OPTIMUM SWITCHING INSTANTS CALCULATION FOR SYNCHRONIZED SWITCHING APPLICATIONS

Constantine Tsirekis Nikos Hatziargyriou Basil Papadias

e-mail: tsirekis@central.ntua.gr *e-mail: nh@mail.ntua.gr* *e-mail: papadias@power.ece.ntua.gr*

National Technical University of Athens, Department of Electrical & Electronics Engineering, Electric Power Division, 9 Heroon Polytehniou Str., 15773 Zografou, Athens, Greece

Key words: Synchronized Switching, Switching Transients, EMTP, Circuit-Breaker

ABSTRACT

One of the most important requirements for all synchronized 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. 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.

I. INTRODUCTION

Synchronized 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.

Besides the previous knowledge of the nature of transients appearing after each switching case (magnitudes, frequencies, attenuation etc.), their acceptable limits and the possible problems occuring when these limits are exceeded, a fundamental requirement for the use of synchronized switching to a particular network configuration is the precise definition of the desired switching instants is required [1, 2, 3]. This definition is quite complex for many reasons, such as the multiplicity of transients which may have different optimum switching instants [2], the multiplicity of phases in three-phase systems leading to three switching operations with interaction between them [4], the existence of parameters with values which are unknown or variable or hard measured (such as the trapped charge in a capacitor bank or the earthing resistance) and the statistical variations of the circuit-breaker arrangement (such as the statistical variations of the dielectric strength of the contacts gap, of the starting instant of contacts movement and of the contacts speed) [5].

In this paper a new methodology is proposed, that overcomes these problems. The basic requirement is the previous calculation of the transient voltage or current expressions in parametric form, as functions of the switching instants and the network parameters [1]. Circuit-breaker characteristics, such as contacts gap voltage withstand characteristic and variations in contacts operating times are considered.

Two study cases have been carried out for the implementation of the method, one for closing and one for opening. Both of them use a real network configuration, for the easy confirmation of the accuracy of the results.

II. BASIC PRINCIPLES

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 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 are 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 importance of each controlled quantity and $\mathbf{t_0}$ the vector of the switching instants for each operation. The constraints of the problem are the upper limits of the interesting transients. 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 [1, 2, 3, 5, 8, 9]. The way these statistical characteristics are taken into account in the proposed method for closing or opening cases, is described in the next paragraphs.

CLOSING CASES

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. 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 Figure 1 [1, 2]:

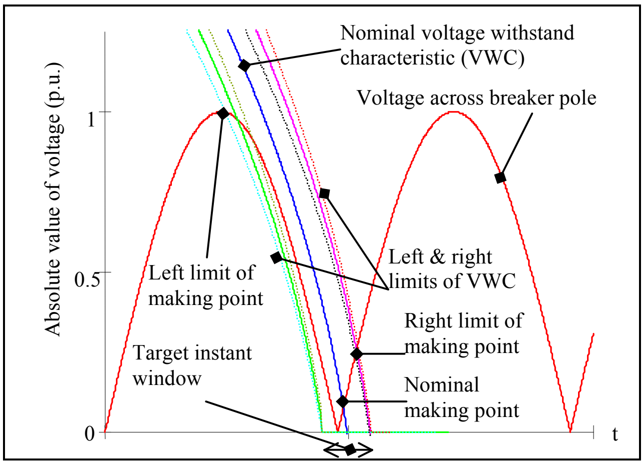

Figure 1. Diagram illustrating the making instant window for a case where target instant corresponds to zero voltage.

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.

OPENING CASES

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 [4, 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 [4, 7] 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. Similarly to the closing cases, the voltage withstand characteristic initiates at the contact separation instant (target instant), as illustrated in Figure 2 [1, 4, 7]:

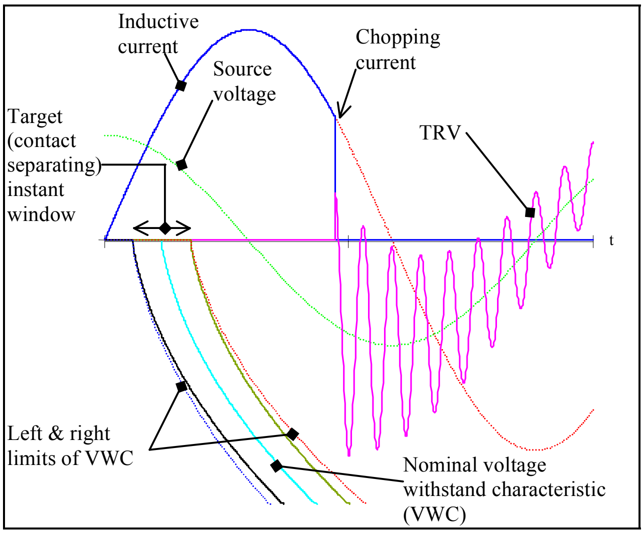

Figure 2. Diagram illustrating the breaking instant window for a case of successful inductive current interruption.

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:

1. Reading user-defined data: The user determines specific values or defines the range and the step of the possible values of each unknown or variable 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.
2. Calculation of the optimum switching instant windows combination: The calculation is executed numerically 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.
3. 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.
4. 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 switching of a shunt capacitor bank studied in this paper is a common study case for synchronized switching applications due to the substantial reduction of the transients that can be achieved [3, 5, 6, 8, 9].

The network configuration used for this study case is a part of a real network where the proposed algorithm is used for the reduction of the transients produced after the switching of a capacitor bank at high-voltage level, scheduled to be installed in the next year. The single-line diagram of the studied network is shown in Figure 3. The 50 Hz source - source impedance combination shown in the upper part of the previous figure represents the upstream network, while the other 50 Hz source represents a small power plant located close to the HV bus. HV/MV transformers are neglected and therefore, loads and compensating capacitors are assumed to be connected directly to the HV:

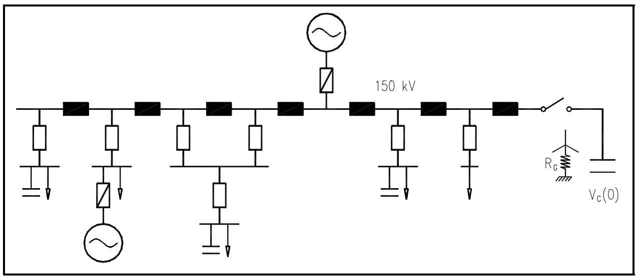

Figure 3. Single-line diagram of the network considered for the capacitor bank switching. Black, empty and hatched boxes represent HV bus sections, feeders connected to the HV bus and source impedances, respectively.

CLOSING CASE

The 25 MVar, 150 kV capacitor bank is switched on and off in a single-step. This means that at the instant of circuit-breaker closing there are no other capacitor banks previously connected to the HV bus, as it would occur in a multiple-steps capacitor bank for the energization of any of the partial capacitances after the first one, which is the case called in the bibliography "back-to-back" capacitor bank energization. However, the present case is actually a "back-to-back" energization due to the shunt capacitances of the feeders connected to the HV bus.

The transients which are intended to be minimized are the inrush currents of the capacitor bank and the phase-to-ground overvoltages of the main bus and of all the other interconnected buses. The upper limits of the inrush currents and phase-to-ground bus overvoltages are 50 p.u. and 2 p.u. respectively. The values of X_i and Y_j derived from these limits for the achievement of the same degree of importance between all interesting transients, are 2500 and 4, respectively.

The data of the circuit-breaker are given by the manufacturer. According to them, the voltage withstand characteristic of the breaker poles is a straight line, with a Rate-of-Decay-of-Dielectric-Strength (RDDS) equal to 63 kV/ms, with a variation of ±20%. The variation of the contacts speed is ±5% and the variation of the starting instant of the contacts movement is ±0.7 ms.

The neutral node of the wye-connected capacitor bank is grounded. This means that the grounding resistance is less than 1 ohm. Its exact value, however, cannot be precisely defined due to measurement faults, weather and humidity variations etc. Another important parameter which affects the optimum switching instants in capacitor bank energization cases is the degree of the trapped charge in the capacitor bank resulting after the bank de-energization

[2]. For these reasons, the trapped charge and the neutral grounding resistance are the parameters, the influence of which to the optimum closing instants is investigated in this study. The range of possible values considered for the grounding resistance is from 0 (for an ideally grounded neutral) to 1 ohm (upper limit of sufficient grounding), with a step of 0.1 ohm. Similarly, 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 voltage is considered, with a step of 0.1 p.u..

Considering that the instant of 0 ms corresponds to a voltage zero across the pole to close first (in this case the pole of phase "a"), the range of values of the possible target instants for the first phase to close is chosen between 20 and 40 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 affects the voltage waveform across the second pole to close. Therefore, the range of values of the possible target instants for the second pole must be extended, in order to include an interval of transient voltage waveform, which may be different from the normal steady-state waveform of the first period. As a consequence, the investigated time intervals are between 20 and 60 ms and between 20 and 80 ms for the second and the third phase to close, respectively. As time step between each possible target instant is chosen the value of 0.1 ms.

Due to space limitation reasons, only some indicative results which are obtained after the application of the proposed algorithm to the present case, are shown in the next figures. As optimum time instant is considered the instant in the middle of the optimum time instant window for each phase. It should be noted, that the polarity of the trapped charge has been chosen so that in the first semi-period of each period (for phase "a" 0 to 10 ms, 20 to 30 ms etc.) the peak voltage across the open breaker poles is higher than that of the second semi-period (for phase "a" 10 to 20 ms, 30 to 40 ms etc.):

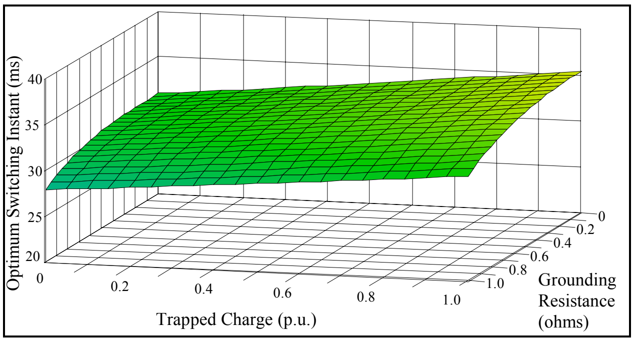

Figure 4. Optimum switching instant for the breaker pole of phase "a", as a function of the trapped voltage and neutral grounding resistance.

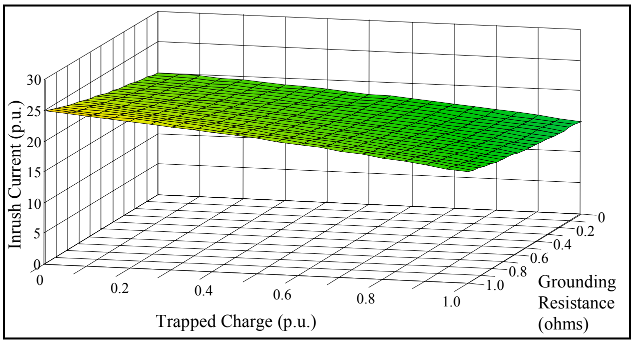

Figure 5. Maximum inrush currents of phase "a", obtaining for the optimum switching instants shown in Figure 4, as a function of the trapped voltage and neutral grounding resistance.

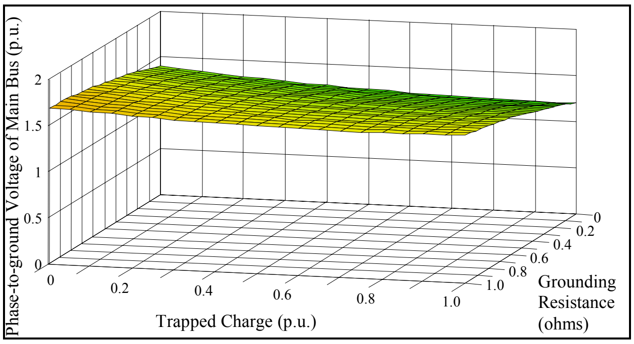

Figure 6. Maximum phase-to-ground overvoltages of phase "a" at the main HV bus, obtaining for the optimum switching instants shown in Figure 4, as a function of the trapped voltage and neutral grounding resistance.

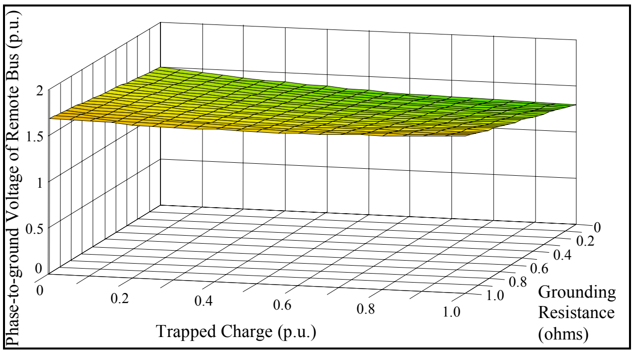

Figure 7. Maximum phase-to-ground overvoltages of phase "a" at a remote bus, obtaining for the optimum switching instants shown in Figure 4, as a function of the trapped voltage and neutral grounding resistance.

From the above results it is obvious that the existence of a high trapped voltage causes a shift of the optimum switching instant window to the semi-period with lower peak voltage across breaker poles and leads to lower inrush currents and slightly lower phase-to-ground bus overvoltages. On the contrary, a high value of the neutral grounding resistance has no practical impact to the optimum switching instant window and causes slightly higher inrush currents and phase-to-ground bus overvoltages.

OPENING CASE

The de-energization of the same capacitor bank is studied next. The only transients which are intended to be minimized are the transient recovery voltages (TRVs) across circuit-breaker poles, the upper limit of which is 3 p.u. Due to the existence of only one kind of interesting transients, the values of X_i and Y_j are 1 and 0, respectively.

The circuit-breaker used for the energization is used for the de-energization case as well. The date given by the manufacturer somehow differ from those given for the previous case. According to them, the voltage withstand characteristic of the breaker poles is a straight line, with a Rate-of-Rise-of-Dielectric-Strength (RRDS) equal to 56 kV/ms, with a variation of ±20%. The variation of the contacts speed is ±5.5% and the variation of the starting instant of the contacts movement is ±0.7 ms.

In this case, the neutral grounding resistance is the only parameter, the influence of which to the optimum closing instants is investigated.

The range of possible values considered for the grounding resistance and the time intervals investigated for each phase to open are the same with the energization case.

Some indicative results which are obtained after the application of the proposed algorithm to the present case, are shown in the next figures:

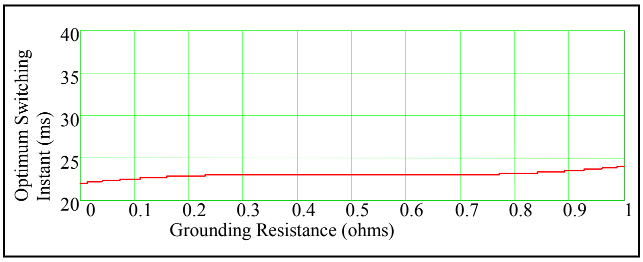

Figure 8. Optimum switching instant for the breaker pole of phase "a", as a function of the neutral grounding resistance.

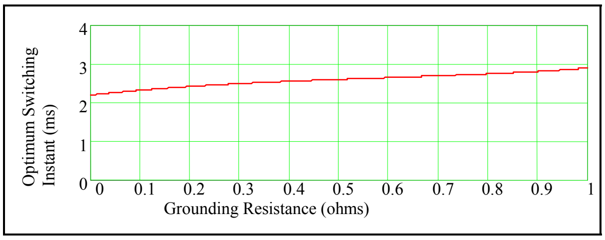

Figure 9. Maximum TRV in breaker pole of phase "a", obtaining for the optimum switching instants shown in Figure 8, as a function of the neutral grounding resistance.

From the above results it is derived thet a high value of the neutral grounding resistance leads to a delay of the optimum switching instant window and causes higher transient recovery voltages.

V. CONCLUSIONS

A new methodology for the calculation of the optimum switching instants for synchronized switching applications, has been presented. The calculation is based on the minimization of a high number of transients, taking into account all possible statistical scatters of the circuit-breaker. It also finds out the impact of any parameter, which is unknown or variable for a particular case, to the optimum switching instant and to the magnitudes of the obtained transients. All the calculations are performed via a single simulation. The systematic approach of the problem by the proposed methodology makes it suitable for any kind of controlled switching applications.

REFERENCES

1. C.D. Tsirekis, N.D. Hatziargyriou, B.C. Papadias, “Controlled Switching Based on the Injection Method”, *Proceedings of the 2001 International Conference on Power Systems Transients*, Rio de Janeiro, Brazil, pp. 405-410, June 2001.
2. 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.
3. 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.
4. 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.
5. 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.
6. 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.
7. 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.
8. CIGRE Task Force 13.00.1: “Controlled Switching: A State-of-the-Art Survey”, 1st Part: Electra No 163, Dec. 1995 - 2nd Part: Electra No 164, Fe. 1996.
9. E. Andersen, S. Berneryd, S. Lindahl: “Synchronous Energization of Shunt Reactors and Shunt Capacitors”, CIGRE Session, Paper No. 13-12, 1988.