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INVESTIGATION THE DEPENDENCE OF TRANSITIONAL VOLTAGES AT SWITCHING-OFF UNLOADED TRANSFORMER ON ITS INPUT CAPACITANCE

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Abstract- The article presents results of research dedicated to study dependence of transitional voltages at switching-off unloaded transformer on its input capacitance being one of the most important parameters which determine nature of the transition process and its physical and computational features. 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. The dependences of voltages across the transformer's terminals and recovery voltages across the circuit-breakers' contacts obtained for one type of transformer are presented and discussed in the present article.

Keywords: Transitional Voltages, Input Capacitance, Arc's Repeated Re-ignitions, Unloaded Transformer, Free Frequency, Electric Strength Restoration.

1. INTRODUCTION

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 [1, 2]. 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.

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 [1]. 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 (Figure 1). 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 [3].

It must be mentioned that changing the transformer input capacitance (C_i) leads to changing of the free frequency according to the relation

$$f_{free} = 1/(2\pi\sqrt{L_\mu C_i}) \quad (1)$$

In general, free transitional voltages appearing during this process can exceed the level of permissible effects on high-voltage insulation [4]. 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 [5].

The main feature of the transitional operations accompanying unloaded power transformer (or autotransformer) switching-off is the relatively high free frequency of the transformer and circuit-breaker voltages that takes place due to the little values of transformers input capacitances [6, 7, 8]. As a result, we get so called stiff problem [9, 10]. The best methods and algorithms included in MATLAB set providing stability of transitional voltages for the problem under consideration are presented in [11].

2. COMPUTATIONAL GROUND

Scheme connection and network equivalent for the problem under study are presented in Figure 1. Mathematical ground and switching-off conditions of the problem studied are considered in some our previous works [5, 12, 13]. In this research, electrical strength restoration laws of SF_6 and vacuum circuit-breakers that used (i.e., functions of the circuit-breaker breakdown voltage with different arc quenching media) are considered in [14, 15].

For the modeling of SF_6 circuit-breakers, it was proposed to use a co-sinusoidal law of electric strength restoration. This law is formalized as following:

$$V_{str}(t) = 2^{-1} V_m \left\{ 1 - \cos\left[\frac{\pi (t - t_{off})}{T_{full}} \right] \right\} \quad (2)$$

where,

$V_{str}(t)$: is the electric strength restoration law;

V_m : is the maximum value of electric strength;

t : is time;

T_{full} : is the full switch-off time of circuit-breaker;

t_{off} : is the initial instant of contact separation [14].

This law:

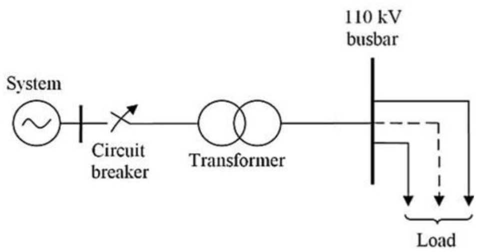
1) takes into consideration inertia of contact;
2) is matched good with the movement law of contact;
3) has acceptable coincidence with the real law for SF_6 circuit-breakers [16].

For vacuum circuit-breakers, it is offered to use the logarithmic restoration law for electric strength restoration as following:

$$V_{str}\left(t\right)=191.43\log\left\{1+5.75x_m\left\{1-\cos\left[\frac{\pi\left(t-t_{off}\right)}{T_{full}}\right]\right\}\right\} \quad (3)$$

where, X_m is the distance between circuit-breaker contacts [15].

This study is dedicated to investigating the dependence of transitional voltages (transformer and circuit-breaker recovery voltages) on transformer input capacitance. There is considered switching-offs of 110 KV transformer with rated apparent power 41 MVA and input capacitance between 6 and 20 nF by SF_6 and vacuum circuit-breakers.



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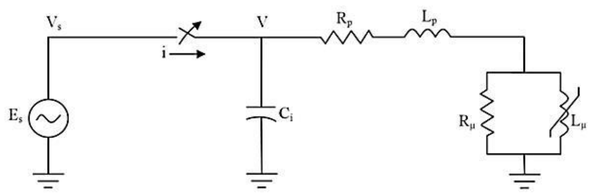

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Figure 1. Switching-off unloaded transformer: a) connection scheme; b) equivalent network

In the Figure 1, R_p is the transformer's primary resistance; L_p is the transformer's primary inductance; R_μ is the transformer's magnetization resistance; L_μ is the transformer's magnetization inductance; C_i is the transformer's input capacitance.

It is known that differential equations formalized transitional switching processes in electrical networks belong to the class of so called "stiff" differential equations [9]. Numerical solution of such class of equations requires paying special attention at selection of simulation method, algorithm, initial step size, accepted tolerances. All these items taken together define the transformed "stiffness" concept in general [10].

So, in this research some stiff ordinary differential equation solvers (ode 23s, ode 23tb, ode 23t and ode 15s) in MATLAB and PSCAD/EMTDC software were used for computer simulation.

While using MATLAB in computer simulation, we must select how the solver behaves during a reset, such as when it detects a zero crossing. The solver reset methods are divided into fast and robust settings (besides ode 23s method). At simulation, 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 [17]. Therefore, in case of switching-offs small inductive currents, it is preferable to select the robust setting for sustaining stability.

3. RESULTS AND DISCUSSION

3.1. Features of Simulation

As it is shown in [12, 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 [1]) for which repeated restrikes of arc cause escalation of transitional voltages. As a rule, the law of electrical strength restoration has a notable impact on the simulation results just for these kinds of transitions [14].

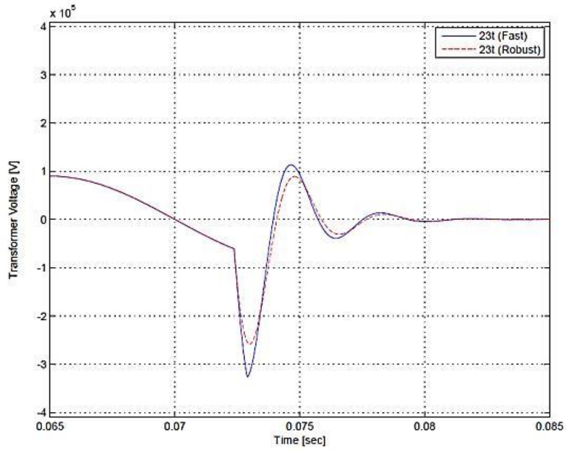
This law is set in simulation models dependently on circuit-breaker type. Repeated re-ignitions and restrikes of arc in circuit-breakers' inter-contact gap takes place at excess recovery voltage over electrical strength and this condition is set to be checked at each step of numerical simulation.

As opposed to the process of switching-off capacitive currents the greatest overvoltages at switching-off unloaded transformers take place at absence arc's repeated re-ignitions and restrikes [1, 2]. 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 overvoltages 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 [11] obtaining stable solutions at simulation the problem under study is possible at use the ode 23s method, the 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 [11] 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 take place just at absence of repeated re-ignitions and restrikes.

It should be noted that, at switching-offs unloaded transformers with voltage limited by repeated re-ignitions, the ratios of overvoltages 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 [19].

Behavior of transitional functions in the simulation process at use different stiff methods (solvers) and algorithms are illustrated in Figures 2 and 3. As shown in Figure 2, fast algorithm of the ode 23t method (assumed to be stiff method [20]) cannot provide satisfactory behavior of solutions that indicates on a notable stiffness of the problem (due to very little input capacitances).



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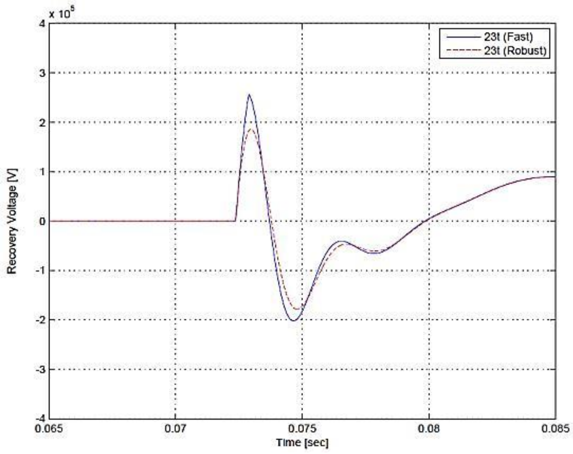

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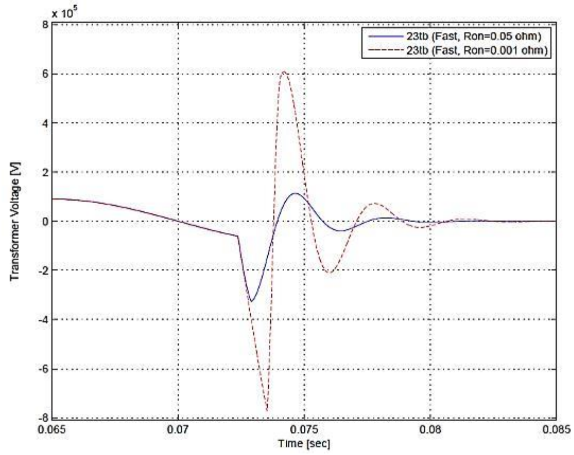
Figure 2. Transitional voltages behavior at use different algorithms of the 23t solver: a) voltage across transformer terminals; b) voltage across circuit-breaker poles



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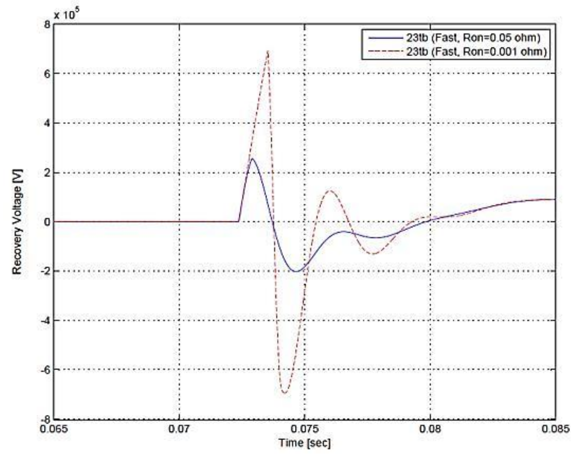

b)

Figure 3. Transitional voltages behavior at use fast algorithm of the 23tb solver for different inner resistances: a) voltage across transformer terminals; b) voltage across circuit-breaker poles

Fortunately, the robust algorithms of this and ode 23tb method, 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.

Use the ode 23tb method (fast algorithm) leads to even worse behavior of transitional functions that is demonstrated in Figure 3. 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 3 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 3 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).

Remind here that all the results were got at use MATLAB r2013a version. Note that use the PSCAD software also provide successful simulation of unloaded transformers switching-offs process.

Now consider how the behavior of solutions for transitional functions depends on the transformer input capacitance. The simulations were performed for the input capacitances equaled to 7.5, 10.0, 12.5 and 15 nF respectively. In this case, the ode 15s method (fast algorithm) is used for computer simulation.

Behavior of transitional functions dependently on the input capacitance of switched-off transformer is illustrated in Figures 4 and 5. All graphs shown refer to percentage differences from their stable values.

Figure 4 shows the dependence of relative deviations of transitional recovery voltage on initial step size for different values of input capacitances. Figure 5 shows the dependence of maximum values of relative deviations of transitional functions on input capacitance.

Considering Figure 4 we can conclude that the better behavior of solutions takes place at greater values of input capacitances whereas the greater deviations of solutions appear at less input capacitances. For clearer demonstration of influence of input capacitance on the behavior of simulated transitional voltages we built the graphs shown in Figure 5 (dependences of their maximum deviations from stable solutions on input capacitance).

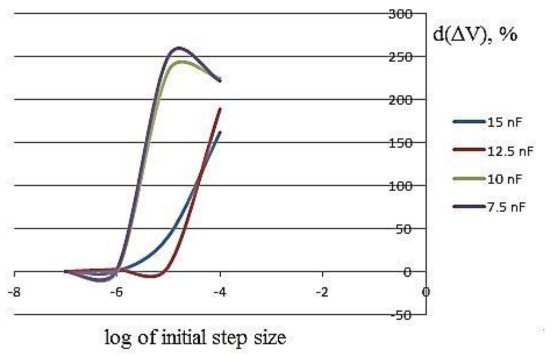

Figure 4. Relative deviations of transitional recovery voltage on initial step size for different values of input capacitances

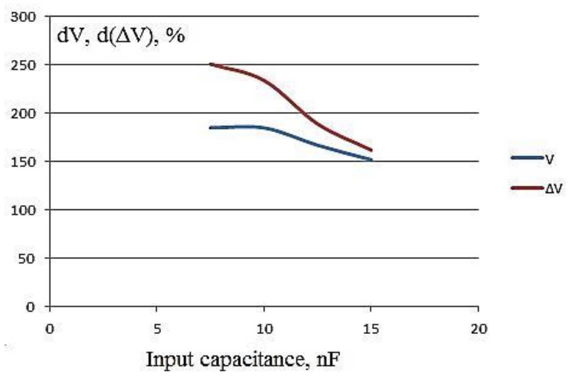

Figure 5. Dependence of maximum values of relative deviations of transitional functions on input capacitances

As it is shown in Figure 5, the greatest deviations of transitional functions correspond to lesser values of input capacitances. This takes place because of at the instant of current chops, the current flowing in the transformer is diverted into the transformer input capacitance. Since the rate of rise of voltage across the transformer terminals is given by $dv/dt = I/C_i$, the voltage rises as the transformer input capacitance decreases. Moreover, we can state that the function of recovery voltage has worse behavior in comparison with the function of voltage across the transformer terminals.

3.2. Effect of Transformer Input Capacitance on Transitional Voltages

The dependences of transitional voltages (transformer voltage V and circuit-breaker recovery voltage ΔV) on input capacitance of 41 MVA, 110 KV transformer are presented in Figure 6.

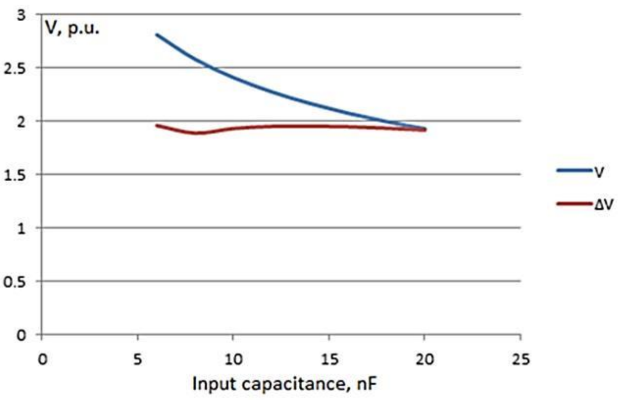

Figure 6. Dependence of transitional voltages on transformer's input capacitance

As it is seen from Figure 6 transitional voltages across the unloaded transformer terminals, notably depend on transformer's input capacitance whereas transitional recovery voltage does not. At this, higher values of voltage across the transformer terminals correspond to the lower input capacitances. This may be easily explained by knowing inverse dependence of maximum possible overvoltage at switching-off small inductive currents on the square root of input capacitance [1].

This is obvious that the free frequency in case of the lesser value of transformer input capacitance is the greatest. It means that the steepness of voltage free oscillations in this case is the higher. Thus, we can state that very low values of transformer's input capacitance cause both high magnitudes of transitional voltages and increasing of the problem stiffness due to higher free frequencies.

Since switching-off unloaded transformers and autotransformers is one of the most dangerous transition modes in high-voltage electric power systems then adequate determination of impacts on insulation via computer simulation (due to getting stable solutions) lets improve protection and coordination of insulation and increase reliability.

4. CONCLUSIONS

Transitional voltages of the switched-off no-load transformer decrease with increasing its input capacitance whereas transitional voltages across the circuit-breakers' poles (recovery voltage) do not.

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.

NOMENCLATURES

1. Acronyms

ODE: Ordinary Differential Equation

2. Symbols / Parameters

I_{ch}: The chopping current
f_{free}: The free frequency
C_i: The transformer's input capacitance
R_p: The transformer's primary resistance
L_p: The transformer's primary inductance
R_μ: The transformer's magnetization resistance
L_μ: The transformer's magnetization inductance
V: The voltage across the transformer terminals
ΔV: The circuit-breaker recovery voltage
$V_{str}(t)$: The electric strength restoration law
V_m: 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_m: The distance between circuit-breaker contacts
dv/dt: The rate of rise of voltage across the transformer terminals

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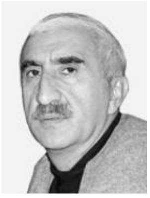
BIOGRAPHIES

Esam Ali Saafan was born in El-Mansoura, Egypt in 1977. He received the B.Sc. and M.Sc. degrees in Electrical Engineering from Faulty of Engineering, University of El-Mansoura, Egypt in 2001 and 2007, respectively. He obtained the Ph.D. degree in High Voltage Engineering from Azerbaijan Technical University, Baku, Azerbaijan in 2012. From 2001 to 2012 he worked in the Electrical Engineering Department, University of El-Mansoura, Egypt as a Lecturer Assistant. Since 2012, he has been a Lecturer in the same university. His research areas include transitional processes in electric power systems and their computer simulation, power systems electromagnetic compatibility.



Tahir Lazimov was born in Baku, Azerbaijan in 1955. He received the Engineer qualification in Electrical Engineering from the Azerbaijan State Oil Academy, Baku, Azerbaijan in 1977, and Ph.D. degree in High Voltage Engineering from the Tomsk Polytechnic Institute, Tomsk, Russia Federation, in 1989. From 1977 to 2004 he worked in the Power Engineering Research Institute, Baku, Azerbaijan. In 2004-2020 he was the Head of Electric Power Systems Department in Azerbaijan Technical University, Baku, Azerbaijan. He is the author of about 200 scientific works. His research areas include transitional processes in power electric systems and their computer simulation, power systems electromagnetic compatibility. He is a Professor and IEEE Senior member, the member of the Scientific Board on Technologies at the Azerbaijan National Academy of Sciences and some scientific councils and editorial boards in Azerbaijan and abroad.