A Modern Method for Reduction of Capacitor Energization Stresses

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Abstract: - Transients produced upon the energization of capacitor banks may be harmful for the capacitor itself, for the switching device and for the adjacent system components. One of the most modern countermeasures for the reduction of these transients is controlled switching. In the present study, an overview of the restrictions concerning the application of this technique for the safe switching of capacitor banks and shunt reactors is presented and the benefits of its use taking into account these restrictions are investigated.

Key-Words: - Shunt Capacitor, Switching Transients, ATP-EMTP Simulation, Controlled Switching

1 Introduction

Switching of capacitor banks usually occurs quite frequently, even in a daily basis, since their connection to the network is essential due to reactive compensation reasons, improving thus the power quality, at least locally. However, capacitor bank energization has been recognized as a possible source of malfunctions for many years. Transients produced may be harmful for the capacitor itself, for the switching device and for the adjacent system components.

Inrush currents, greater than 4 p.u., appear upon energization of a single-step capacitor bank [1, 2]. The high frequency of these inrush currents and consequently the low energy which they contain, makes them non-dangerous. However, the existence of another capacitor bank previously connected to the same bus (“back-to-back” energization case) causes high inrush currents, probably greater than 100 p.u. [1, 2]. The energization of the second and subsequent steps of a multiple-step capacitor bank can be also considered as back-to-back energization. Furthermore, the existence of transmission lines and, especially, cables connected to the same bus at the instant of the energization, comprise also a back-to-back energization case, due to their shunt capacitances. Thus, in practical cases, every capacitor bank energization is more or less a back-to-back energization case, with the corresponding consequences.

Besides the high inrush currents, travelling overvoltage waves appear at the far end of the lines connected to the same bus. The value of these overvoltages may exceed 3 p.u., possibly resulting in damages of equipment fed through these lines (transformers, sensitive electronic and telecommunication equipment etc.) [3].

A variety of countermeasures, either alone or in conjunction, are used by the electric utilities for the reduction of these transients to safe levels. The most usual traditional techniques applied for the limitation of the energization stresses comprise the use of pre-insertion resistors or inductors, fixed inductors and surge arresters. The power consumption and the requirements of heat dissipation and space adequacy along with the significant stochastic nature of the surge arresters performance, are some indicative disadvanatges of these methods.

Next to the various conventional techniques, controlled (synchronized) switching has been developed as a reliable mean to reduce switching stresses. This modern technique is based on the automatic adjustment of the circuit-breaker mechanism by an auxiliary device ("controller") in such a way, that switching operation takes place at a point-on-wave which minimizes switching transients. Its advantage against the rest "conventional" methods is that it can theoretically eliminate switching transients totally. However, various statistical deviations in the characteristics of the controller and the circuit-breaker itself may affect the success of this method.

In this paper, an overview of the phenomena caused by capacitor bank energization is presented and the effectiveness of synchronized switching for the limitation of the associated stresses in the Hellenic Interconnected Power System is investigated. Various parameters, such as neutral grounding condition, dielectric characteristics and statistical variations of the whole switching arrangement are taken into account.

2 Capacitor Energization Transients

The one-line diagram of the simplified equivalent network which is used for the calculation of transient voltages and currents produced upon the energization of a shunt capacitor bank, is shown in the next figure:

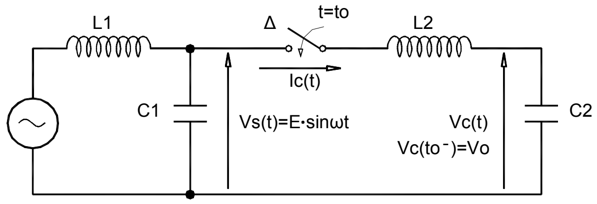

Fig. 1: Simplified one-line diagram for the energization of a three-phase shunt capacitor with ideally grounded neutral.

The following notations are used in the previous figure:

- $L1$ is the equivalent inductance of the upstream network
- $C1$ is the equivalent capacitance of the upstream network, including the presence of already connected capacitor banks, transmission lines and cables
- $L2$ represents the stray inductance of the bus and the various cable connections between the bus, the circuit-breaker and the reactor
- $C2$ is the capacitor bank's capacitance
- *Vs(t)* is the voltage in the network side of the breaker Δ, given by the relation *E·sin(ω·t)*
- *Vc(t)* is the capacitor's voltage
- *Ic(t)* is the inrush current

In the general case, the probable existence of trapped charge at the capacitor bank, obtained after a recent de-energization of it, should be taken into account. The result of this is that just before the closing instant $t=t_o$, the capacitor voltage is V_o, where $|V_o| \leq E$. On the contrary, the resistances in the whole network contribute only to the damping rate of the transients and they have no effect to the magnitude of those transients. Therefore, for the estimation of the maximum transients, all resistances can be neglected.

According to the above assumptions, the following per unit expressions for the transient capacitor's voltage *Vc(t)* and the inrush current *Ic(t)* flowing through the circuit-breaker are derived:

$$\begin{aligned} V_C(t) = {} & \sin\omega t + T_{11}\cdot\sin\omega_{o1}(t-t_o) + \\ & + T_{12}\cdot\cos\omega_{o1}(t-t_o) + T_{21}\cdot\sin\omega_{o2}(t-t_o) + \\ & + T_{22}\cdot\cos\omega_{o2}(t-t_o) + V_{DC} \end{aligned} \tag{1}$$

$$\begin{aligned} I_C(t) = {} & \cos\omega t - T_{12}\cdot\frac{\omega_{o1}}{\omega}\cdot\sin\omega_{o1}(t-t_o) + \\ & + T_{11}\cdot\frac{\omega_{o1}}{\omega}\cdot\cos\omega_{o1}(t-t_o) - \\ & - T_{21}\cdot\frac{\omega_{o2}}{\omega}\cdot\sin\omega_{o2}(t-t_o) + \\ & + T_{22}\cdot\frac{\omega_{o2}}{\omega}\cdot\cos\omega_{o2}(t-t_o) \end{aligned} \tag{2}$$

where

$$\omega_{oj} = \sqrt{\frac{B \pm \sqrt{B^2 - 4\cdot L1\cdot L2\cdot C1\cdot C2}}{L1\cdot L2\cdot C1\cdot C2}}, \quad j = 1, 2 \tag{3}$$

$$B = L1\cdot C1 + L1\cdot C2 + L2\cdot C2 \tag{4}$$

$$T_{11} = \frac{\omega\cdot(\omega^2-\omega_{o2}^2)\cdot(\omega_{o1}^2\cdot L1\cdot C1 - 1)\cdot\cos\omega t_o}{\omega_{o1}\cdot(\omega_{o1}^2-\omega_{o2}^2)\cdot(1-\omega^2\cdot L1\cdot C1)} \tag{5}$$

$$\begin{aligned} T_{12} = {} & + \\ = {} & \frac{(\omega^2-\omega_{o2}^2)(\omega_{o1}^2\cdot L1\cdot C1-1)\cdot\omega_{o1}\cdot\sin\omega t_o}{(\omega_{o1}^2-\omega_{o2}^2)\cdot(1-\omega^2\cdot L1\cdot C1)} + \\ & + \frac{V_o\cdot(\omega^2-\omega_{o2}^2)(\omega^2-\omega_{o1}^2)(\omega_{o1}^2\cdot L1\cdot C1-1)}{\omega_{o1}\cdot(\omega_{o1}^2-\omega_{o2}^2)\cdot(1-\omega^2\cdot L1\cdot C1)} \end{aligned} \tag{6}$$

$$T_{21} = -\frac{\omega\cdot(\omega^2-\omega_{o1}^2)\cdot(\omega_{o2}^2\cdot L1\cdot C1 - 1)\cdot\cos\omega t_o}{\omega_{o2}\cdot(\omega_{o1}^2-\omega_{o2}^2)\cdot(1-\omega^2\cdot L1\cdot C1)} \tag{7}$$

$$\begin{aligned} T_{22} = {} & \\ = {} & \frac{(\omega^2-\omega_{o1}^2)(1-\omega_{o2}^2\cdot L1\cdot C1)\cdot\omega_{o2}\cdot\sin\omega t_o}{(\omega_{o1}^2-\omega_{o2}^2)\cdot(1-\omega^2\cdot L1\cdot C1)} + \\ & + \frac{V_o\cdot(\omega^2-\omega_{o1}^2)(1-\omega_{o2}^2\cdot L1\cdot C1)(\omega^2-\omega_{o2}^2)}{\omega_{o2}\cdot(\omega_{o1}^2-\omega_{o2}^2)\cdot(1-\omega^2\cdot L1\cdot C1)} \end{aligned} \tag{8}$$

$$\begin{aligned} V_{DC} = {} & \\ = {} & \frac{V_o\cdot L1\cdot L2\cdot C1\cdot C2(\omega^2-\omega_{o1}^2)(\omega^2-\omega_{o2}^2)}{(1-\omega^2\cdot L1\cdot C1)} \end{aligned} \tag{9}$$

It can be easily observed, that both voltage and current expressions consist of two component groups, one with power frequency ω and one with natural frequency ω_o. Therefore, the most adverse peak values of the current and voltage expressions equal to the sum of the peak values of each respective component group, that is

$$V_{C,peak}(t_o) = 1 + \sqrt{T_{11}^2 + T_{12}^2} + \sqrt{T_{21}^2 + T_{22}^2} + |V_{DC}| \quad (10)$$

$$I_{C,peak}(t_o) = 1 + \\ = \frac{\omega_{o1}}{\omega} \cdot \sqrt{T_{11}^2 + T_{12}^2} + \frac{\omega_{o2}}{\omega} \cdot \sqrt{T_{21}^2 + T_{22}^2} \quad (11)$$

The maximum peak values are obtained for $t_{o1} = (2k\cdot\pi+\pi/2)/\omega$ or $t_{o2} = (2k\cdot\pi-\pi/2)/\omega$ (k is any integer), depending on the sign of V_o. More specifically,

- if $V_o > 0$, t_{o2} are the maximizing instants,
- if $V_o < 0$, t_{o1} are the maximizing instants and
- if $V_o = 0$, both t_{o1} and t_{o2} maximize the peak values.

Considering that the voltage across breaker poles is $Vs(t) - V_o$, it can be derived from the previous results that the maximum transient overvoltages and inrush currents appear for closing at peak voltage between breaker poles.

Similarly, the minimum peak values are obtained for $t_{o3} = k\cdot\pi+\sin^{-1}(V_o /E)]/\omega$ (k is any integer), i.e. for closing at zero voltage between breaker poles.

Defining as AT the proportional voltage rise caused by the capacitor connection, by means of Fig. 1, the following expression can be derived:

$$L1 \cdot C2 \cong \frac{AT}{\omega^2 \cdot \left(1 + AT + AT \cdot C1/C2\right)} \quad (12)$$

From the substitution of the previous t_o values to Eq. (4) and (5), the maximum and minimum peak values of the transient overvoltages and inrush currents are derived:

$$V_{C,peak,max} = 1 + V_{fo1,max} + V_{fo2,max} + V_{const} \quad (13)$$

$$I_{C,peak,max} = 1 + I_{fo1,max} + I_{fo2,max} \quad (14)$$

$$V_{C,peak,min} = 1 + V_{fo1,min} + V_{fo2,min} + V_{const} \quad (15)$$

$$I_{C,peak,min} = 1 + I_{fo1,min} + I_{fo2,min} \quad (16)$$

where

$$V_{fo1,max} \cong \frac{C1 \cdot |F|}{2 \cdot (1+AT) \cdot C2 \cdot (C1+C2)} + \\ + |V_o| \cdot \frac{C1 \cdot |F|}{2 \cdot (1+AT) \cdot C2 \cdot (C1+C2)} \quad (17)$$

$$V_{fo2,max} \cong \\ \cong \frac{C1 \cdot \left|AT \cdot (C1+C2) \cdot \left(1+|V_o|\right) + C2 \cdot \left(1-|V_o|\right)\right|}{2 \cdot (1+AT) \cdot C2^2} + \\ + \frac{C1 \cdot \left|AT \cdot (C1+C2) \cdot \left(1+|V_o|\right) + C2 \cdot \left(1-|V_o|\right)\right|}{2 \cdot (1+AT) \cdot C2 \cdot (C1+C2)} \quad (18)$$

$$V_{const} \cong \frac{|V_o|}{4 \cdot (1+AT)} \cdot \frac{|F|}{C2} \quad (19)$$

$$I_{fo1,max} \cong \\ \cong \frac{|F| \cdot \sqrt{\left|AT(C1+C2) + C2\right|}}{4(1+AT) \cdot C2 \sqrt{\frac{L2 \cdot AT}{2L1 \cdot C1} \cdot (C1+C2)}} + \\ + \frac{|V_o| \cdot |F| \cdot \sqrt{\left|AT(C1+C2) + C2\right|}}{4(1+AT) \cdot C2 \sqrt{\frac{L2 \cdot AT}{2L1 \cdot C1} \cdot (C1+C2)}} \quad (20)$$

$$I_{fo2,max} \cong \\ \cong \frac{\sqrt{2} \cdot \left|AT \cdot (C1+C2)\left(1-|V_o|\right) + C2 \cdot \left(1+|V_o|\right)\right|}{4 \cdot (1+AT) \cdot C2 \cdot \sqrt{\frac{AT \cdot (C1+C2)}{F}}} + \\ + \frac{\sqrt{2} \cdot \left|AT \cdot (C1+C2)\left(1-|V_o|\right) + C2 \cdot \left(1+|V_o|\right)\right|}{4 \cdot (1+AT)(C1+C2) \cdot \sqrt{\frac{AT \cdot (C1+C2)}{F}}} \quad (21)$$

$$V_{\mathrm{fo1,min}} \cong \\ \cong \sqrt{\frac{(1-V_o^2) AT \cdot L2 \cdot C1^3 \cdot |F|}{2 \cdot L1 \cdot C2 \cdot (1+AT)^2 \cdot (C1+C2)^3}} \quad (22)$$

$$V_{fo2,min} \cong \\ \cong \frac{C1 + 2 \cdot C2}{C2} \cdot \sqrt{\frac{AT \cdot D}{2 \cdot (C1+C2) \cdot (1+AT)}} \quad (23)$$

$$I_{fo1,min} \cong \frac{C1 \cdot |F| \cdot \sqrt{(1-V_o^2)}}{2 \cdot C2 \cdot (1+AT) \cdot (C1+C2)} \quad (24)$$

$$I_{fo2,min} \cong$$

$$\cong \frac{C1 + 2 \cdot C2}{2} \cdot \sqrt{\frac{D}{(C1 + C2) \cdot (1 + AT) \cdot F}} + \qquad (25)$$

$$+ \frac{(C1 + 2 \cdot C2) \cdot AT}{2} \cdot \sqrt{\frac{D \cdot (C1 + C2)}{(1 + AT) \cdot F}}$$

$$D = AT \cdot (C1 + C2) \cdot \left(1 + V_o^2\right) + C2 \cdot \left(1 - V_o^2\right) \qquad (26)$$

$$F = AT \cdot (C1 + C2) - C2 \qquad (27)$$

In most cases, the voltage rise caused by the connection of shunt capacitors does not exceed 15%. Therefore, for the range of values of AT between 1 to 15%, the maximum and minimum peak values of the transient overvoltage and inrush currents vary according to the next figures ($L2/L1$=0.3%):

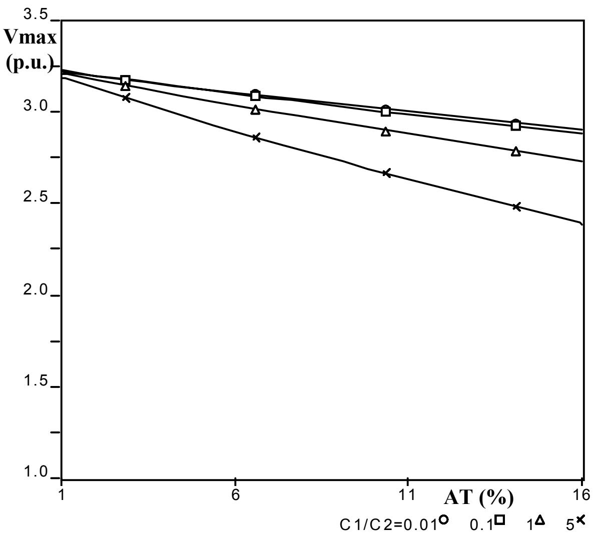

Fig. 2: Maximum peak values of transient voltage

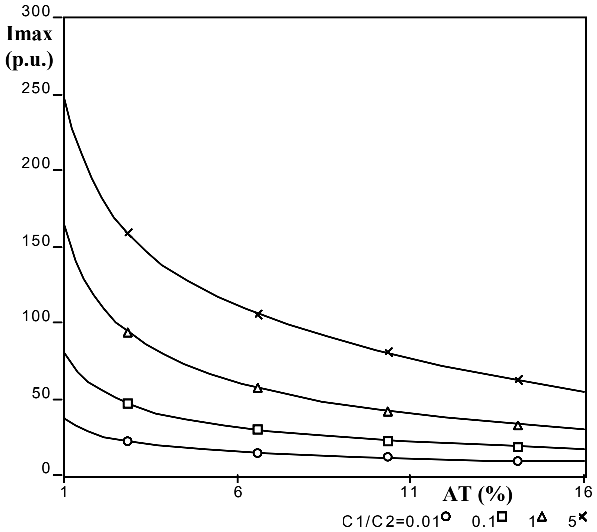

Fig. 3: Maximum peak values of inrush current

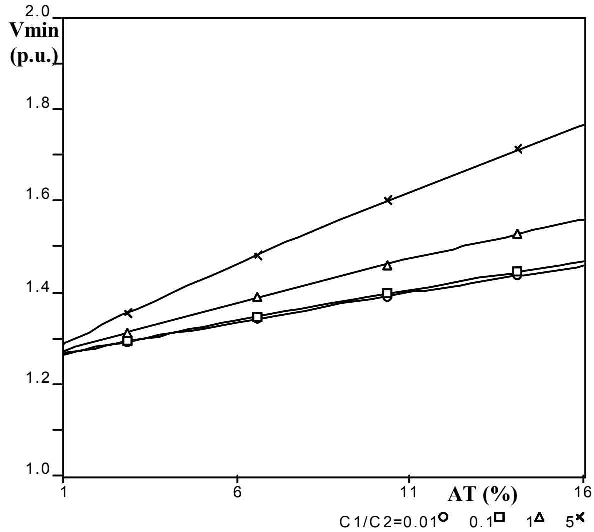

Fig. 4: Minimum peak values of transient voltage

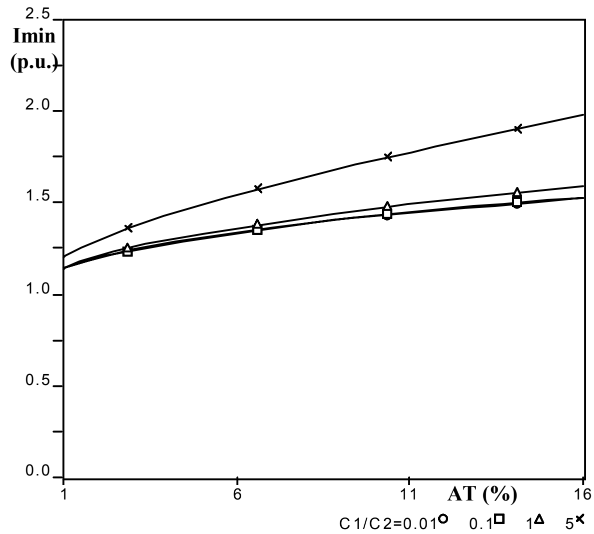

Fig. 5: Minimum peak values of inrush current

As it can be easily seen in the previous figures, which correspond to the most adverse case of $|V_o|$ = 1 p.u., the maximum transient overvoltage of the capacitor is less than 3.5 per unit, regardless of the value of the capacitance $C1$ connected at the same bus prior the switching of the new capacitor. On the contrary, the value of the already connected capacitance play a significant role to the magnitude of the inrush current, as the latter can well exceed 100 p.u. for a ratio $C1/C2$ at least in the order of unity. This is due to the low values of $L2$, according to Eq. (20). Considering as an example the Greek Interconnected Power System, where the short-circuit reactance of the upstream 150 kV network vary between 2 and 56 ohms, while the reactance between two adjacent circuit-breaker bays in 150 kV busbars is less than 6 mohms, it can be easily derived that the ratio $L2/L1$ may be much lower, leading to even higher inrush currents.

On the other hand, closing at zero voltage across breaker poles suppresses transient overvoltages and inrush currents below 2 p.u.. Therefore, the minimization of the maximum transients may be worth the application of controlled switching.

3 Controlled Switching Application

An important point which should be investigated for all controlled switching applications is the statistical distribution of controlled circuit-breaker characteristics, which complicates the study of synchronized switching performance [4 to 8]. In fact, in almost all 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 Fig. 6 [4]:

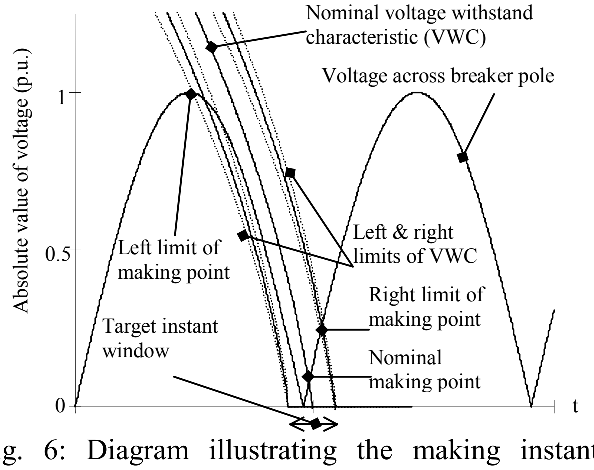

Fig. 6: Diagram illustrating the making instant window for a case where favourable target instant corresponds to zero voltage across breaker pole.

Two basic comments can be made on Fig. 6:

1. The voltage withstand capability of the circuit-breaker along with the various statistical variations cause a significant shift to the optimum target instant window (and consequently to the favourable mechanical closing of the contacts) from the instant corresponding to zero voltage, in order to achieve pre-striking (thus electrical current flow initiation) near zero voltage instants.
2. For the majority of controlled energizations, pre-striking will occur at an instant close that corresponding to zero voltage, but not exactly at that specific instant. Therefore, transient overvoltages and inrush currents with peak values greater than those indicated in Figures 4 and 5 should be expected.

From the last remark, it is obvious that a further investigation is needed for the effect of the making instant deviations to the ability of energization transients reduction. Such an investigation is carried out in the form of study case described in the following paragraph.

4 Study Case

For the realistic formulation of the problem, a real substation of the interconnected power system of Greece is used as an implementation. This is the Agios Stefanos 400/150 kV substation, to the 150 kV busbars of which a single-step 25 Mvar capacitor bank will be connected. The simplified diagram illustrating the examined system is shown in Fig. 7:

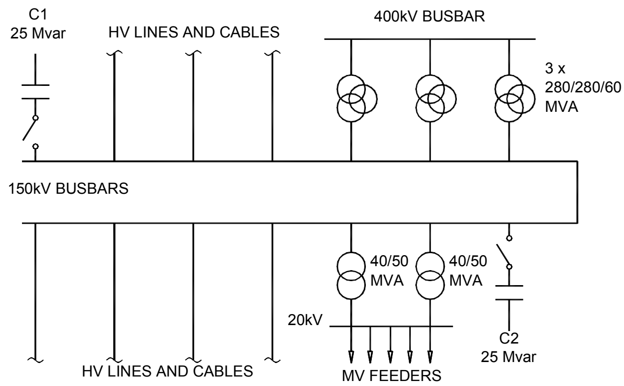

Fig. 7: Single-line diagram of the network considered for HV shunt capacitor energization.

The most adverse transients appearing during the uncontrolled closing operation of the switching device, are calculated using the widely known ATP/EMTP computer program [9]. The optimum switching instants are calculated by the Controlled Switching Calculation Program (CSCP) developed at NTUA [10]. Interaction of the three phases and the various statistical deviations of circuit-breaker characteristics are considered in this program.

As mentioned previously, the optimum closing instant for each phase corresponds to the zero voltage between the breaker contacts in the respective phase. However, the Rate-of-Decay of Dielectric Strength (RDDS) and the deviation of the starting instant of contacts movement (ΔT) have an unfavourable effect on the final results, as clearly seen in Figures 8 and 9.

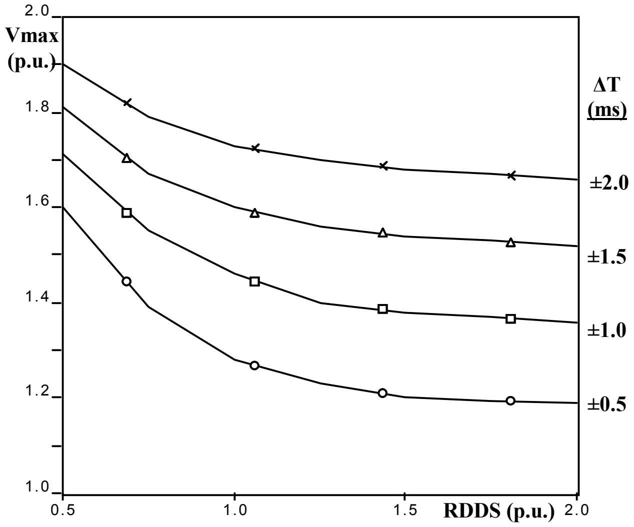

Fig. 8. Effect of RDDS and ΔT to the maximum voltage upon controlled energization.

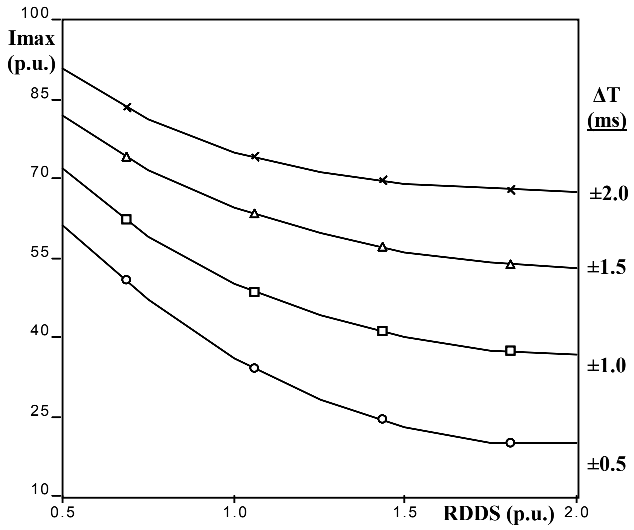

Fig. 9. Effect of RDDS and ΔT to the maximum inrush current upon controlled energization.

As shown in the previous figures, the requirement which must be fulfilled by the controlled switching arrangement for the limitation of the maximum voltages and inrush currents below 1.4 and 40 per unit, respectively, comprises a maximum deviation of starting instant of contacts movement (ΔT) ±1 ms combined with a "fast" switching device with a Rate-of-Decay of Dielectric Strength (RDDS) greater than 1.5 per unit (1 p.u.=V·ω, where V the amplitude of the sinusoidal source-side phase-to-ground voltage and ω the angular power frequency).

5 Conclusions

An implementation of synchronized switching to the energization of shunt capacitors has been presented. Phenomena generating the most adverse energization stresses have been analysed and the possible benefits obtained by means of synchronized switching have been investigated. Various parameters, such as dielectric characteristics and statistical variations of the switching device, probably affecting the effectiveness of this modern technique, have been taken into account.

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