target instant windows for each pole to close.

Considering that the instant of 0 ms corresponds to a source-side voltage zero of the phase to close first (in this case R), the range of values of the possible target instants for the first phase to close is from 0 to 20 ms, since the waveform of the voltage across the respective opened contacts is the same in every 50 Hz period. In general, closing of the first pole might affect the voltage waveform across the second pole to close, so in that case the range of values of the possible target instants for the second pole would have to be extended, so that it would include an interval of transient voltage waveform, which would be different from the normal steady-state waveform of the first period. In the present case however, where the capacitor bank neutral is ideally grounded, the voltage waveforms across each breaker pole is not affected by the previous closing of other poles. Therefore, assuming that the sequence of the phases to close is R - T - S (which provides the shortest possible duration of the closing operation), the investigated time intervals is between 0 and 23.33 ms for the second phase to close and between 0 and 26.66 ms for the third one. As time step between each possible target instant is chosen the value of 1 μs.

The results of the procedure are listed in Table 1. As optimum time instant is considered the instant in the middle of the optimum time instant window for each phase.

Table 1

Optimum target instants for the energization of a capacitor bank with grounded neutral and maximum phase-to-ground overvoltages and inrush currents achieved - Injection Method application

V_0 (p.u.)	**$t_{0,R}$ (ms)**	**$t_{0,S}$ (ms)**	**$t_{0,T}$ (ms)**	**V_R (p.u.)**	**V_S (p.u.)**	**V_T (p.u.)**	**I_R (p.u.)**	**I_S (p.u.)**	**I_T (p.u.)**
0.0	10.48	17.14	13.81	1.248	1.248	1.248	1.952	1.952	1.952
0.1	10.83	17.49	14.16	1.231	1.231	1.231	1.874	1.874	1.874
0.2	11.16	17.82	14.49	1.226	1.226	1.226	1.793	1.793	1.793
0.3	11.52	18.18	14.85	1.214	1.214	1.214	1.715	1.715	1.715
0.4	11.91	18.57	15.24	1.209	1.209	1.209	1.637	1.637	1.637
0.5	12.35	19.01	15.68	1.198	1.198	1.198	1.563	1.563	1.563
0.6	12.75	19.41	16.08	1.196	1.196	1.196	1.486	1.486	1.486
0.7	13.09	19.75	16.42	1.189	1.189	1.189	1.404	1.404	1.404
0.8	13.51	20.17	16.84	1.180	1.180	1.180	1.328	1.328	1.328
0.9	13.99	20.65	17.32	1.172	1.172	1.172	1.240	1.240	1.240
1.0	14.53	21.19	17.86	1.170	1.170	1.170	1.174	1.174	1.174

The respective results after EMTP simulations are shown in Table 2. For the modelling of the circuit-breaker characteristics the circuit-breaker model [9] has been used. As it can be easily seen, the results have a sufficient conformity.

Table 2

Optimum target instants for the energization of a capacitor bank with grounded neutral and maximum phase-to-ground overvoltages and inrush currents achieved - Results from EMTP simulations

V_0 (p.u.)	**$t_{0,R}$ (ms)**	**$t_{0,S}$ (ms)**	**$t_{0,T}$ (ms)**	**V_R (p.u.)**	**V_S (p.u.)**	**V_T (p.u.)**	**I_R (p.u.)**	**I_S (p.u.)**	**I_T (p.u.)**
0.0	10.50	17.17	13.80	1.248	1.248	1.248	1.953	1.953	1.952
0.1	10.86	17.50	14.18	1.233	1.233	1.233	1.879	1.879	1.874
0.2	11.12	17.83	14.52	1.229	1.229	1.229	1.798	1.798	1.793
0.3	11.54	18.17	14.83	1.218	1.218	1.218	1.717	1.717	1.715
0.4	11.92	18.56	15.22	1.211	1.211	1.211	1.630	1.630	1.637
0.5	12.35	18.99	15.66	1.201	1.201	1.201	1.565	1.565	1.563
0.6	12.77	19.40	16.09	1.195	1.195	1.195	1.498	1.498	1.486
0.7	13.10	19.75	16.45	1.189	1.189	1.189	1.415	1.415	1.404
0.8	13.52	20.18	16.87	1.181	1.181	1.181	1.340	1.340	1.328
0.9	14.02	20.63	17.31	1.176	1.176	1.176	1.253	1.253	1.240
1.0	14.55	21.18	17.89	1.171	1.171	1.171	1.192	1.192	1.174

From the previous results it is obvious that the ideally grounded neutral makes the problem of the optimum target instants finding in each phase independent from the other phases. The effect of an ungrounded neutral can be found out with the repetition of the procedure, with the only difference that the investigated time intervals should become 0 to 40 ms and 0 to 60 ms for the second and third phase to close respectively. The results are shown in the next Tables.

Table 3

Optimum target instants for the energization of a capacitor bank with ungrounded neutral and maximum phase-to-ground overvoltages and inrush currents achieved - Injection Method application (The value of $t_{0,R}$ has been chosen randomly, as it has no influence)

V_0 (p.u.)	$t_{0,R}$ (ms)	$t_{0,S}$ (ms)	$t_{0,T}$ (ms)	V_R (p.u.)	V_S (p.u.)	V_T (p.u.)	I_R (p.u.)	I_S (p.u.)	I_T (p.u.)
0.0	11.00	20.46	12.17	1.281	1.558	1.294	2.295	2.407	2.309
0.1	11.00	21.74	13.51	1.276	1.501	1.281	1.987	2.168	2.048
0.2	11.00	22.78	14.64	1.265	1.469	1.271	1.937	2.058	1.979
0.3	11.00	23.81	15.95	1.256	1.425	1.262	1.851	1.965	1.871
0.4	11.00	24.85	17.32	1.244	1.384	1.258	1.736	1.845	1.763
0.5	11.00	25.72	18.92	1.238	1.348	1.244	1.635	1.746	1.656
0.6	11.00	26.94	19.98	1.222	1.308	1.230	1.568	1.676	1.588
0.7	11.00	28.17	20.14	1.214	1.262	1.223	1.444	1.557	1.460
0.8	11.00	29.17	21.38	1.200	1.234	1.213	1.382	1.496	1.408
0.9	11.00	30.56	22.43	1.196	1.201	1.202	1.277	1.453	1.340
1.0	11.00	31.91	23.58	1.187	1.176	1.197	1.197	1.304	1.207

Table 4

Optimum target instants for the energization of a capacitor bank with ungrounded neutral and maximum phase-to-ground overvoltages and inrush currents achieved - Results from EMTP simulations

V_0 (p.u.)	$t_{0,R}$ (ms)	$t_{0,S}$ (ms)	$t_{0,T}$ (ms)	V_R (p.u.)	V_S (p.u.)	V_T (p.u.)	I_R (p.u.)	I_S (p.u.)	I_T (p.u.)
0.0	11.00	20.56	12.21	1.294	1.565	1.309	2.302	2.410	2.320
0.1	11.00	21.68	13.40	1.287	1.510	1.288	1.993	2.176	2.054
0.2	11.00	22.71	14.51	1.276	1.476	1.281	1.943	2.065	1.987
0.3	11.00	23.74	15.88	1.266	1.432	1.276	1.860	1.976	1.887
0.4	11.00	24.80	17.19	1.254	1.398	1.265	1.741	1.854	1.776
0.5	11.00	25.76	19.03	1.243	1.354	1.255	1.639	1.754	1.663
0.6	11.00	27.04	20.10	1.232	1.310	1.243	1.576	1.687	1.594
0.7	11.00	28.11	20.22	1.221	1.276	1.232	1.448	1.565	1.472
0.8	11.00	29.23	21.42	1.209	1.243	1.221	1.389	1.506	1.413
0.9	11.00	30.62	22.49	1.201	1.210	1.212	1.282	1.465	1.352
1.0	11.00	31.85	23.50	1.193	1.187	1.206	1.199	1.310	1.215

V. CONCLUSIONS

As a general conclusion derived by the previous tables, the small differences between the results obtained using Injection Method and those obtained via EMTP show the reliability of the proposed methodology. As far as the study cases concerned, it can be easily seen that the higher values of the capacitor bank trapped charge, the higher time delay to the optimum target instants is caused. Furthermore, the higher values of trapped charge and consequently the lower initial voltages across circuit-breaker poles, contribute to the appearing of lower transient overvoltages and inrush currents

VI. REFERENCES

[1] B.C. Papadias, *Power System Analysis*, Vol. II, Textbook, National Technical University of Athens (NTUA), 1985 (In Greek).

[2] J. Panek, “Test Procedures”, *IEEE Tutorial Course “Application of Power Circuit-Breakers”*, Course Text 75CHO975-3-PWR, 1975.

[3] CIGRE WG13.07, “Controlled Switching of HVAC Circuit-Breakers - Guide for Application Lines, Reactors, Capacitors, Transformers”, 1st Part, *Electra* No 183, April 1999 - 2nd Part, *Electra* No 185, August 1999.

[4] CIGRE WG13.04, “Shunt Capacitor Bank Switching - Stresses and Test Methods”, 1st Part, *Electra* No 182, February 1999 - 2nd Part, *Electra* No 183, April 1999.

[5] CIGRE WG13.02, “Interruption of Small Inductive Currents”, Chapter 1 and 2, *Electra* No 72, October 1980 - Chapter 3 Part A, *Electra* No 75, March 1981 - Chapter 3 Part B, *Electra* No 95, July 1984 - Chapter 4 Part A, *Electra* No 101, July 1985 - Chapter 4 Part B, *Electra* No 113, July 1987.

[6] W.M.C. van den Heuvel, B.C. Papadias, “Interaction Between Phases in Three-Phase Reactor Switching”, 1st Part, *Electra* No 91, December 1983 - 2nd Part, *Electra* No 112, June 1987.

[7] A. Holm, R. Alvinsson, U. Akesson, O. Karlen, “Development of Controlled Switching of Reactors, Capacitors, Transformers and Lines”, *33rd CIGRE Session*, paper 13-201, Paris, 1990.

[8] A.C. Carvalho, W. Hofbauer, P. Högg, K. Fröhlich, “Controlled Switching as a Reliable Mean to Reduce Stresses Imposed to the Circuit-Breaker and to the Network”, *Colloquium of CIGRE SC 13 in Florianópolis*, Report 1.10, September 1995.

[9] R. Rocha, J.L. Tavora, “EMTP Model for Controlled Switching by Means of a TACS Routine”, *Proceedings of the 1997 International Conference on Power Systems Transients*, Seattle, USA, pp. 254-259, June 1997.