Abstract: - Transients produced upon shunt reactor switching (closing or opening), may be harmful for the reactor itself, for the switching device and for the adjacent system components. A variety of countermeasures, either alone or in conjunction, are used by the electric utilities for the reduction of these transients to safe levels. In the present study, an overview of the various common techniques for the safe switching of shunt reactors is presented and a comparison between the benefits of their use is made.

Key-Words: - Shunt Reactor, Switching Transients, ATP-EMTP Simulation, Synchronized Switching

1 Introduction

Switching of shunt reactors usually occurs quite frequently, even in a daily basis, since their connection to the network is due to reactive compensation reasons during the low demand periods (nights or weekends). Therefore, transients produced by switching on and off shunt reactors have to be investigated. Another reason for the usefulness of the analysis of transients produced upon circuit-breaker closing is that this analysis may comprise an initial tool for the understanding of the much more complicated phenomena following a reignition of the breaker contacts during an opening process.

Besides the conventional countermeasures (pre-insertion resistors or inductors, fixed inductors, surge arresters) used for the limitation of transients caused by the energization of network elements, such as capacitor banks, transformers and transmission lines, synchronized switching has been developed as a reliable mean to reduce switching stresses [1, 2]. 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 [1, 4, 5].

In the present paper, an overview of the possibly prejudicial phenomena caused by shunt reactor energization is presented and an investigation of the effectiveness of synchronized switching application for the limitation of the associated stresses is carried out.

2 Energization Stresses

Investigation of the phenomena appearing during the energization of three-phase shunt reactors can be discriminated into two parts, according to the grounding way of reactor's neutral node, namely for

• directly grounded neutral
• isolated neutral and
• neutral grounded via a non-zero impedance.

2.1 Grounded Neutral

As a simplified tool for the initial approximation of the phenomena, an ideal three-phase reactor of inductance L and zero resistance is used, the one-line diagram of which is shown in Fig. 1:

Fig. 1: Simplified one-line diagram for the energization of an ideal three-phase reactor with neutral grounded via an inductance Ln.

In this case, neutral grounding inductance Ln is zero.
In the case of systems with directly grounded neutral, the circuits of the three phases are independent and therefore they behave as three individual single-phase circuits. By means of simple calculations performed for the circuit of Fig. 1 and assuming that source voltage of phase "a" is given by the relation $E_S \cdot \sin(\omega \cdot t)$, the following expression is derived for neutral current after the operation of all the three poles:

$$I_n(t) = \frac{E_S}{L \cdot \omega} \left[ \cos(\omega t_a) + \cos(\omega t_b - 120') + \cos(\omega t_c + 120') \right]$$

(1)

where $I_n(t)$ is the neutral current, $E_S$ is the phase-to-ground peak voltage of the source and $t_a, t_b, t_c$ the closing instants of each breaker pole.

As it can be easily seen, the above expression depicts a generally non-zero dc current. The maximum possible absolute value of this dc current is 3 per unit and is obtained for switching at zero voltage across breaker contacts.

From Fig. 1 it can be also derived that reactor's voltage is 1 p.u. However, practical applications are quite far from the situation illustrated in Fig. 1, due to the following reasons:

- Shunt reactors are not ideal and their resistance is not negligible.
- Capacitive couplings between reactor windings and ground as well as between reactor windings themselves, must be taken into account.
- Source-side network is more complicated than an infinite bus.

As a first consequence, transient overvoltages appear at reactor bus. The maximum value of this overvoltage, obtained for switching at peak voltage across circuit-breaker contacts, is generally modest (less than 1.25 p.u.) and therefore not harmful [1].

From the other side, the dc neutral current is damped out due to the various resistances of the total circuit. However, the rate of this damping is low. The long duration of this high current may lead to the activation of zero sequence protective relays.

### 2.2 Isolated Neutral

Similarly to the previous case, an ideal three-phase reactor of inductance $L$ and zero resistance with ungrounded neutral is used, the one-line diagram of which is derived from Fig. 1, with the neutral grounding impedance branch is omitted.

Assuming that the energization sequence of the three phases is a-b-c, the following expressions are derived for the three phase currents after the completion of the three-phase energization process:

$$I_a(t) = \frac{E_S \cdot \cos(\omega t_a)}{L \omega} + \frac{E_S}{2L \omega} \left[ \sqrt{3} \cos(\omega t_b - 150') + \cos(\omega t_c + 120') \right]$$

(2)

$$I_b(t) = -\frac{E_S \cdot \cos(\omega t - 120')}{L \omega} + \frac{E_S}{2L \omega} \left[ \sqrt{3} \cos(\omega t_b - 150') - \cos(\omega t_c + 120') \right]$$

(3)

$$I_c(t) = -\frac{E_S}{L \omega} \left[ \cos(\omega t + 120') - \cos(\omega t_c + 120') \right]$$

(4)

The designations of the above equations are the same with those of Eq. (1), with the difference that closing instant of phase "a" does not appear in Eq. (2)-(4), since the first phase closing does not result in any current flow in a system with isolated neutral. From these equations it is derived that the maximum peak phase current is

$$I_{ph,\text{max}} = \frac{E_S}{L \omega} \cdot \frac{3 + \sqrt{3}}{2}$$

(5)

or 2.36 p.u. for the two phases-to-close and 2 p.u. for the third one. These maximum values are obtained for closing at phase angles corresponding to zero voltage difference between the first two phases-to-close and to zero phase voltage for the third one.

Similarly to the grounded neutral case, phase currents are damped out due to the various resistances of the circuit, but again the damping rate is low, causing probably the activation of overload protection systems.

### 2.3 Non-zero Neutral Grounding Impedance

This case may considered as the generalized case of the energization of three-phase reactors with any netral grounding condition, since it includes the previous two cases (grounded and isolated neutral) assuming that neutral grounding impedance is zero and infinity, respectively. The one-line diagram corresponding to this general case of grounding inductance of $L_n$ is shown in Fig. 2.

Assuming that the energization sequence of the three phases is again a-b-c, the following expressions are derived for the three phase and neutral currents after the completion of the three-phase energization process, with the same designations as equations (1)-(4):
where

\[ \varphi_a(t) = \tan^{-1}\left(\sqrt{\frac{L+Ln}{L+3Ln}}\right) \]  

(10)

The generalization character of the case is easily proved. Equations (2)-(4) are derived from the respective equations (6)-(8) for an infinite \( L_n \), which represents the isolated neutral. Similarly, by substitution of \( L_n \) with zero, which represents a directly grounded neutral, Eq. (9) is transformed to Eq. (1), depicting a dc current.

From Eq. (6)-(8) it can be derived that the maximum peak phase and neutral currents are 2.36 p.u. for the peak phase current and 3 p.u. for the dc neutral current and appear for infinite and zero \( L_n \), respectively. The important matter is, however, that they are obtained for closing at zero voltage across each breaker pole.

3 Stresses Limitation

The most usual techniques generally used for the limitation of the closing stresses in power systems are the following:

1. Pre-insertion resistors
2. Pre-insertion inductors
3. Fixed inductors
4. Surge arresters

5. Controlled (synchronized) switching

According to the first two methods, a branch consisting of a "secondary" circuit-breaker and a resistor or inductor, respectively, is installed in parallel to the main switching device. Closing of the auxiliary breaker prior to closing of the main breaker, inserts an additional series impedance to the switched circuit, leading in transients reduction. The result is, that transients produced by the subsequent closing of the main breaker are generally limited to safe levels. The technique can be more effective by the installation of more than one such parallel branches, with the most external one closing first. However, space limitations in the substations and power absorbance on the closing resistors reduce the effectiveness of the method.

Unlike the first two techniques, where the auxiliary resistors or inductors are connected temporarily, the third one requires the permanent connection of an inductor. This method has the advantage of the total absence of the secondary circuit-breakers as well as of any synchronizing mechanisms. From the other side, the permanent connection of such an inductor, intended to be used only for switching purposes, results in even higher losses. It is obvious that the use of inductors makes the application of the second and third methods to reactor switching cases useless.

The use of surge arresters intends to delimit primarily the transient overvoltages produced upon energization.

Application of conventional techniques to the examined cases of shunt reactor energization, seems to be of no sense, since the reduction of the, already not significant, transient overvoltages, would be the only benefit obtained by their use. From the other side, application of synchronized switching would be effective, since the magnitude of the reactor's neutral dc current is dependent on the closing instants of the three poles of the switching device, as described in previous paragraphs.

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 [1, 5]. 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 Figures 2 and 3 [1, 5]:

Fig. 2: Diagram illustrating the making instant window for a case where favourable target instant corresponds to zero voltage across breaker pole.

From Eq. (1) it is derived that for the grounded neutral cases, neutral current can be eliminated for simultaneous operation of the three poles (i.e. \( t_a = t_b = t_c \) in Eq. 1) or for closing instants corresponding to the peak voltage across each breaker pole for reactors with grounded neutral. It is obvious that the first condition can never be practically met, even for switching devices with simultaneous mechanical operation of the three poles, as pre-strike takes place at different instants for each pole, resulting in different making instants. However, the second condition is possible to be achieved, by means of a controlled circuit-breaker with independent poles operation.

Similarly to the grounded neutral case, for the isolated neutral case the optimum instants correspond to the peak phase-to-phase voltage for the two first poles-to-close and the peak phase voltage for the third pole. In other words, the optimum making instant corresponds to the peak voltage across each pole-to-close. This can be also derived for the generalized case of neutral grounding via an impedance. Therefore, the optimum target instant window for both cases (grounded and ungrounded neutral) can be determined according to the illustration of Fig. 3:

Fig. 3: Diagram illustrating the making instant window for a case where favourable target instant corresponds to peak voltage across breaker pole.

Two basic comments can be made on Fig. 5:

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 peak voltage, in order to achieve pre-striking (thus electrical current flow initiation) near peak voltage instants.

2. For the majority of energizations, pre-striking will occur at an instant close that corresponding to peak voltage, but not exactly at that specific instant. Therefore, a dc current component 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 elimination ability of the dc current components. 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 sub-system 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 lengthy HV submarine cables from two different locations. During the low demand periods, excessive reactive power produced by the capacitance of these cables causes a voltage increase (up to 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. The simplified diagram illustrating the examined system is shown in Fig. 4:

![Fig. 4: Single-line diagram of the network considered for shunt reactor energization. Black, empty and hatched boxes represent HV bus sections, HV feeders and submarine cables, respectively.](image)

Although reactor's neutral is grounded in the actual system, the investigation is carried out for both grounded and ungrounded neutral cases (which, as described in paragraph 2, are the most adverse as far as neutral and phase currents, respectively), just for comparison reasons.

Concerning the calculations of the most adverse transients appearing during the uncontrolled and controlled closing operation of the switching device, the widely known ATP/EMTP computer program has been used [6].

For the uncontrolled case, simulation has been performed for closing at the most adverse instants. For the controlled energization, simulations have been performed for a making instant spread of ±1.0 ms, which is typical for controlled circuit-breakers, and the most adverse results for each switching window are recorded.

For the neutral grounded case, the maximum neutral current, appearing for uncontrolled energization, is 3 per unit having a low damping rate as shown in Fig. 5, while the maximum transient phase-to-ground overvoltage at reactor's bus shown in Fig. 6 is 1.1 p.u.

![Fig. 5: Maximum neutral current during energization of reactor with grounded neutral. The sinusoidal curve represents one steady-state phase current.](image)

As expected, no improvement to the magnitude of transient overvoltage is achieved with the application of synchronized switching. Fig. 7 shows, however, that after an initial spike in its waveform, neutral current remains in quite low levels.

![Fig. 7: Neutral current after controlled energization of reactor with grounded neutral. The sinusoidal curve represents one steady-state phase current.](image)

Similarly to the grounded neutral case, maximum transient overvoltages obtained for the isolated neutral case are also not significant (less than 1.2 p.u.). Their waveform is shown in Fig. 8:

![Fig. 6: Transient phase-to-ground voltage during energization of reactor with grounded neutral. The smooth curve represents the steady-state voltage.](image)
Fig. 8: Transient phase-to-ground voltage during energization of reactor with isolated neutral. The smooth curve represents the steady-state voltage.

As shown in Fig. 9, for the uncontrolled case the phase current comprises a dc component with low damping rate. The magnitude of this dc component exceeds 1.0 p.u., resulting in a peak phase current of over 2.0 p.u., which may cause overloading problems, due to its long duration.

Fig. 9: Maximum phase current after energization of reactor with isolated neutral. The sinusoidal curve represents the steady-state current in the same phase.

In this case, application of controlled switching results in the total effacement of the dc current component, as shown in Fig. 10:

Fig. 10: Phase current during controlled energization of reactor with isolated neutral. The purely sinusoidal curve represents the steady-state current in the same phase.

5 Conclusions

An implementation of synchronized switching to the energization of shunt reactors 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 neutral grounding condition, dielectric characteristics and statistical variations of the switching device, probably affecting the effectiveness of this modern technique, have been taken into account.

It can be mentioned succinctly, that the main advantage of synchronized switching is that it results to a very sufficient elimination of the dc neutral current and the dc components of phase currents appearing after all energizations of reactors with any possible neutral grounding condition.

From the other side, the contribution of synchronized switching to the reduction of the transient overvoltages is negligible. However, the latter are not a source of damage in practical cases.

References:


