Control of Shunt Capacitors and Shunt Reactors Energization Transients

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Abstract **–Transients produced upon the energization of capacitor banks and shunt reactors may be harmful for the capacitor or reactor 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.**

Keywords – Capacitor bank switching, shunt reactor switching, switching transients, controlled switching

I. INTRODUCTION

Switching of capacitor banks and shunt reactors 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, their energization has been recognized as a possible source of malfunctions for many years [1-7]. 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 [3, 4]. 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.

Besides the various conventional techniques, controlled (synchronized) switching has been developed as a reliable mean to reduce switching stresses [3-16]. 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 [3, 17].

In this paper, an overview of the possibly prejudicial phenomena caused by the energization of capacitor banks and shunt reactors is presented and an investigation of the effectiveness of synchronized switching application for the limitation of the associated stresses is carried out. All various statistical deviations and dielectric characteristics of the whole arrangement are taken into account.

II. SHUNT REACTOR ENERGIZATION TRANSIENTS

Transient overvoltages are produced via the energy exchanges between the various inductances and capacitances of the network including the reactor, the buses, the upstream network and the cable connections between all of them. The maximum transient overvoltages are obtained for closing at an instant corresponding to peak voltage across breaker poles and their magnitude depends on the values of the network parameters. Defining as VR the proportional voltage rise before the reactor connection and as VD the proportional voltage drop caused by the reactor connection, it can be derived, that the maximum per unit transient overvoltage $v_{L,\max}$ is approximately given by the following expression:

$$v_{L,\max} = 1 + \frac{VD \cdot VR}{1 + VR - VD \cdot VR} \quad (1)$$

In most usual cases, shunt reactors are connected when voltage rise tends to exceed 10% and achieves a voltage compensation (VD) reaching even 100%. Therefore, for the ranges of values of 10 to 30% and 0 to 100% for VR and VD, respectively, the maximum peak value of the transient overvoltage varies according to Fig. 1:

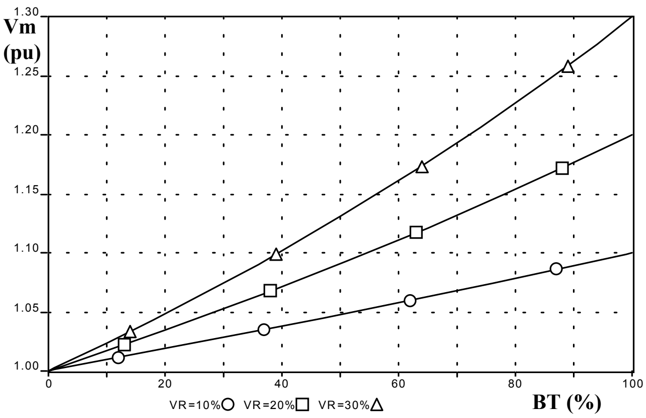

Fig. 1: Maximum peak values of reactor's transient overvoltage in relation to VD for various values of VR

As it can be easily seen in this figure, even in cases that the reactor is intended to compensate extreme voltage drops (in the order of 30%), the maximum transient overvoltage of the reactor is modest (less than 1.3 per unit).

Furthermore, it can be derived, that the maximum inrush currents for the three phases and neutral are obtained for closing at zero voltage between the breaker poles. The diagram shown in Fig. 2, which depicts the variation of the maximum inrush currents as a function of the ratio Z_n/Z, where Z and Z_n are the impedances of the reactor and the neutral grounding branch, respectively.

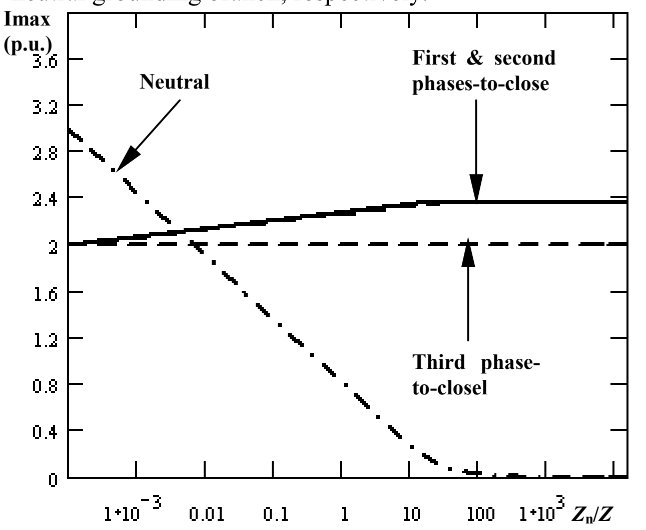

Fig. 2: Maximum peak values of reactor's inrush currents in relation to the ratio Z_n/Z

As it can be easily seen in the previous figure, the maximum phase currents are 2 per unit (in all phases) for a directly grounded neutral and almost 2.4 per unit (for the first two phases-to-close) for isolated neutral. Each one of these inrush currents contains a slowly-damped DC component with magnitude of almost 1 and 1.4 per unit, respectively. The long duration of these high DC current components may lead to a temporary overloading of reactor windings and undesired activation of phase protective relays.

Similarly, the maximum neutral inrush current is 3 per unit and appears for a directly grounded neutral (for isolated neutral it is, of course, zero). It is an exclusively DC current with low damping rate and for this reason it may be kept in such high values for several cycles, possibly leading to undesired activation of zero sequence protective relays.

III. Capacitor Bank Energization Transients

Problems produced by the energization of capacitor banks are well documented in the literature [1-6, 8-16]. Inrush currents, greater than 4 p.u., appear upon energization of a single-step capacitor bank. 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 200 p.u. [4]. 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 the shunt capacitances of these elements. 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 4 per unit, possibly resulting in damages of equipment fed through these lines (transformers, sensitive electronic and telecommunication equipment etc.) [4].

It has to be noted, that the maximum transient overvoltages and inrush currents are both obtained for closing at an instant corresponding to peak voltage across breaker poles and their exact magnitude depends on the values of the network parameters. On the other hand, the minimum peak values of transient overvoltages and inrush currents of approximately 1.0 and 2.0 per unit, respectively, are obtained for closing at zero voltage between the breaker poles.

IV. Controlled Switching

The most modern method applied for the limitation of the switching transients is controlled (synchronized) switching. Application of synchronized switching to the present cases (energization of shunt reactors and capacitor banks) can be effective, since the magnitudes of the produced transients are strongly dependent on the closing instants of the three poles of the switching device, as described in the previous paragraphs.

The main parts of a typical controlled switching arrangement are shown in Fig. 3. This typical arrangement consists indicatevely of the following:

1. The switching device (circuit-breaker or load break switch) with the capability of independent operation of each pole.
2. A number of devices for the measuring of instant values of voltages at both sides of the switching device (for closing cases) or of voltages and currents at one side of the switching device (for opening cases). Those measurements are provided by means of conventional devices (measuring transformers, voltage dividers) [3, 5, 8, 14] or modern electronic sensors [8, 17].

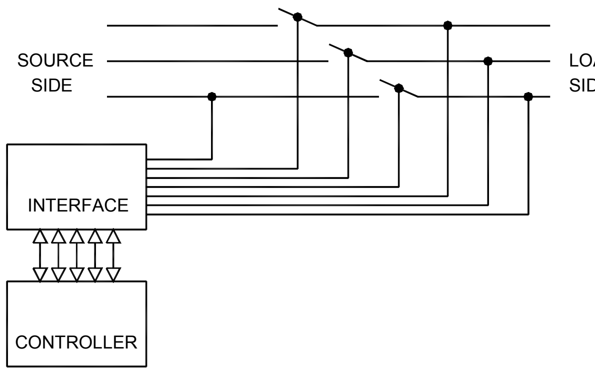

Fig. 3: Main parts of a typical controlled switching arrangement.

3. A controller, which is the "brain" of the system. It receives the signals from the measuring devices, deter-

mines the appropriate reference phase angles and sends the switching commands to each pole of the switching device by means of a suitable interface so that the closing or opening operation occurs at the optimum instant.

Fundamental requirement for all controlled switching applications is the precise definition of the Optimum Switching Instants. This definition is probably not trivial, since the switching instant leading 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 leading to the minimization of interesting voltages and/or currents at the same or at other network locations. It is obvious that shunt reactor switching a typical of such cases, since the closing instants resulting in current minimization are also the most adverse instants from the overvoltage aspect. However, as the maximum magnitude of these overvoltages is not significant, the optimum switching instants for the examined cases are chosen so as to minimize the DC components of neutral and phase currents for any neutral grounding condition, respectively.

Another important point which should be investigated is the statistical distribution of controlled circuit-breaker characteristics, which complicates the study of synchronized switching performance [3-16]. In fact, in almost all cases the electrical closing 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. 4 and 5 [3-16].

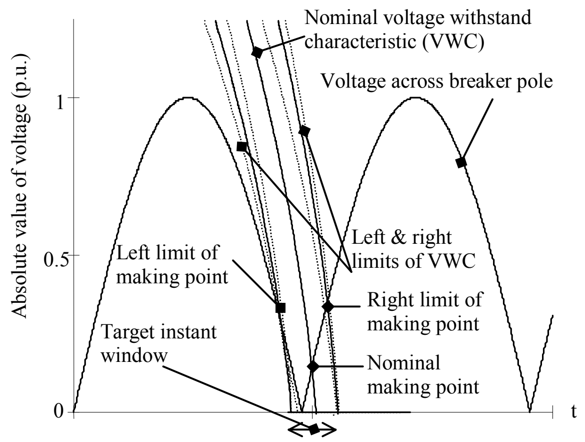

Fig. 4: Diagram illustrating the making instant window for a case where the most favourable target instant corresponds to zero voltage across breaker pole

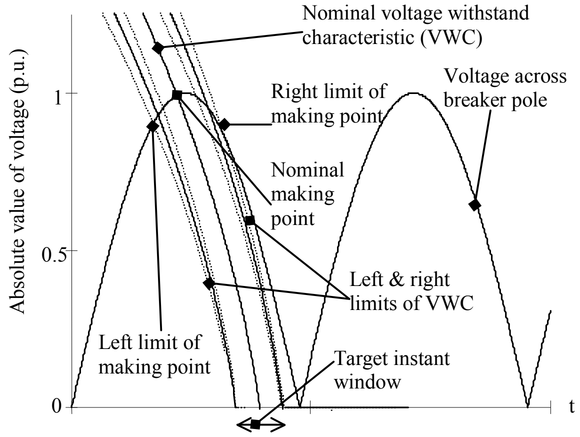

Fig. 5: Diagram illustrating the making instant window for a case where the most favourable target instant corresponds to peak voltage across breaker pole

From all the above issues, it is obvious that a further investigation is needed for the effect of the making instant deviations to the final degree of energization transients reduction. Such an investigation is carried out in the form of study cases described in the following paragraph.

V. Study Cases

A. System Configuration

For the realistic formulation of the problem, a real subsystem of the interconnected power system of Greece is used as an implementation. This is the power system of the greek island Cephalonia, which is fed by the interconnected power system of Greece through one lengthy HV submarine cable. During the low demand periods (winter nights for example), excessive reactive power produced by the capacitance of these cables causes a voltage increase (over 1.1 p.u.) to the HV/MV substations of the island. For the absorption of the surplus reactive power, HV shunt reactors of 22.5 MVar are connected to the island-side end of the cables. On the other hand, two HV shunt capacitors banks of 25 Mvar each are connected for the compensation of the high voltage drop appearing during the high demand summer days. The simplified diagram illustrating the examined system is shown in Fig. 6:

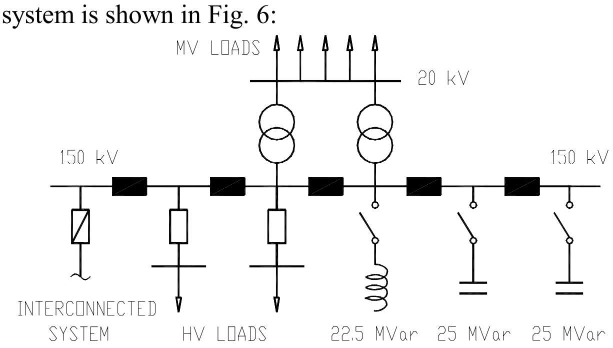

Fig. 6: Network considered for shunt reactor and shunt capacitor energization. Black, empty and hatched boxes represent HV bus sections, HV feeders and submarine cables, respectively.

Although reactor and capacitor neutrals are grounded in the actual system, investigation is carried out for both grounded and isolated neutral cases (which, it can be derived that are the most adverse ones [3, 4, 7]), just for comparison reasons.

B. Simulation Tools

Concerning the calculations of the most adverse transients appearing during the uncontrolled closing operation of the switching device, the widely known ATP/EMTP computer program has been used.

The calculation of the optimum switching instants is performed by means of Controlled Switching Calculation Program (CSCP), which has been developed in NTUA [15, 16]. Interaction of the three phases and the various statistical deviations of circuit-breaker characteristics are considered in this program.

C. Calculation of Most Adverse Transients

By means of the "systematic switch" feature of ATP/EMTP program, the maximum peak values of the transients produced by the energization of the shunt reactor and the back-to-back energization of the two capacitor banks in the examined location are calculated. The results show that:

- For the energization of the reactor with grounded neutral, the maximum possible phase currents are almost exactly equal to 2 per unit, while the maximum neutral current is somehow lower than 3 per unit.
- The maximum inrush currents of the two first phases-to-close exceed the value of 2.3 per unit and the maximum inrush current of the third phase-to-close is slightly greater than 2 per unit.
- The maximum value of the inrush currents appearing after the back-to-back energization of the capacitor banks considered with grounded neutral is 192 per unit, while the corresponding maximum transient overvoltages reach the value of 4.68 per unit.
- For back-to-back energization of the capacitor banks with ungrounded neutral, the maximum inrush currents are a little lower (180 per unit), but the maximum transient overvoltages are slightly higher (4.83 per unit).

D. Shunt Reactor Controlled Energization

As it has been mentioned previously, the optimum closing instant for each phase corresponds to the peak voltage between the breaker contacts in the respective phase. Closing at these instants eliminates totally the neutral current and the DC components of phase currents. However, the Rate-of-Decay of Dielectric Strength (RDDS) and the deviation of the starting instant of contacts movement (ΔT) have an unfavourable effect to the final results, as clearly seen in the Fig. 7 to 10.

In particular, as it can be seen in Fig. 7 and 8, the requirements which must be fulfilled by the controlled switching arrangement for the limitation of the maximum inrush currents below 1.5 per unit in the grounded neutral reactor case are the following:

- Maximum deviation of starting instant of contacts movement (ΔT) ±1 ms in conjunction with a relatively "fast" switching device with a Rate-of-Decay of Dielectric Strength (RDDS) greater than 1.0 per unit (1 per unit =V·ω, where V the amplitude of the sinusoidal voltage between breaker poles and ω the angular power frequency

or

- Maximum ΔT of ±0.7 ms with a switching device of practically any contact speed.

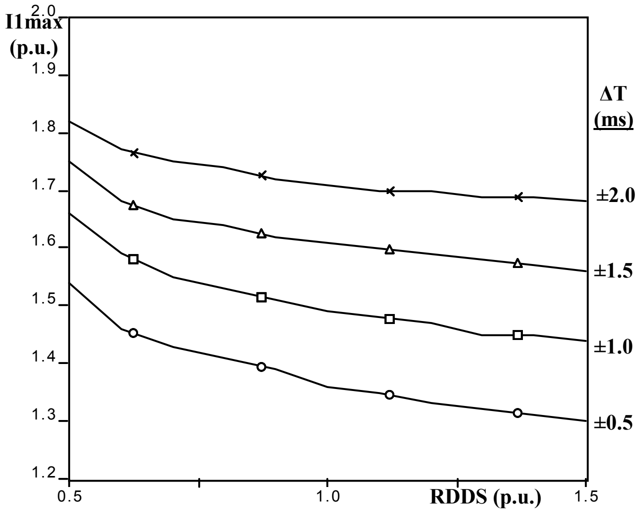

Fig. 7: Effect of RDDS and ΔT to the maximum phase inrush current upon controlled energization of reactor with grounded neutral.

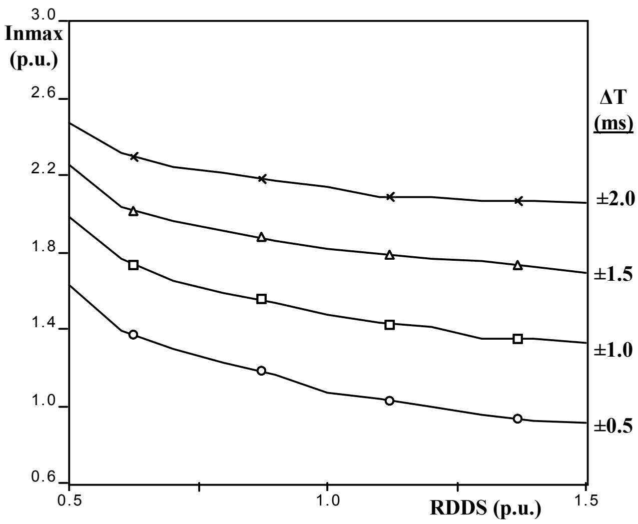

Fig. 8: Effect of RDDS and ΔT to the maximum neutral inrush current upon controlled energization of reactor with grounded neutral.

On the contrary to the grounded neutral case, according to Fig. 9 and 10, it seems that the limitation of the inrush current below 1.5 per unit is not practically possible for the two first phases-to-close, at least by means of the best known technological performance of today's and of near future controlled switching arrangements. Alternatively, if the limit of 1.7 per unit is acceptable, the required characteristics are a ΔT of approximately ±0.6 ms in conjunction with a relatively "fast" switching device with an RDDS greater than 1.0 per unit.

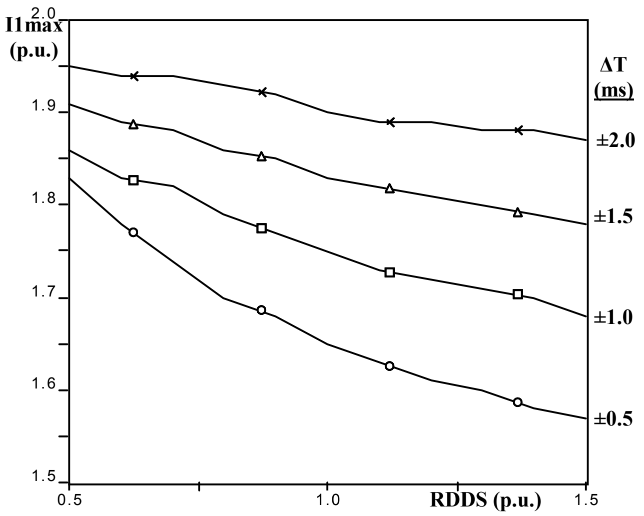

Fig. 9: Effect of RDDS and ΔT to the maximum inrush current of the first two phases-to-close upon controlled energization of reactor with isolated neutral.

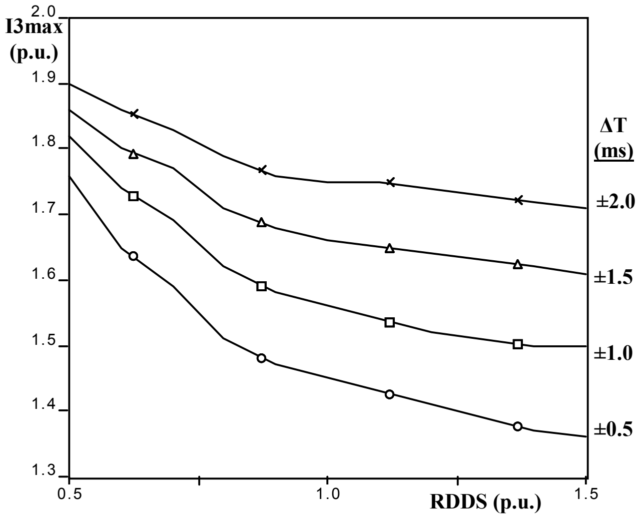

Fig. 10: Effect of RDDS and ΔT to the maximum inrush current of the third phase-to-close upon controlled energization of reactor with isolated neutral.

E. Shunt Capacitor Controlled Energization

On the contrary to the reactor case, now the optimum closing instants correspond to the zero voltage between the breaker contacts in each phase. Thus, according to Fig. 4, the requirements in this case is expected to be more stringent. However, their effect may be moderated due to the nature (high frequency, fast damping) of the produced transients. Indeed, the acceptable limits of the maximum peak values of these transients are 60 per unit for the inrush currents and 2.5 per unit for the transient overvoltages. The following figures show the influence of the Rate-of-Decay of Dielectric Strength (RDDS) and the deviation of the starting instant of contacts movement (ΔT) to the simulation results of controlled energization of shunt capacitors.

As it can be noticed in Fig. 11 and 12, the requirements which must be fulfilled by the controlled switching arrangement for the limitation of the maximum transients below acceptable limits in a grounded neutral capacitor back-to-back energization case are the following:

- Maximum deviation of starting instant of contacts movement (ΔT) ±1 ms in conjunction with a relatively "fast" switching device with a Rate-of-Decay of Dielectric Strength (RDDS) greater than 1.1 per unit

or

- Maximum ΔT of ±0.5 ms in conjunction with a more "slow" (and thus common) switching device with a RDDS greater than 0.75 per unit.

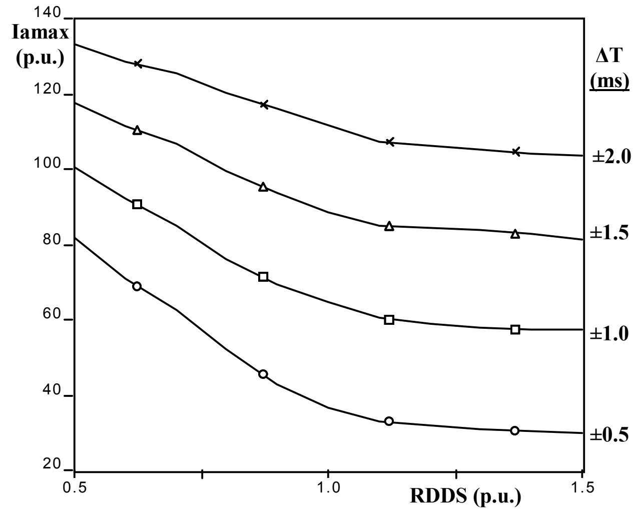

Fig. 11: Effect of RDDS and ΔT to the maximum inrush current upon controlled back-to-back energization of capacitor with grounded neutral.

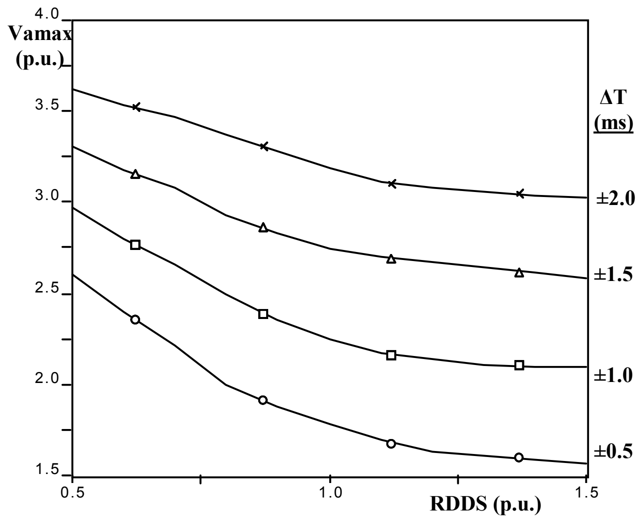

Fig. 12: Effect of RDDS and ΔT to the maximum transient overvoltage upon controlled back-to-back energization of capacitor with grounded neutral.

The results are more adverse in the isolated neutral case, as the voltage between breaker contacts prior to closing is 1.73 per unit for the second phase-to-close (closing of the first phase causes no current flow and therefore its closing instant may be uncontrolled). Thus, it is now more difficult for the prestrike to occur at or near zero voltage (Fig. 4). According to Fig. 13 and 14, the necessary requirement for successive controlled switching application is the use of an arrangement with a maximum ΔT of approximately ±0.6 ms in conjunction with a relatively "fast" switching device with a RDDS greater than 1.1 per unit.

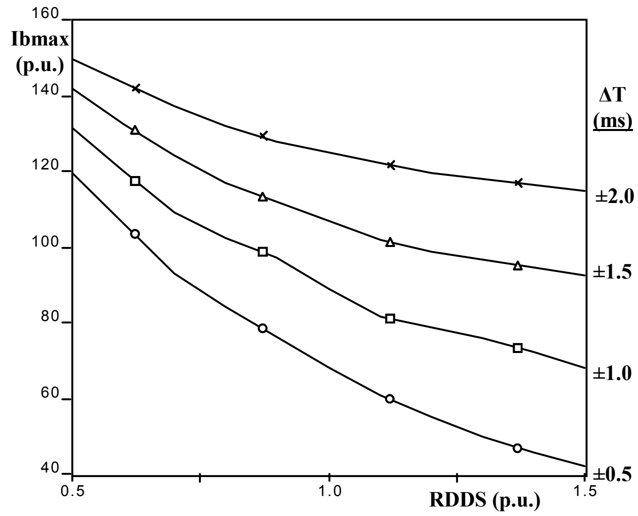

Fig. 13: Effect of RDDS and ΔT to the maximum inrush current of the first two phases-to-close upon controlled energization of capacitor with isolated neutral.

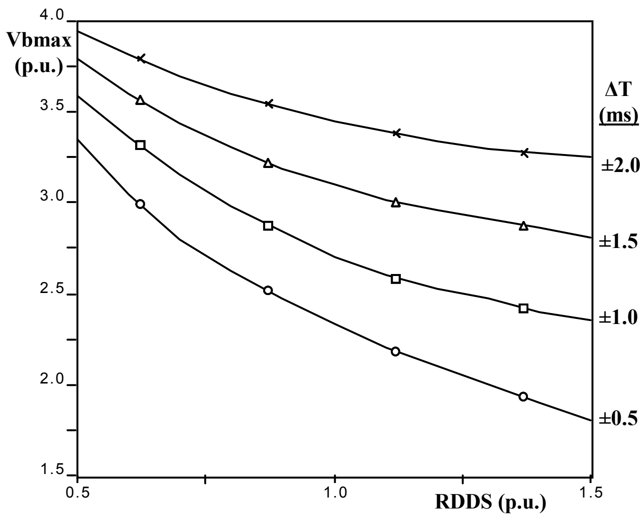

Fig. 14: Effect of RDDS and ΔT to the maximum transient overvoltage of the first two phases-to-close upon controlled energization of capacitor with isolated neutral.

VI. Conclusions

An implementation of synchronized switching to the energization of shunt reactors and shunt capacitors has been presented. Phenomena generating the most adverse energization stresses have been described and the possible benefits obtained by means of synchronized switching have been investigated. Various parameters, such as neutral grounding condition, dielectric characteristics and statistical variations of the switching device, affecting the effectiveness of this modern technique, have been taken into account. It can be mentioned succinctly, that the main requirement for effective application of synchronized switching is the use of controlled switching arrangements with quite small deviation of starting instant of contacts movement and high contact speed. With this requirement fulfilled, a very sufficient reduction of the dc current components and high frequency inrush currents and transient overvoltages appearing after the energizations of reactors and capacitors, respectively, is achieved, but only for grounded neutral cases. For isolated neutrals, the requirements are so stringent, which, in the case of reactor energization, makes the controlled switching application practically non-beneficial.

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