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NUMERICAL SIMULATION OF CAPACITIVE AND SMALL INDUCTIVE CURRENTS SWITCHING-OFF IN HIGH-VOLTAGE SYSTEMS

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Abstract- Study of transitional processes in electric power systems being one of the main factors determining their reliability, is one of the most important problems for researchers working in area of electrical power engineering. Rapid developing of software of engineering problems and hardware, taken place for the last few decades significantly widen numerical research capabilities. Presently numerical modeling and computer simulation are widely used as primary research tool for the most of engineering problems. Therefore, ensuring the adequacy of mathematical models requires a comprehensive study of the features of simulation tools in relation to the problems to be solved. The switching transitional processes in high-voltage systems are formalized in mathematical models as the system of first order “stiff” differential and algebraic-differential equations with non-linearity and some logical conditions for setting current interruptions (current chopping) and arc’s repeated re-strikes and re-ignitions, that determines complexity of the problem. Some computational features in Matlab set of the problem under consideration conditioned by the methods (ode solvers) and algorithms (fast and robust ones) used, impact of some physical phenomena and parameters and also influence of type of circuit-breaker (vacuum and SF_6) on transitional voltages’ behavior and stability of solutions are generalized and presented in this article. All the researches’ results and conclusions were obtained by the working up of numerous acts of computer simulation carried out in wide ranges of initial step size and relative tolerance. So stiff ordinary differential equations’ solvers included in the Matlab set are investigated in this work from the point of view stability in the context of transitions in electric power systems. Quantitative and qualitative distinctions conditioned by the four different stiff methods (solvers) are studied on high-voltage power capacitor banks switching-off. It is shown in the work that in some cases even a little quantitative distinction of transitional functions’ instantaneous values from ones for stable solutions due to step-to-step accumulation of local errors may cause qualitative distinctions in solutions’ behavior. Switching of capacitor banks in FACTS networks are also studied in the research.

There are considered and investigated the key computational features of computer simulation transitional processes at switching-offs unloaded transformers by SF_6 and vacuum circuit-breakers at use different stiff ordinary differential equations’ solvers and algorithms realized them. In this article the influences of some physical factors (free frequencies, attenuation, and type of circuit-breaker) on the simulation process and solutions’ stability are shown. There were given the possible interpretations for the reasons and phenomena being responsible for the worsening of stability at numerical research transients in electric power systems.

At the same time the article presents results of research dedicated to study dependence of transitional voltages at switching-off unloaded transformer on its input capacitance. This parameter is one of the most important parameters which determine nature of the transition process and its computational features. This is because of very small values of the input capacitance of transformers and autotransformers causes, on the one hand, high free frequencies of transition process and considerably high stiffness of differential equations that mathematically formalize the process under consideration, on the other.

This article also presents the results of a study of some of the physical and computational features of unloaded transmission lines’ switching-offs. It has been established that there is no monotonic dependence between the values of transient voltages when high-voltage overhead lines are disconnected, against their length. The influence of the type of circuit-breaker (SF_6 or vacuum) on transient voltages has been investigated. The article examines the features of using ordinary differential equation solvers in computer modeling from the point of view of the solutions' stability and the time consumption in simulation.

Keywords: Computer Simulation, Simulation Parameters, Ode Solvers, Stability of Solutions, Stiffness, Transitional Voltages, Local and Global Error, Repeated Re-Strike, Input Capacitance, Fre Frequency, Electric Strength Restoration, Flexible AC Transmission System (FACTS).

1. INTRODUCTION

High voltage circuit-breakers are among the most important equipment in power systems. They are designed not only to interrupt the high magnitude of short-circuit currents. It is expected that high voltage circuit-breakers must be operated in any applications, such as switching of different loads (capacitor banks, reactors and unloaded transformers or transmission lines) without problems. The requirements of these types of switching are not only different, but might even conflict with those of the high current interruption.

It is known that switching transients are one of the most dangerous for the reliability of the electrical systems. In one's turn from these varieties of switching transients we must especially notice two types of switching-off. The first one is switching-off the capacitive currents of the capacitor banks having great rated values of jet power and unloaded power transmission lines. The second one is switching-off the small inductive currents of unloaded transformers and autotransformers.

Since 70s of the previous centuries, it has been known that, the main way to study transitional processes in electric power systems is the modeling and computer simulation [1, 2]. This significantly increased requirements to numerical methods adequacy and models used. So, numerical methods themselves and their applicability to the solving of different research problems under consideration with the required accuracy and acceptable time-consuming have become the separate subject of study [3, 4].

The main concept in the view of considered problem is so called "stiffness" of differential equations that mathematically formalizing relations between transitional functions (voltages and currents) and their first temporal derivatives. This concept is periodically undergoing some transformations conditioned by working new methods. Initially defined as one depended exclusively on differential equation itself (its coefficients) [5] it became then wider and defined also as one depended on problem's solvability [4] i.e., the problem being "stiff" by classical definition was not assumed to be "stiff" if it could be solved via applying any new method worked-up just for solving this class of problems. Note that these methods are also called "stiff" methods, e.g., 4 from 8 ordinary differential equation (ode) solvers in Matlab set [6]. Also note that numerical research and computer simulation of electromagnetic especially the transitional processes of switching in electrical power systems belong to the "stiff" problems' category [7], [8].

The urgency of the problem is confirmed by numerous studies in this area conducted during the last decade [9-13]. There are considering some computational features of computer simulation transitional processes in electric power systems in this work. The transitional functions studied are voltage across the terminals of switched-off installation and recovery voltage (RV) between circuit-breaker poles.

The computational features at numerical simulation switching processes in electric power systems are mainly conditioned by:

- characteristic parameters of switched-off installation and network especially free frequency and attenuation;
- method (ode solver) and algorithm (fast or robust) used;
- simulation parameters (initial step size and tolerances);
- type of circuit-breaker and so on. The first point reflects the classical definition of differential equations' stiffness [5]. The first three points taken together determine the widened concept of "stiffness" [4], [14], [15].

2. RESEARCH GROUND AND DATA

The electrical installations had been studied were 110 KV power capacitor banks and unloaded transformers, and 220 KV unloaded power transmission lines. All the parameters were presented in details in [8], [16]. The electric and equivalent schemes are presented in Figures 1, 2 and 3, respectively [8], [16].

3. THEORETICAL GROUND OF THE RESEARCH

The following numerical methods from Matlab set for solving stiff ordinary differential equations listed in [14] were used for simulation of transitional processes under study:

a) ode 15s: It is a variable-order solver. It uses the backward differentiation formulas, which are usually less efficient.

b) ode 23s: It is a one-step solver. It is often more efficient than ode15s at crude tolerances. It can solve some kinds of stiff problems.

c) ode 23t: It is an implementation of trapezoidal rule. This solver can be used if the problem is moderately stiff.

d) ode 23tb: It is an implementation of the trapezoidal method with backward differentiation. Like ode23s, this solver has been often more efficient than ode15s at crude tolerances [14].

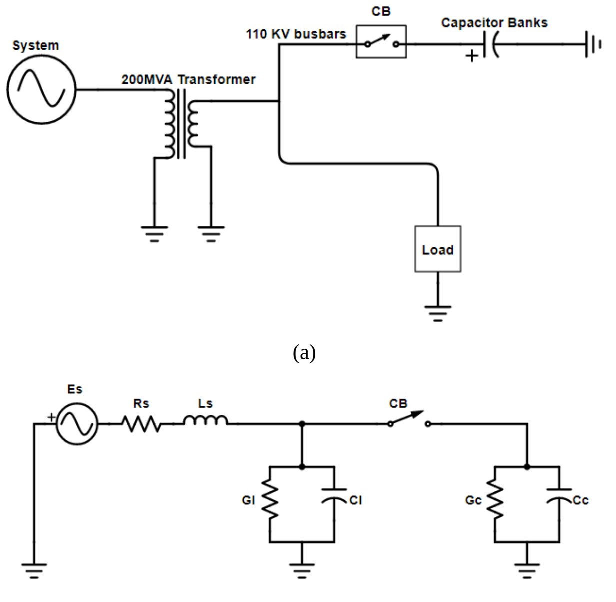
All the numerical methods used for simulation in this work have two algorithms (fast, robust), except the ode 23s method. Both fast and robust algorithms were used at simulation for all cases under studying. The research had been implemented in wide ranges of simulation parameters. The initial step sizes values changed between 10^{-8} and 10^{-4} seconds, the relative tolerance values changed between 10^{-6} and 10^{-4}.

Note that above-minded methods (solvers) were created just for solving stiff differential equations. Use of different methods and algorithms gives us an opportunity to evaluate the stiffness of problem.

Note, that according to used algorithm we take into account the phenomena of a current chopping and repeated re-ignitions of the arc. Current interruption in circuit-breakers (i.e., arc quenching) is set at condition,

$$|i| \le I_{ch} \tag{1}$$

where, i is decreasing current through the contacts or arc, I_{ch} is chop current depending on the circuit-breaker type, which is one of the important parameters of circuit-breakers from the point of view expecting magnitudes of transitional voltages at switching-offs [15].



(a)

(b)

Figure 1. Single phase representation of capacitor bank switching-off [8], (a) electric scheme, (b) equivalent network

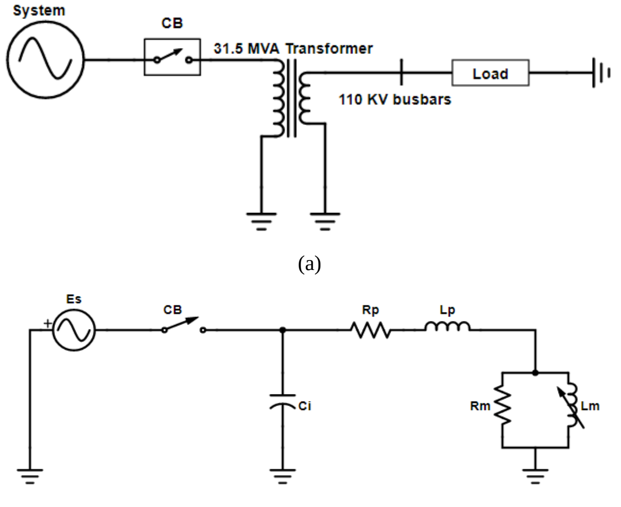


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Figure 2. Single phase representation of unloaded transformer switching-off [8], (a) electric scheme, (b) equivalent network

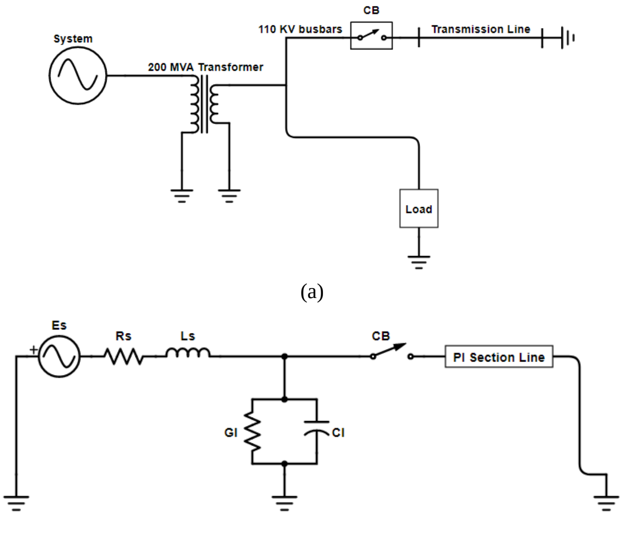
Repeated ignitions and strikes of arc between the circuit-breakers' poles are set at the following condition.

$$|\Delta V| \geq V_{es}(t) \tag{2}$$

where, ΔV is a recovery voltage (between poles of the circuit-breaker), and $V_{es}(t)$ is a function of circuit-breaker's electric strength restoration [15].

As it is known there are numerous characteristics of circuit-breakers that determined their influence on the switching process. The more effective characteristics during switching-off processes are electric strength restoration, chopping current and full operation time [16].

It is known that at the instant of circuit-breaker switching-off, a moving contact starts to separate away from the fixed contact and causing the electric strength in the interrupting medium (gap) starts to increase.



(a)

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Figure 3. Single phase representation of unloaded power transmission line Switching-off [16], (a) electric scheme, (b) equivalent network

At the instant of successful current interruption, transient recovery voltage (TRV) appearing between the circuit-breaker contacts with high value for a very short duration of time. It means that from the instant of arc extinguished a competition between TRV and circuit-breaker dielectric withstand begins. If the rate of rise of *TRV* is more than the electric strength restoration speed of the circuit-breaker a breakdown occurs and creates an arc in the interrupting medium which causing a current to continue to flow between the circuit-breaker contacts. Then the value of TRV returns back to zero and does not appear again before the arc is extinguished. Therefore, the dielectric withstand in the interrupting medium of the circuit-breakers is an important parameter and essential for the switching analysis.

For the modeling of dielectric properties of the inter-contact spaces of circuit-breakers, many researchers suggested to use a co-sinusoidal law of electric strength restoration. This co-sinusoidal law is formalized and written as Equation (3):

$$V_{es}(t) = 2^{-1} V_{\max} \left\{ 1 - \cos\left[\frac{\pi\left(t - t_{off}\right)}{T_{full}} \right] \right\} \tag{3}$$

where, $V_{es}(t)$ is the acceptable electric strength restoration law of circuit-breakers, $V_{\max}$ is the greatest value of circuit-breaker electric strength, t is the time, T_{full} is the full switch-off time of circuit-breaker contacts, t_{off} is the initial instant of circuit-breaker moving contact separation [16].

The main advantages of this law as following:

I. Takes into consideration the inertia of circuit-breaker contact;

II. Has a great matching with the movement law of circuit-breaker contact;

III. Has acceptable coincidence with the real law for SF_6 circuit-breakers [17].

The co-sinusoidal law may be used both for auto-compression and vacuum circuit-breakers. This law gives the most successful approximation for real $V_{es}(t)$ curves of auto-compression (SF_6) circuit-breakers. Some authors use the linear restoration law to model vacuum circuit-breakers [18], [19]. According to this law the electric strength increases as the increasing inter-contact distances which make the vacuum circuit-breaker (VCB) bigger in volume and the arc will be unstable. Thus, the nature of this law is not matching with the physical nature of the vacuum inter-contact gaps [15]. Therefore, an improved way is used to model the dielectric strength of vacuum circuit-breaker. This way is marked as logarithmic restoration law. This law takes into account the inertia of contact and inconstancy of strength of vacuum gaps [20]. So, this law has a good matching with the physical nature of the vacuum inter-contact gaps. The logarithmic restoration law for VCB dielectric strength on the base of empirical curve given in [21] as following:

$$V_{es}(t) = 191.43\log\left\{1+5.75X_{\max}(1-\cos A)\right\}$$

$$A = \left[\frac{\pi\left(t-t_{off}\right)}{T_{full}}\right] \tag{4}$$

where, $X_{\max}$ is the maximum distance between circuit-breaker contacts [16].

As shown in Figure 4 [16] the dielectric strength restoration by linear, co-sinusoidal and offered (logarithmic) laws are presented graphically. The graphical representations of these laws are denoted as 1, 2 and 3, respectively. Note that the logarithmic law has a little change (between −7% to +4%) from the corresponding empirical law. This law also gives satisfactory approximation for all the switching period.

4. METHODS AND ALGORITHMS USED AND SOLUTIONS STABILITY

Our investigations have shown that, the methods and algorithms used for computer simulation transitional processes in electric power systems may have very notable and sometimes even decisive influence on solutions stability. Thus, some methods and algorithms are not able to provide stability of solutions for some transitions caused by high-voltage electrical installations switching and consider it in details for different transitions.

4.1. Switching-off Power Capacitor Banks

As you know, computer simulation is one of the main, and sometimes the only means of studying scientific and engineering problems. This is very important for solving many problems in the electric power engineering, especially when studying switching transients in electric power systems. Still B. Swanson noted at the end of the seventies of the last century that the numerical simulation is becoming the main tool for the study of transients due to the high cost of field studies and fundamental flaws of physical modeling of the problem under consideration [22]. It notably increases requirements to the adequacy of numerical modeling and computer simulation of the physical processes.

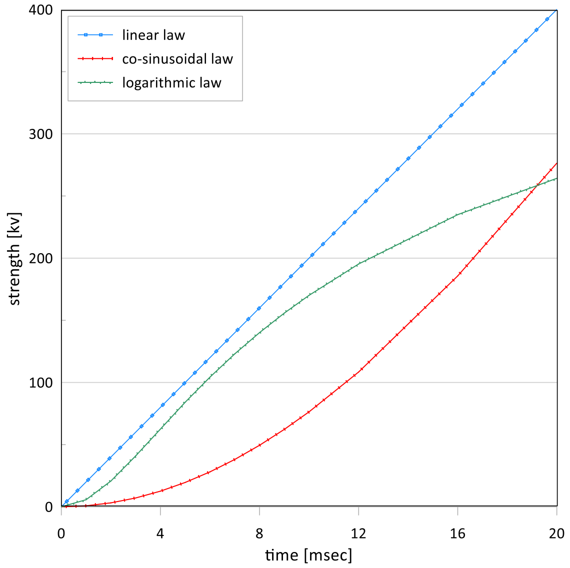


Figure 4. Linear (1), co-sinusoidal (2) and logarithmic (3) laws of circuit-breaker's electric strength restoration [16]

The stiff ordinary differential equation solvers included in Matlab are explored in this section for stability in the context of power system transients. The quantitative and qualitative differences caused by four different stiff methods (solvers) used in a wide range of initial step size and tolerances when disconnecting high-voltage power capacitor banks are investigated.

This section is devoted to the study of the influence of the global error caused by local rounding and limiting errors that occur at each modeling step and accumulate from step to step on the development of the transient process and the magnitude of the transitional functions.

The results of computer simulation switching-off capacitor banks by vacuum circuit-breaker at use different ode solvers in wide ranges of initial step size and tolerances equals (10^{-6}, 10^{-4}) are presented in Figure 5 [23]. This figure concern to the overvoltage's across the terminals of the capacitor banks at these tolerances.

Now consider how to distinguish a stable solution from an unstable one. The basic rule for recognizing an unstable solution is that it has a significant quantitative difference from stable solutions, while all stable solutions of the same problem (obtained using different modeling methods and modeling parameters) are equal, within a very small calculation error, not exceeding tenths or even hundredths of a percent. In other words, all stable solutions are the same; the unstable solution is markedly different. From Figure 5 we noted the following:

- The final approach of the overvoltage values to their stable values has taken place with a decrease in the initial step size for all stiff methods included in the Matlab set, i.e., ode 23tb, ode 23t, ode 15s and ode 23s. Note that the ode 23t solver gives small deviations from the functions obtained by the ode 23tb, ode 15s, and ode 23 s solvers, even with the smallest initial step sizes used in computer simulations. Note also that the same conclusion can be drawn with respect to the convergence of transition functions changing by tolerance at fixed initial step sizes.

- The largest deviation of the transition functions in the problem under consideration when using all the above modeling methods (ode solvers) and the modeling parameters given in this study does not exceed 5-6%.
- Add here that behavior of transitional functions is more uniform at varying tolerance rather than initial step size [23]. So, varying of tolerance at fixed initial step size is preferable at looking for stable solutions.

Note that computer simulation of transient processes when disconnecting unloaded transformers and autotransformers in electric power systems has some similarities with the problem under consideration [24]. The main difference between these problems is the greater stiffness and, consequently, the poorer solvability of the problem of disconnecting unloaded transformers.

From previous the stiff ode solvers ode 23tb, ode 15s and ode 23s and corresponding algorithms included in Matlab set provide good stability at the computer simulation in the case of high-voltage power capacitor banks switching-off [16]. In our opinion it is conditioned by relatively little (about a few hundred Hertz) free oscillations frequencies typical for capacitor banks rated reactive powers and source's (transformer's) inductances. Just the solver ode 23t does not provide stability for this kind of problems as shown in Figure 5.

Note here that use of robust algorithms at simulation switching-offs capacitor banks is inexpedient because that solutions for transitional functions are got unstable, and have very notable deviations from stable solution (got by use the fast algorithms) in all the ranges of simulation parameters.

Note that presented features of the ode solvers were stated for the cases when circuit-breaker arc influence on switching processes was not taken into consideration.

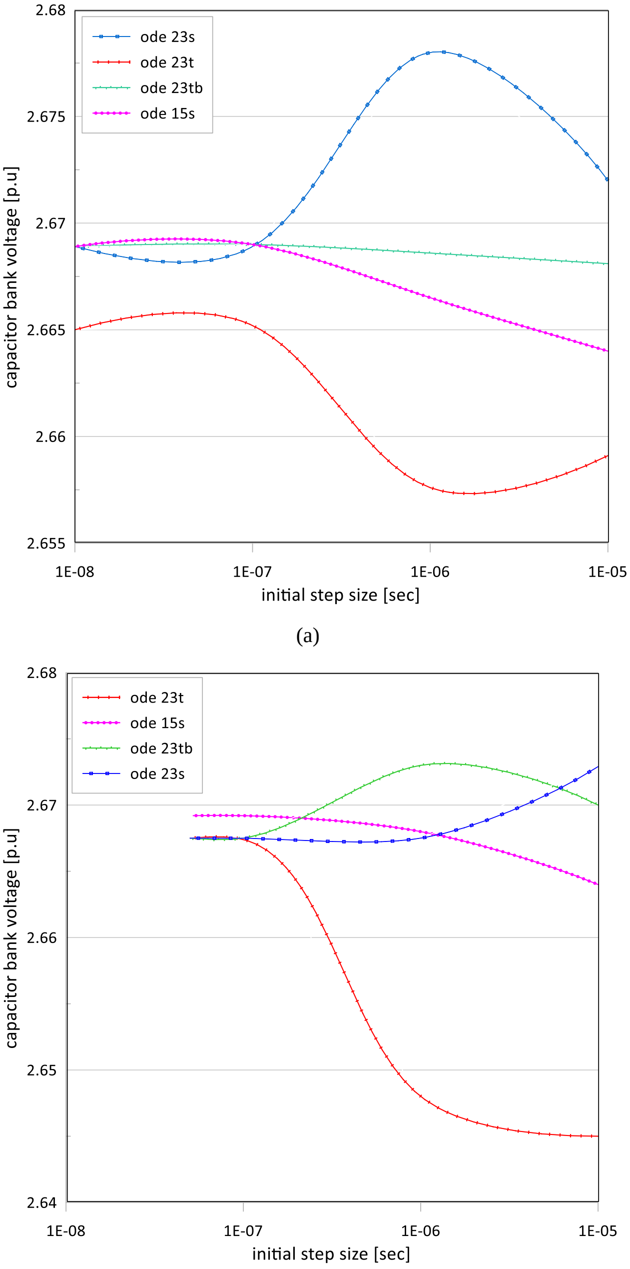
Although the above-presented conclusions were got for certain range of network parameters (typical for real installations of rated voltages until 220 kV), we suppose that they are general enough.

In conclusion of this section, we present curves illustrating the different behavior of solutions (voltage ratios across the installation terminals) when using fast and robust algorithms of the same simulation method, Figure 6 [23].

Our researches show that in general either of algorithms used (fast or robust) of the same method may be preferable dependently on the problem solved.

4.2. Switching-Off Unloaded Transformers (Autotransformers)

It is widely known that, switching-offs unloaded power transformers and autotransformers in electric power systems is one of unfavorable operation modes due to their dangerous impact on high-voltage insulation [25], [26]. So, a study of this kind of switching and prevention of its possible undesirable impact on high-voltage insulation has always been important in the view of necessity to provide reliable functioning of system's equipment.



(a)

(b)

Figure 5. Behavior of solutions (ratios of voltage across the installation terminals) at use fast algorithms for switching-off 110 kV capacitor bank of 75 MVAr [23], (a) at relative tolerance 10^{-6}, (b) at relative tolerance 10^{-4}

The problem studied a priori has a complicated character. As it was shown in [7] numerical modeling of transitions in electric power systems belongs to the "stiff" problem's category [4], [5], [27]. Computer modeling and simulation of those problems have usually faced with the stability problem. Possible loss of stability is conditioned by accumulation of local errors leading to the growth of global error with subsequent "repulsion" of the solution from the stable one.

As previously noted, successful computer simulation of the stiff problems requires primarily determination of appropriate method (ode solver) and simulation parameters (initial step size, and tolerance) providing stability of solutions, e.g., sometimes it may be required also determination of the best algorithm (fast or robust) concerned to the same method [28].

There are some physical parameters and phenomena characterizing transients under consideration and affecting on results of computer simulation from the point of view of stability. The following sections discuss each briefly.

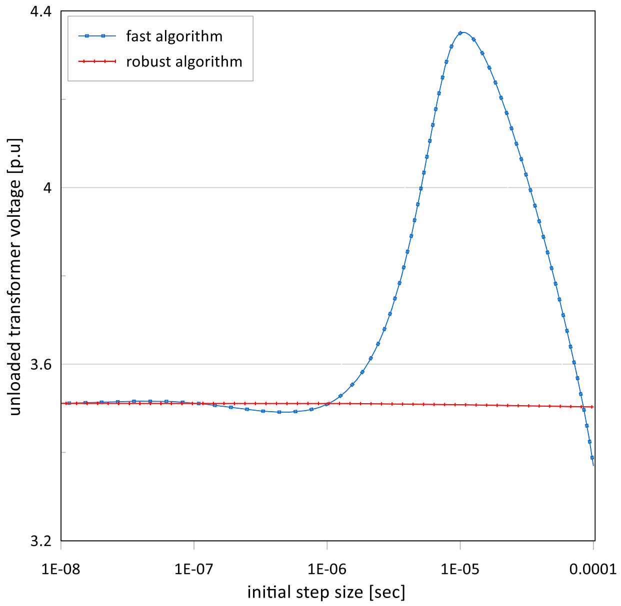


Figure 6. Behavior of solutions at use fast and robust algorithms (relative tolerance 10^{-6}) for switching-off 110 kV unloaded transformer of 41 MVA [23]

4.2.1. Influence of Free Frequencies on Computer Simulation's Stability

As it was shown in [16], [23] higher free frequencies may lead to worsening of stability via increasing of local errors. It takes place because of greater steepness of transitional functions at higher free frequencies. Note that at network transformations taken place at quenching and re-ignitions (re-strikes) of arc in inter-contact spaces of circuit-breakers there may appear free oscillations of more than one frequency. In general, it may require use of significantly little values of initial step size at computer simulation. It must be noticed here that as a rule solution for transitional functions obtained at simulation of switching-offs unloaded transformers has worse stability in comparison with ones got for switching-offs power capacitor banks [16], [23].

On our opinion, it is conditioned by very little value of transformers' (and autotransformers') input capacitance which is about 1 or 2 dozen of nano-farad [28], [29]. By this reason, free frequencies in the circuit containing transformer's magnetization inductance and input capacitance reach high values. Thus, higher free frequencies lead to increasing of local and global errors and obstruct obtaining stable solutions. As it is seen from Figure 7 [28], the higher free frequencies conditioned by lesser input capacitances leads to worse stability for voltage across the transformer's terminals and recovery voltage.

Note that at lesser relative tolerances there have taken place significantly greater deviations of transitional voltages from their stable values.

The curves shown in the Figure 7 were got at use the Rosenbrock method ode 23s, simulations were implemented at relative tolerance equaled 10^{-6}. The conclusions and explanations given are acceptable for all the stable methods. The same tendency has taken place for switching-off power capacitor banks. Stability of solutions is better for capacitor banks of greater (reactive) power since greater power corresponds to greater capacitance and less frequency of free oscillations.

4.2.2. Influence of Attenuation in Switched-off Circuit and Arc Resistance on Computer Simulation's Stability

It is known that resistive elements in physical systems may affect positively on asymptotic stability that is conditioned by attenuation of transitional functions due to energy losses [30]. The main attenuating factors in the problem under consideration are resistance of the switched-off transformer itself and resistance of arc in inter-contact space of circuit-breaker (note that values of the arc resistances depend on circuit-breaker type [31]).

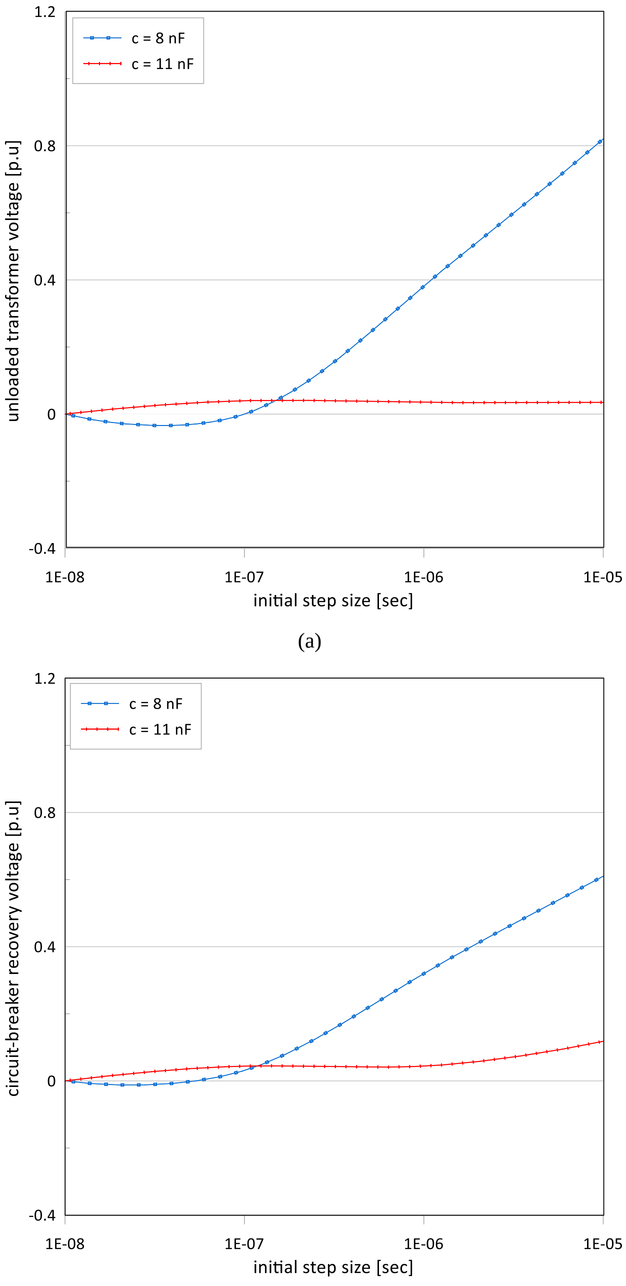
Higher attenuation factors in the electrical circuits during the transitional process will lead to greater damping of free frequencies. In computational aspect it means that change of transitional functions as a result we get less local and global errors and in general, better stability of solutions.

These general suppositions and explanations are not unequivocally. So, as it was shown in [8] taking arc resistance seeming a priori a factor leading to the greater attenuation does not always improve stability. Moreover, at use some ode solvers stability may be even worsened [8], [23]. We suppose that it is conditioned by closer (due to additional attenuation) magnitudes of transitional functions of two consecutive points in areas of lesser steepness.

4.2.3. Influence of Circuit-Breaker's Type on Computer Simulation's Stability

Our previous researches showed that type of circuit-breaker can seriously influence on the flow of transition process and magnitudes of transitional functions of voltages and currents [16], [24], [32]. The type of circuit-breaker (vacuum and SF_6 ones in our researches) can impact on the switching transitional process via value of chop (or chopping) currents, electric strength restoration law and full switching time [20], [28], [32].

Here we are interested in influence of circuit-breaker type on computer simulation's stability. There we can note the following feature conditioned by circuit-breaker type we observed at the computer simulation. As a rule, transitional functions at switching-off electrical installations (power capacitor banks, unloaded transformers and autotransformers, unloaded power transmission lines) have worse stability for the cases of switching by vacuum circuit-breakers. It is conditioned by higher magnitudes of over voltages and recovery voltages taken place at use vacuum circuit-breakers [16], [20]. As a result, in general we get higher instantaneous values of transitional voltages and currents and higher local errors affecting on global error and stability.



(a)

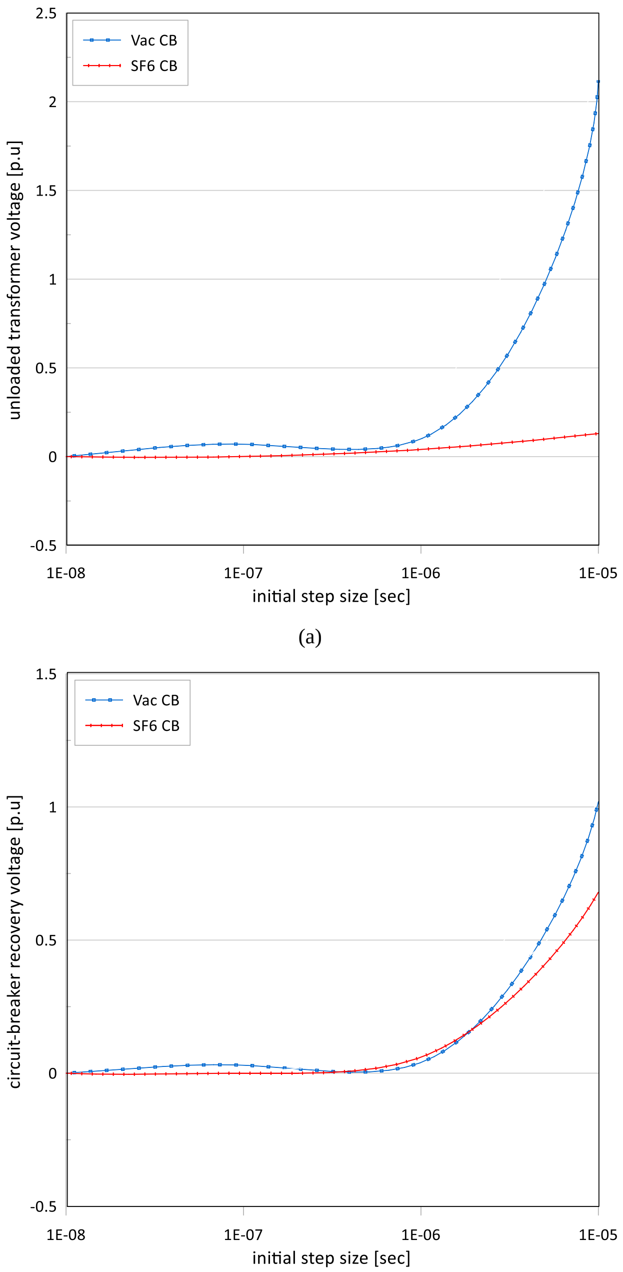
(b)

Figure 7. Calculated deviations of transitional voltages from their stable magnitudes for different input capacitances of switched-off transformer [29], (a) across transformer terminals, (b) across circuit-breaker poles (RV)

The given explanation is well illustrated in Figure 8 [29]. As it is seen from these Figures, computer simulation of switching-off unloaded transformers by vacuum circuit-breaker is accompanied by higher deviations of transitional functions from their stable solutions (due to above given reasons). The curves concerned to the unloaded transformer switching-off (Figure 8) were got at use the Rosenbrock method ode 23s with relative tolerance equaled 10^{-6}. The conclusions and explanations given are valid for all the stable methods listed previously.

Notice that conditions for option the initial step size taking circuit-breaker chop current into consideration given in [33] are easily satisfied because of its very little values needed to provide stability of solutions.

The example of stable solutions for switching-off unloaded transformer is given in Figure 9 [29].



(a)

(b)

Figure 8. Calculated deviations of transitional voltages at switching-off unloaded transformer from their stable magnitudes for different types of circuit-breakers [29], (a) across transformer terminals, (b) across circuit-breaker poles (RV)

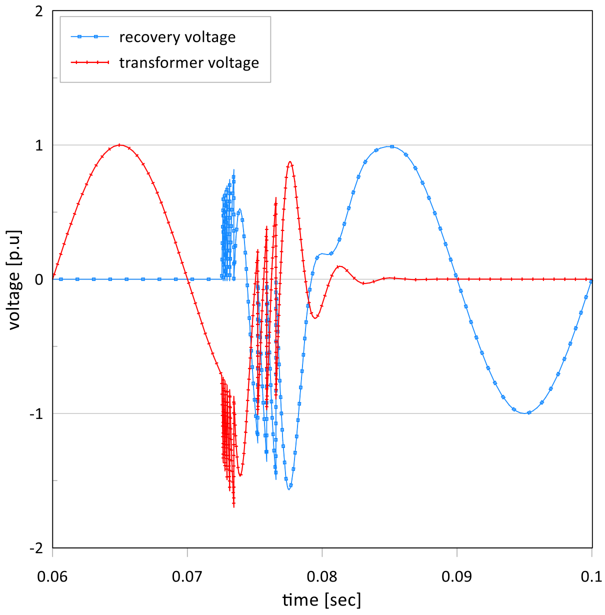


Figure 9. Simulated transitional voltages (stable solutions) at switching-off unloaded transformer [29]

As it is known solution's stability of differential Equations and their systems are closely related to the stiffness concept [4], [34], [35]. Our above presented researches showed once again that the stiffness is a complicated definition which must be estimated with taking into consideration methods (ode solvers) and simulation parameters.

At the end of this section, it should be noted that, fast algorithms of ode 23tb and 23t solvers cannot provide stability and even solvability at computer simulation whereas their robust algorithm provides getting of stable solutions. The Rosenbrock method and solver ode 23s (having the only algorithm) easily provides convergence of solutions. The ode solver ode 15s works effectively with the robust algorithm and worse (but satisfactory) with the fast algorithm [23].

4.2.4. Influence of Unloaded Transformer Input Capacitance on Computer Simulation's Stability

As it was stated earlier over voltages at switching-offs unloaded power transformers is conditioned by magnetic field's energy stayed in the transformer core after chopping of switched-off current and their followed exchange between magnetization inductance and input capacitance of the transformer [24]. In other words, interruption at non-zero current, i.e., at chopping current I_{ch} means that there is some amount of energy given by $L_\mu I_{ch}^2/2$ which is trapped in the transformer core. In this expression L_μ is the magnetization inductance of the transformer.

Following the chop, the stored energy transferred to the nearby capacitance (transformer input capacitance) which results in a voltage increasing due to its high-frequency oscillations [36, 37].

It must be mentioned that changing the transformer input capacitance C_i leads to changing of the free frequency according to the relation $f_{free} = 1/(2\pi\sqrt{L_\mu C_i})$.

In general, free transitional voltages appearing during this process can exceed the level of permissible effects on high-voltage insulation [21]. Note that the creation and use of high-voltage circuit-breakers with low (no more than 5 amperes) chop currents led to a decrease in the maximum possible over-voltages. However, transitional voltages (especially recovery voltage) can exceed the allowable level, even when using modern circuit-breakers [24].

As it is shown in [16], [18] and some other works, type of circuit-breaker has an impact on transitional voltages at switching of electrical installations. This impact is conditioned by different electrical strength restoration laws, different chop currents and switching-off times of circuit-breakers. Since chop currents of modern SF_6 and vacuum circuit-breakers are practically the same (they do not exceed 5 Amperes) and switching-off times differ a little, then the main important factor for the process under study will be electrical strength restoration law.

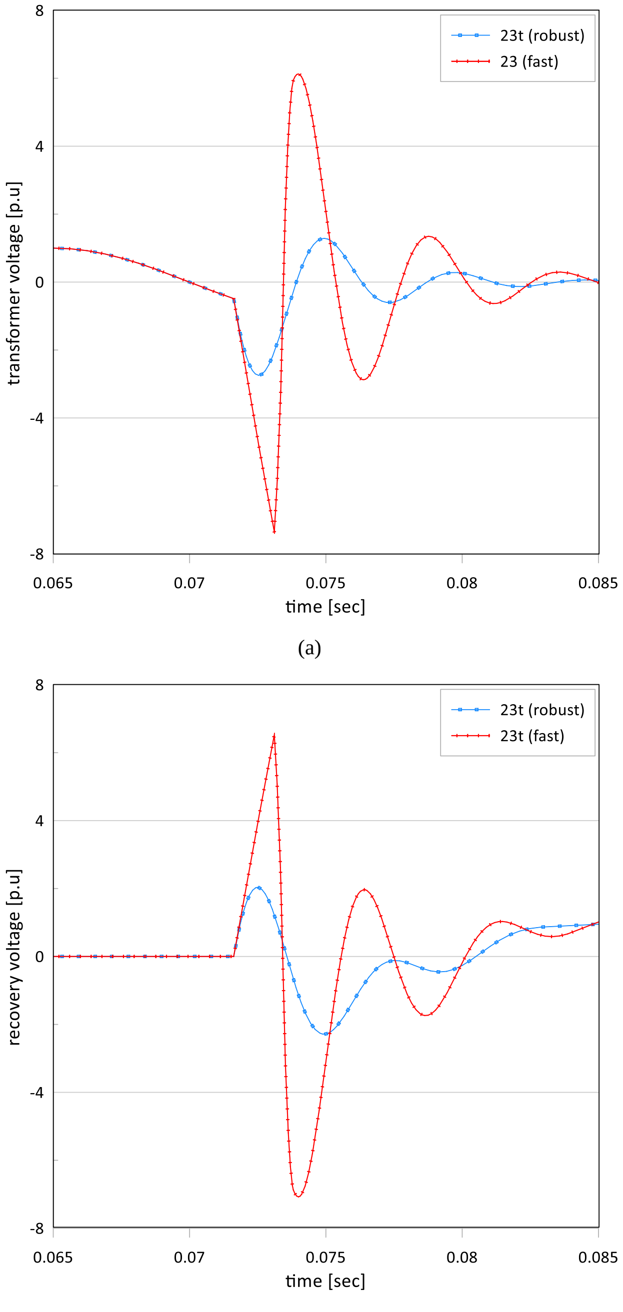
But there are some differences in the causes responsible for the maximum overvoltage applied to different installations. There are some kinds of switching process (e.g., capacitor bank and unloaded transmission line switching-off) for which repeated re-strikes of arc cause escalation of transitional voltages [20], [32]. As a rule, the law of electrical strength restoration has a notable impact on the simulation results just for these kinds of transitions [23].

This law is set in simulation models dependently on circuit-breaker type. Repeated re-ignitions and re-strikes of arc in circuit-breakers' inter-contact gap takes place at excess recovery voltage over electrical strength and this condition is set to be checked at each step of numerical simulation.

As opposed to the process of capacitive currents switching-off, the greatest over voltages at switching-offs unloaded transformers occurs at absence of arc's repeated re-ignitions and re-strikes [24, 25]. At these cases curves of recovery voltage and electrical strength restoration law do not intersect during the switching-off process. It means that for this kind of switching the maximum ratio of over voltages will depend just on chop current. The minded feature let us avoid some difficulties taking place at simulation of switching by vacuum circuit-breakers with the Matlab software.

As it was shown in [28] obtaining stable solutions at simulation the problem under study is possible at use ode 23s method, ode 23tb (robust algorithm) and ode 23 methods, while the ode 15s method has a little worse behavior of solutions in case of fast algorithm. All the algorithms used for the simulation were non-adaptive ones. Note that results presented in [28] were obtained for the case of SF_6 circuit-breaker. Simulations with Matlab for the case of vacuum circuit-breaker face with some difficulties such as a big time-consuming, conditioned by necessity of use adaptive algorithms and setting very little simulation parameters. Fortunately, this is required just for study processes accompanied by arcs' repeated re-ignitions whereas the worst transitional modes in the considered problem occur just when repeated re-ignitions and re-strikes do not exist.

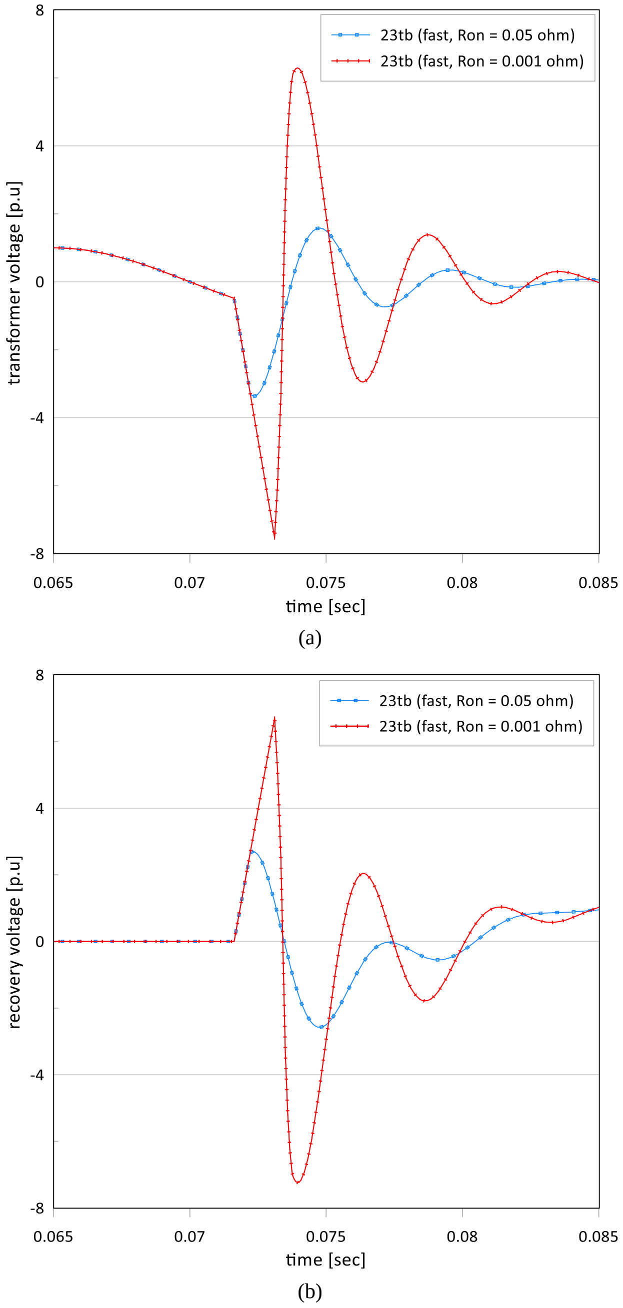
It should be noted that, at switching-offs unloaded transformers with voltage limited by repeated re-ignitions, the over voltages and recovery voltages are relatively independent of the transformer input capacitance. This is because of the dissipated energy during repeated re-ignitions are nearly the same in case of varying the value of transformer input capacitance [39].



(a)

(b)

Figure 10. Transitional voltages behavior at use different algorithms of the ode 23t solver [39], (a) across transformer terminals, (b) across circuit-breaker poles (RV)



(a)

(b)

Figure 11. Transitional voltages behavior at use fast algorithm of the ode 23tb solver for different inner resistances [39], (a) across transformer terminals, (b) across circuit-breaker poles (RV)

Behavior of transitional functions in the simulation process at use different stiff methods (solvers) and algorithms are illustrated in Figures 10 and 11 [39]. As shown in Figure 10, fast algorithm of the ode 23t method (assumed to be stiff method [16]) cannot provide satisfactory behavior of solutions that indicates on a notable stiffness of the problem (due to very little input capacitances) [38, 39].

Fortunately, the robust algorithm of ode 23t and ode 23tb solvers, and also the Rosenbrock method (ode 23s solver having the only algorithm) and both algorithms of ode 15s solver let us successfully get stable solutions of the problem under study. In other words, if there is no difference in results between the two settings, it is preferable to select the fast setting.

If the results in fast setting are not correct or not stable, it is preferable to select the robust setting. Therefore, in case of switching-offs small inductive currents, it is preferable to select the robust setting for sustaining stability.

Use the ode 23tb method (fast algorithm) leads to even worse behavior of transitional functions that is demonstrated in Figure 11. Simulation with robust algorithm of this method let us get a stable solution as it has taken place for ode 23t method. But they are in Figure 11 is shown the other way to get a stable solution to demonstrate the computational nature of big deviations of solutions from their stable values. As it is seen from Figure 11 setting of certain greater resistances of switched-on circuit-breaker (which physically presents resistance of closed contacts) provides getting of stable solutions. Note that setting the inner resistance as 50 milliohms instead of 1 milliohm brings a very negligibly influence on simulation results (magnitudes of transitional voltages and currents).

4.3. Switching-off Unloaded Power Transmission Lines

The disconnection of power lines has always been a very important problem for electric power systems [2], [26]. This is due to the influence of transient switching voltages on the coordination of high-voltage insulation of electrical installations, the design and setting of relay protection and automatic emergency control, electromagnetic compatibility of power systems, etc.

As mentioned earlier, the characteristics of circuit-breakers have a noticeable effect on the course of switching processes and the magnitude of transient voltages and currents [6], [23]. As shown in [32], disconnection of unloaded power lines by vacuum circuit-breakers is accompanied by large values of transient voltages compared to SF_6. Note that in the study presented in [32], the linear law of recovery of electric strength was used for the case of a 110 kV vacuum circuit-breaker. An improved law for 110 kV vacuum circuit-breakers was developed and published in [20].
This study examines some of the physical and computational features of the process of disconnecting unloaded 110 kV power transmission lines (20 to 95 km long).

4.3.1. Transient Voltage Versus Line Length

Earlier in [32], we stated that the switching (disconnecting) over voltages at the power line terminals and the recovery voltage at the breaker poles have lower ratios for shorter line sections, both when using auto compression (SF_6) and vacuum breakers. We explained this by a decrease in the phase angle between the voltage and the shutdown current of the unloaded line (having a capacitive nature), since this current is directly proportional to the line length, as a result, the moment in time corresponded to the actual switching. The turn-off time (i.e., quenching the arc) will move away from the moment corresponding to the maximum voltage (at the same interruption current). On the other hand, at higher breaking currents, the instant corresponding to the real tripping time will shift to the instant corresponding to the maximum voltage. This explanation is illustrated in Figure 12 (0.005 second is a quarter period of the standard 50 Hz frequency) [40].

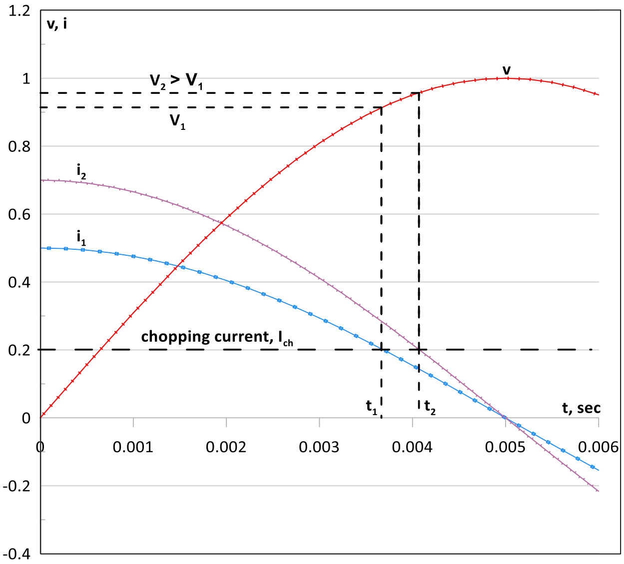
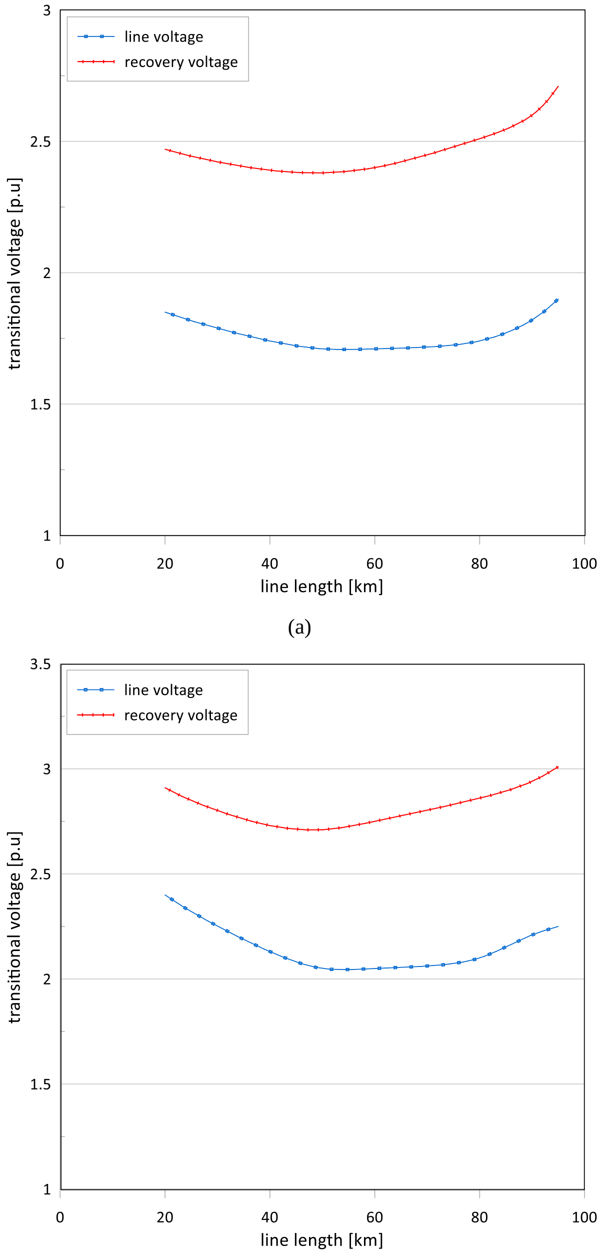


Figure 12. Residual voltages at switching-off power transmission lines of higher length [40]

Note that the results given in [32] were obtained for 110 kV transmission lines with a length of more than 50 kilometers. Our last study revealed a more complex dependence of the transient voltages when disconnecting power lines on their length in a wider length range [32]. The lengths of 50-95 kilometers correspond to the results presented in [32], i.e., disconnection of transmission lines of this length range is accompanied by increased values of transient voltages over a greater length.

Figure 13 shows the calculated dependences of transitional voltages at 110 kV power transmission lines against their lengths while switching-off by using SF_6 and vacuum circuit-breakers [40]. On the contrary, as can be seen from Figure 13, for a length range of less than 50 kilometers, we observe higher transient voltages at a shorter length. These results, obtained for shorter lines, can be explained by the influence of free oscillations of transient voltages, which have high frequencies for shorter lengths, e.g., for the 110 kV overhead line under consideration, the frequency of free oscillations varies from 1200 Hz to 12 kHz over a length of 10 to 100 kilometers with higher frequencies corresponding to the shorter length.

While the switching-off process for longer lines runs more smoothly due to lower free frequencies (with a lower slope of transient voltages). When disconnecting shorter lines, we are faced with the possibility of interrupting the high-frequency current at a moment corresponding to the higher values of the transient voltages (due to the superposition of steep high-frequency free transient voltages). This leads to a worsening of the transient process and an increase in the likelihood of repeated re-ignition in the inter-contact spaces of the circuit-breakers [40].



(a)

(b)

Figure 13. Calculated dependences of transitional voltages at 110 kV power transmission lines switching-off against their lengths at use [40], (a) SF_6 circuit-breaker, (b) vacuum circuit-breaker

4.3.2. Computational Stability

Numerous numerical experiments implemented using stiff solvers of ordinary differential equations from the Matlab-Simulink set made it possible to reveal the following computational features of the problem under consideration:

- The use of the 23t ode solver (both fast and robust algorithms), the 23tb robust ode solver algorithm and the 23s ode solver (Rosenbrock's method) provides stable solutions in the range of initial step sizes of no more than 1 nanosecond. Standard and relative tolerances are no more than 10^{-6}. Decreasing the line length does not impair the stability of the solutions.
- The use of a robust algorithm of one solver 15s provides stable solutions in the range of initial step sizes of no more than 1 nanosecond and relative tolerances of no more than 10^{-7}, while a fast algorithm of the same method provides stability at lower values of relative tolerance. In addition, decreasing the line length worsens the robustness of the solutions when using the fast algorithm.

We previously investigated the dependence of transient voltages when disconnecting an unloaded transmission line on the type of switch [32, 40] and then stated that disconnections when using vacuum switches are accompanied by an increase in voltage values by (4-5) % on line terminals and recovery voltages compared to SF_6 terminals. In this study, we used the simplest (linear) law of recovery of the electrical strength of a vacuum circuit-breaker [18]. Our latest research has shown that this leads to a serious underestimation of the differences in transient voltages due to the type of circuit-breaker due to the inadequacy of the linear recovery law. In computer simulations, using a much more adequate logarithmic recovery law presented in [20], significantly larger differences were obtained.

At the end of this section, we conclude that; this kind of transient is reliably simulated using the ode 23s solver, the ode 23t solver (fast and robust algorithms), the ode 15s solver, and the ode 23tb robust solver algorithm. The fast 23tb solver algorithm gives the worst (but sometimes satisfactory) solution stability. It should be noted that obtaining stable solutions for disconnecting unloaded power lines may require significantly more time compared to other considered transitions [40].

4.4. Switching in FACTS Networks

Present now the results of investigation of expediency of use above minded stiff ode solvers for simulation of transients conditioned by switching in schemes of FACTS (Flexible Alternating Current Transmission Systems), consisting of mechanically switched power capacitor banks (MSC), thyristor-controlled reactor (TCR) and harmonic filters (FC) [41].

Whereas the reactive (capacitive) power produced by MSC is not controllable, the inductive power produced by TCR can be controlled by changing of bidirectional thyristor valve's firing angle between 0 and 180 degrees, wherein less values of the firing angles will correspond to the higher values of reactive (inductive) power consumed from the substation busbars by TCR [42]. FACTS are being intensively researched and applied at the present time [42- 47].

Two typical FACTS schemes in the cases of delta connected TCR and star connected TCR are presented in the Figures 14 and 15, respectively [48]. Note that delta connected FACTS contains just 5th and 7th harmonic filters that is conditioned by known compensatory effect for third harmonics in delta connected three-phase systems whereas star connected FACTS should contain 3rd harmonic filter. Some examples of simulation switching transients for FACTS installation are presented below in the Figure 16 and Figure 17 [48].

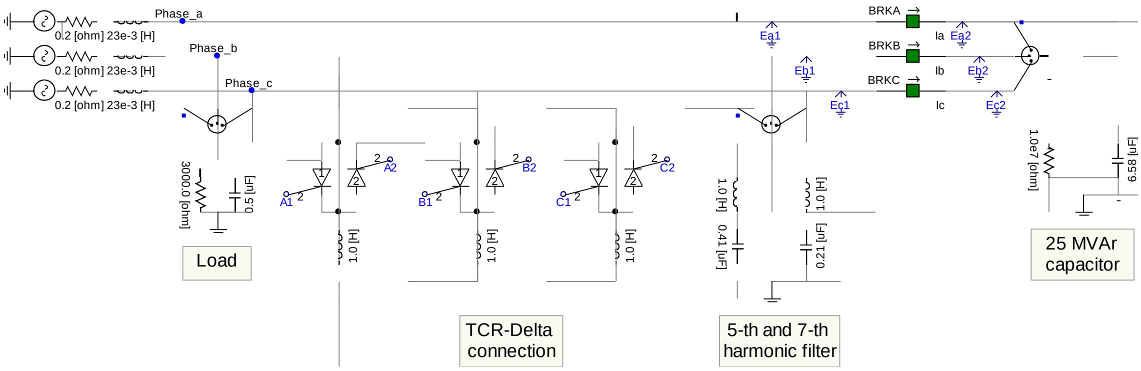


Figure 14. FACTS network with delta-connected TCR [48]

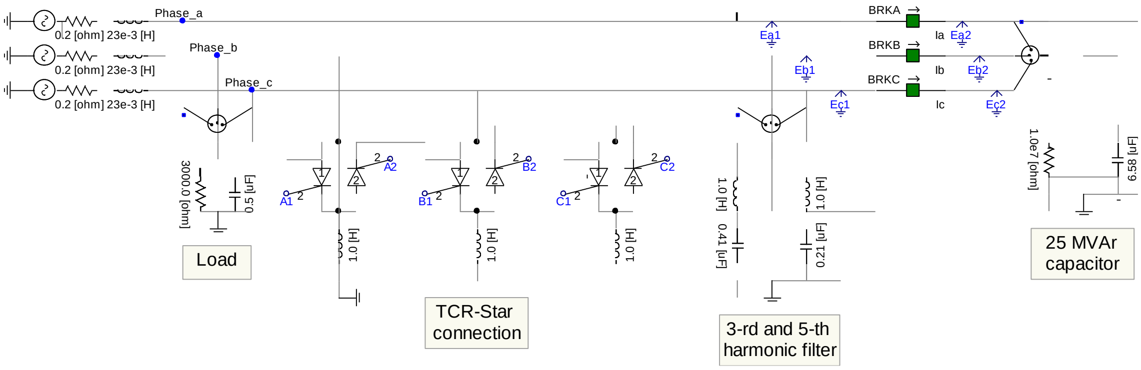


Figure 15. FACTS network with star-connected TCR [48]

Figure 16 presents transitional voltages across the MSC terminals at its switching-off by SF_6 circuit-breaker (in the scheme with delta connected TCR). Significantly differed magnitudes of over voltages by phases are explained by the impact of the isolated neutral bias voltage appeared due to the delta connected scheme. As a result, some phases (e.g., phase-A in Figure 16) can be switched-off even with no arc's repeated re-strikes that leads to minded difference of overvoltage magnitudes.

Figure 17 presents transitional voltage on the MSC busbars at its switching-on (in the scheme with star connected TCR). Since star connected scheme leads to phase symmetry of voltages and currents, we demonstrated just an only phase (phase-A, in this case) voltage in the Figure 17.

We could expect a priori that simulation of switching transitional processes for the installations contained thyristor valves could worsen behavior and stability of solution because of periodical sudden jumps of transitional functions conditioned by interruption of current flowing through TCR at thyristors' firing instants.

In spite of these initial assumptions, our investigation showed that there are no additional simulation difficulties in terms of the stability and behavior of solutions (transitional functions), as this might be expected given the presence of thyristor valves in FACTS networks. In our opinion, this takes place due to the significant filtering effect of the large capacitance of the MSC that leads to notable smoothing of all high-frequency harmonics of voltages and currents arising from the operation of the TCR thyristor valve. Even switching-off of MSC by vacuum circuit-breaker was not accompanied by worsening of solutions behavior and stability.

This means that transitional processes in the FACTS schemes conditioned by switching MSC can be reliable simulated by use some following Matlab stiff ode solvers (23s, fast and robust algorithms of 15s and 23tb solvers) [49].

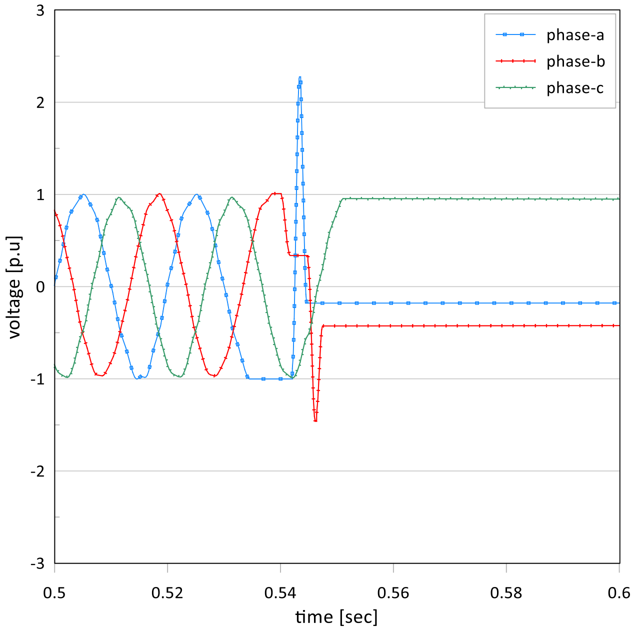


Figure 16. Transitional voltages across the terminals of MSC 110 kV, 25 MVAr at its switching-off by SF_6 circuit-breaker (TCR are delta connected, the firing angle of thyristors equals 120 degrees) [48]

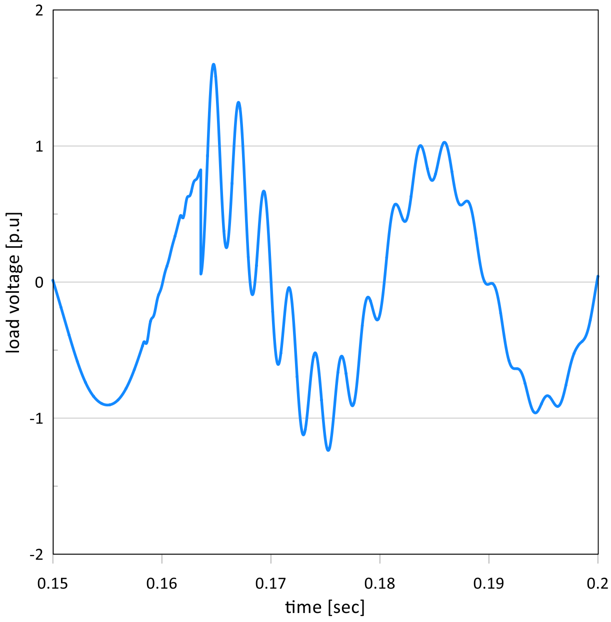


Figure 17. Transitional voltage on the busbars of MSC 110 kV, 25 MVAr at its switching-on (TCR are star connected, the firing angle of thyristors equals 60 degrees) [48]

5. IDENTIFYING OF STABLE SOLUTIONS

The Matlab software contains various ode solvers including 4 ones for solving "stiff" differential Equations and their systems. This allows us to recognize (identify) stable solutions by comparison (convergence of solutions got by use different solvers at decreasing the values of initial step size or/and relative tolerance). This identification is based on the fact of uniqueness of the stable solution whereas unstable solutions differ from each other as illustrated in the Figure 18 [23].

As it is seen from the Figure 18 solutions for transitional recovery voltage converge in the point corresponded to the stable solution (about 3.43 p.u. in the considered case) at decreasing initial step size. Greater values of set the initial step size and/or relative tolerance will lead to removal from the stable solution.

6. INFLUENCE OF SOME TRANSITIONAL PHENOMENA ON STABILITY

There are several transitional phenomena being able to impact notably on switching processes and magnitudes of transitional voltages. The most influential of them are repeated re-strikes and re-ignitions in circuit-breakers [26], arcing between separating contacts of circuit-breaker [1], chopping of switched-off current when it approaching to zero [15]. So, these phenomena should be taken into consideration in transitions' numerical models to provide adequacy of simulation. Let us consider now how the consideration of minded phenomena can impact on computer simulation's stability.

6.1. ARC'S Repeated Re-Strikes and Re-Ignitions

Numerous computer simulation acts have been implemented in our researches showed that appearance of arc's repeated re-ignitions and re-strikes in circuit-breakers' inter-contact spaces may have some impact on solutions stability. Thus, notable increasing of transitional functions' steepness due to very steep descends of recovery voltage at repeated switching leads to corresponding increasing of a local error, and as a result, the global error. So, realization of the ode15s method for initial step size equaled to 10^{-4} seconds becomes impossible. For this case the deviations of over voltages and recovery voltages from their stable values become greater for all the considered methods [24].

Our research experience shows that the best method for simulation the transitions accompanied with several number of repeated switching is the Rosenbrock method realized in the ode 23s solver.

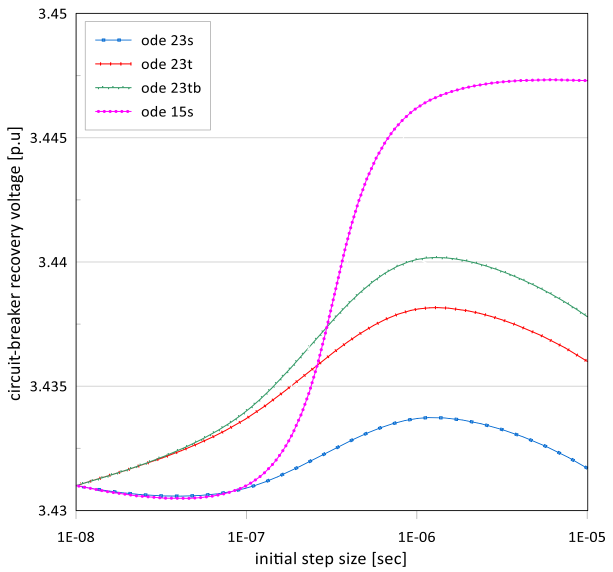


Figure 18. Behavior of solutions at use fast algorithms (relative tolerance 10^{-6}) for switching-off 110 kV unloaded transformer of 41 MVA [23]

6.2. ARC Resistance

Influence of arc resistance and arcing time on stability of solutions has complicated and unobvious character [8].

It was taken into consideration in some our previous works [8], [50]. Taking arc resistance into consideration at the computer simulation in case of capacitive currents switching-offs leads to stability improvement at use the ode 23tb method, while a little worsening of transitional functions' behavior at uses the ode 23t method. In comparison with these methods the ode 15s method has the worst stability and long simulation time-consuming required for a single simulation.

Taking arc resistance into consideration in case of small inductive currents switching-offs does not notably impact on transitional functions' stability at use the ode 23tb or ode 15s method and worsens stability at use the ode 23t method. The 15s method has very long simulation time also for this switching.

6.3. Current Chopping

Taking this phenomenon into consideration does not have any noticeable impact on stability. But it is necessary to set the value of initial step size by taking into account some characteristics of switching-off currents [33] to provide adequacy of modeling current chopping.

7. INFLUENCE OF SOME PHYSICAL PARAMETERS ON STABILITY

Some parameters of switched-off circuit such as capacitances, inductivities and resistances may have significant influence on stability of transitional voltages. Their influence is conditioned by their impact on free frequencies of transitional process and attenuation of transitional voltages and currents’ free oscillations. There we are considering just influence of total connected capacity being the least studied research case for the problem investigated.

Influence of capacitance of connections to the same bus-bars (as the switched-off 110 kV power capacitor banks) on stability and behavior of solutions was studied in [51]. Note that this capacitance is proportional directly to the total length of all the connections to the bus-bars.

The research carried out showed that solvers ode 23tb (fast algorithm), ode 15s (fast algorithm), and ode 23s used in computer simulation for the problem under consideration demonstrate better stability at initial step size no more than 1.0 millisecond and relative tolerance 10^{-6}. The best behavior at little capacitances obtained for the case of ode 23s method. At higher capacitances, the behavior of solutions at uses all the previous mentioned methods are similar. The solver ode 23t (both fast and robust algorithms) showed the worst solvability and stability among the entire ode solvers included in the Matlab software.

8. SOME MORE FEATURES

Change of calculated values of over voltages and recovery voltages is more uniform at fixed initial step size and varied tolerance than at fixed tolerance [16]. This should be taken into consideration at the computer simulation while searching stable solutions.

As a rule, behavior and stability are worse for transitional function of recovery voltage [16], so stability of problems under study should be evaluated by ones just for recovery voltages.

9. CONCLUSIONS

The method (ode solver) and algorithm realizing them, used for computer simulation switching-offs of electrical installations may have decisive influence on behavior of transitional voltages and solutions’ stability.

As a rule, obtaining stable solutions requires using different solvers and algorithms for each problem considered. Simulation parameters also have great impact on behavior and stability of solutions. The most universal simulation tool for the problems under study is the Rosenbrock’s method realized in the ode 23s solver.

Some phenomena and physical parameters included in the models (arc’s repeated re-ignitions, current chop and others) may have moderate influence on transitional voltages behavior and stability. Type of circuit-breaker also has impact on stability of solutions due to different laws of their electrical strength restoration that reflect on local and global computational error.

Some calculative features of switching-off high-voltage capacitor banks show that the accumulation of local errors due to the nature of the generally accepted computer modeling technique (step-by-step calculation and rounding at each step) can seriously affect the adequacy of the results. In particular, in the problem under consideration, the accumulation of errors leads to a noticeable calculated change in the recovery voltage and can affect the conditions for the occurrence of a repeated re-ignition in the circuit-breaker. As a result, we can obtain qualitatively different behavior of the transition functions compared to those obtained using more suitable (from the point of view of stability) methods and/or more optimal modeling parameters (initial step size and tolerance).

Relatively small values of input capacitances typical for high voltage transformers and autotransformers cause a sufficiently high stiffness of the differential equations of switching transients and the problem in whole. At use inappropriate method or algorithm this leads to significant deviations of maximum magnitudes of transitional voltages from the ones taken place for stable solutions.

Researches concerned to switching-off power transmission lines let us to reveal the main feature of computer simulation of this transient in comparison with switching-off power capacitor banks and unloaded transformers (auto-transformers). This is notably greater time required for obtaining stable solutions. In our opinion it is conditioned by higher free frequencies (about 1350-6000 Hz for 110 kV power transmission lines of length 20-90 kilometers, higher frequencies correspond to less lengths). It leads to the necessity of use very little initial step sizes (at most 1 nanosecond at relative tolerance no more than 10^{-6}) providing stability of solutions. Subsequently on smoother parts of solutions, this will lead to an unnecessarily larger amount of computation with a corresponding increase in the simulation time.

Using of initial step sizes more than 1 nanosecond at relative tolerances less than 10^{-6} does not ease obtaining the stable solutions. In other words, stability of solutions is more sensitive to the value of initial step size rather relative tolerance.

NOMENCLATURES

1. Acronyms

ODE: Ordinary Differential Equation
RV: Recovery Voltage
TRV: Transient Recovery Voltage
VCB: Vacuum Circuit-Breaker
FACTS: Flexible AC Transmission System
MSC: Mechanically Switched Power Capacitor Bank
TCR: Thyristor-Controlled Reactor

2. Symbols / Parameters

I_{ch} : The chopping currents
ΔV : The circuit-breaker recovery voltage
R_s : The source resistance
R_p : The transformer’s primary resistance
R_μ : The transformer’s magnetization resistance

L_s : The source inductance
L_p : The transformer's primary inductance
L_μ : The transformer's magnetization inductance
C_l : The load capacitance
C_c : The capacitor bank capacitance
C_i : The transformer's input capacitance
G_l : The load conductance
G_c : The capacitor bank conductance
E_s : The e.m.f. of voltage source
f_{free} : The free frequency
V : The voltage across the equipment
$V_{es}(t)$: The electric strength restoration law
$V_{\max}$: The maximum value of electric strength
T_{full} : The full switch-off time of circuit-breaker
t_{off} : The initial instant of contact separation
$X_{\max}$: The maximum distance between CB contacts

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