Experimental Investigations of Overvoltages on High-Voltage Motors Insulations in Industrial Plants

Petar Vukelja[1], Radomir Naumov[2], Jovan Mrvić[3], Dejan Hrvić[4]

Abstract - **The results of experimental investigations of overvoltages appearing on the insulation of 6 kV motors in industrial plants are presented in the paper. The investigatons of overvoltages were carried out at switching-in and switching-out of motors and at earth-fault appearance in six industrial plants. Switchings-in and switchings-out of motors were carried out by means of minimum oil circuit-breakers. On the basis of the analysis of investigation results, the measures which should be undertaken in order to reduce stresses on stator windings insulation of high-voltage motors are suggested.**

Keywords: - **Insulation, Overvoltage, Motor, Industry**

I. INTRODUCTION

The most spread electric-power networks in industrial plants are 6 kV voltage networks. These are cable networks having isolated neutral point. They are supplied from 35 kV or 110 kV networks, through 35kV/6kV or 110kV/6kV transformers. On the end of cable lines, a few tens up to a few hundreds of meters long, high-voltage voltage motors and 6kV/0.4kV tranformers are connected. Switchings-in and switchings-out are carried out through switching devices at the beginning of cable lines. These are most frequently minimum oil circuit-breakers. Overvoltage phenomena in these networks are frequent. They are most frequently due to switching devices operation, and than to earth fault and short-circuit. Overvoltages stress, and can endanger the insulation of 6 kV network and therefore the stator winding insulation of 6 kV motors, as well.

In this paper the results of experimental investigations of overvoltages on stator windings of high-voltage motors in six industrial networks are presented. The overvoltages were investigated at switching-in and switching-out 6 kV motors and at the establishment and interruption of earth fault. The overvoltages were recorded by means of digital oscilloscopes, with using capacitive voltage dividers which truly transfer the phenomena of the order from 1 MHz to several Hz.

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II. OVERVOLTAGES AT EARTH FAULT APPEARANCE

An earth fault in the network with isolated neutral point has no influence to the operation of high-voltage motors. In the majority of industrial networks, an earth fault is only signalized and just after determination of its location is cleared, taking into care not to interrupt technological processes being in course. Investigations of overvoltages at the establishment and interruption of earth fault were carried out in all six 6 kV networks [4,6,8].

The earth fault have been established by switching-in one of the cable lines in the network on which one of phase conductors was previously connected to the earthing. Over 40 cycles of earth fault switching-in and switching-out were carried out in the networks of industrial plants.

Intermittent earth-fault is performed in three networks of industrial plants. It was established and interrupted, by means of isolated stick with an earthed metal part fixed on the top, by its approaching to, and removing from one of the 6 kV phase conductors. During performing intermittent earth fault, several tens and even hundreds of earth fault establishments and interruptions occurred.

The overvoltages appearing at earth fault establishment defined in relative units (p.u.) in relation to the peak value of phase-to-phase voltage in stable regime immediately before earth fault occurrence, have not surpassed 2.6 p.u.. At intermittent earth-fault the highest measured overvoltage was 3.3 p.u.. Their frequencies and steepnesses also are not high. At earth fault establishment, the frequency of their oscillation moves up to a few kHz. With earth fault interruption, overvoltage appeared most frequently on the phase which have had the earth fault, but not above 1.8 p.u.. For one of the motors, the transient voltages on two phases, that is, on the stator-winding insulation, at earth-fault appearance in the third phase, are shown in Fig. 1.

In three networks the earth fault interruption gave rise to the appearance of the second subharmonic ferroresonance with overvoltages to earth up to 2.3 p.u. [4,6]. Phase-to-phase voltages to which high-voltage motors are connected, in the course of ferroresonance stay unchanged and they operate normally. However, phase-to-earth voltages are significantly higher than normal. Besides basic harmonic (50 Hz) they contain much expressed second subharmonic (25 Hz) and somewhat less expressed harmonic having frequency of several Hz.

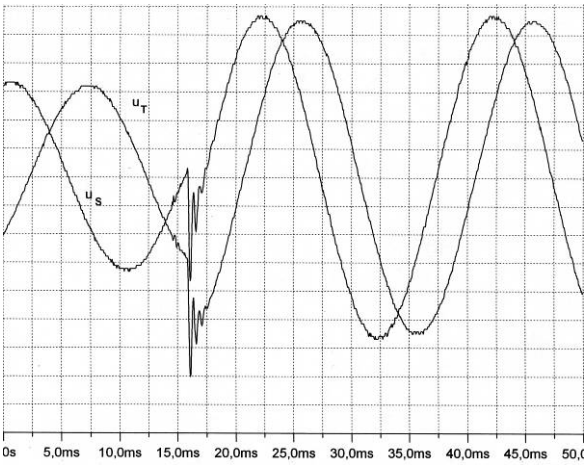

Fig. 1. Transient phase-to-earth voltages u_S and u_T on the stator-winding insulation of the 6kV, 600kW motor, at earth-fault appearance on the R-phase.

III. SWITHCINGS-IN AND SWITCHINGS-OUT OF HIGH-VOLTAGE MOTORS

The investigations of overvoltages on the insulation of high-voltage motors at their switching-in and switching-out are carried out in four networks of industrial plants on all together 13 motors having power from 170 kW to 2 MW [5,6,7]. These are induction motors with cage rotor. The motors were switched in and out by means of domestic and foreign minimum oil circuit-breakers. Switchings-out were performed during motor normal operation and during acceleration. Switchings-out in acceleration, that is switchings-out immediately after motor switching-in, are not rare appearance. Most frequently they occur when all technological conditions for starting the facility driven by the motor are not fulfilled, or the over-current protection of the motor is not properly adjusted. The transient phase-to-phase voltages at motor switching-in and switching-out were recorded in all three phases.

The transient voltage process at switching-in lasts for a few ms. The frequency of oscillations usually do not surpass a few kHz. The highest overvoltage measured during 93 switchings-in of motor, that is, in the sample of 93x3=279 elements amounts 2 p.u., and mean overvoltage value in the sample is 1.2 p.u.. For one of the motors, the transient voltages on two phases, that is, on the stator-winding insulation, at motor starting-up are shown in Fig. 2.

The transient process during motor switching-out in normal operation in every one of phases lasts shortly – 1 to 2 ms. Damped oscillations appear, having frequency up to a few Hz. After this transient process, the phase-to-phase voltages decrease gradually with frequency, which also decreases. The highest overvoltage measured at 46 switchings-out during motor normal operation, that is, in the sample of 46x3=138 elements, is 2.4 p.u., and the mean overvoltage value in the sample is 1.2 p.u.. For one of the motors, the transient voltages on two phases, that is, on the stator-winding insulation, at motor switching-out during normal operation, are shown in Fig. 3.

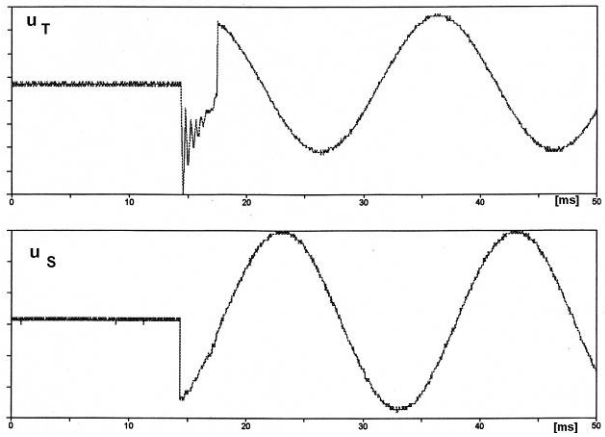

Fig. 2. Transient phase-to-earth voltages u_T and u_S on the stator-winding insulation of the 6kV, 630kW motor, at its starting-up.

The transient process at switching-out of the motor in acceleration on every one of phases lasts shortly, 1-2 ms with damped, high oscillations, having frequency a few kHz. After transient process, phase-to-phase voltages fall to zero value. The highest overvoltage measured during 49 switchings-out of the motor in acceleration, that is, in the sample of 49x3=147 elements, is 4.65 p.u., and the mean value of overvoltage in the sample is 2.2 p.u..

In figure 4, for one of the motors, the transient voltage process is shown on two phases of the stator winding insulation, at motor switching-out during acceleration.

IV. TEST AND WITHSTAND VOLTAGES OF STATOR WINDINGS INSULATION OF HIGH-VOLTAGE MOTORS

In the IEC 60034-15 Standard, the test voltage of stator winding insulation to earth of motors is power frequency, short-duration voltage:

$$U_i=(2U_n+1)\ \text{kV}$$

and lightning impulse voltage:

$$U_a=(4U_n+5)\ \text{kV}$$

(U_n – motor rated voltage in kV).

For motors having rated voltage U_n=6 kV, the peak value of power-frequency test voltage is $13\sqrt{2}$ kV, and in relative units, in relation to the peak value of phase-to-earth voltage ($6\sqrt{2}/\sqrt{3}$) kV of the 6 kV network, it amounts 3.8 p.u.; the test value of lightning impulse voltage expressed in the same way, in relative units, amounts 5.9 p.u..

In the Technical recommendation TP 32 of the Power Industry of Serbia [1] the power-frequency test voltage of the motor stator winding is the same as in IEC 600034-15 Standard.

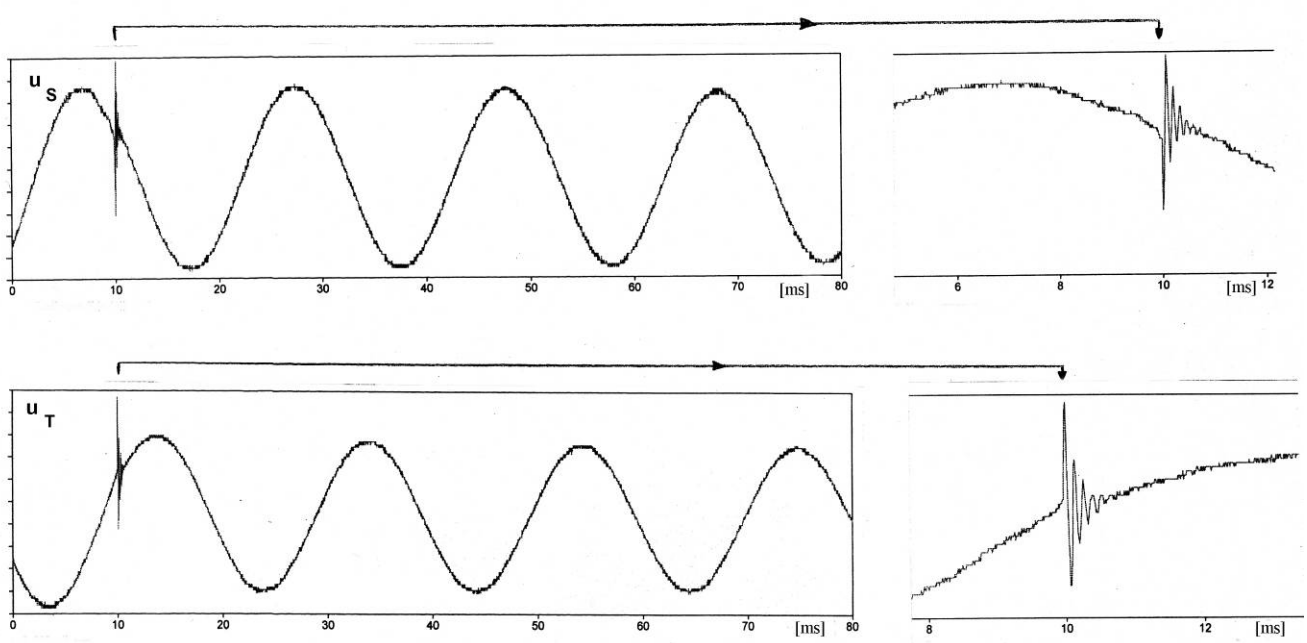

Fig. 3. Transient phase-to-earth voltages u_S and u_T on the stator-winding insulation of the 6kV, 630kW motor, at its switching-out during normal operation.

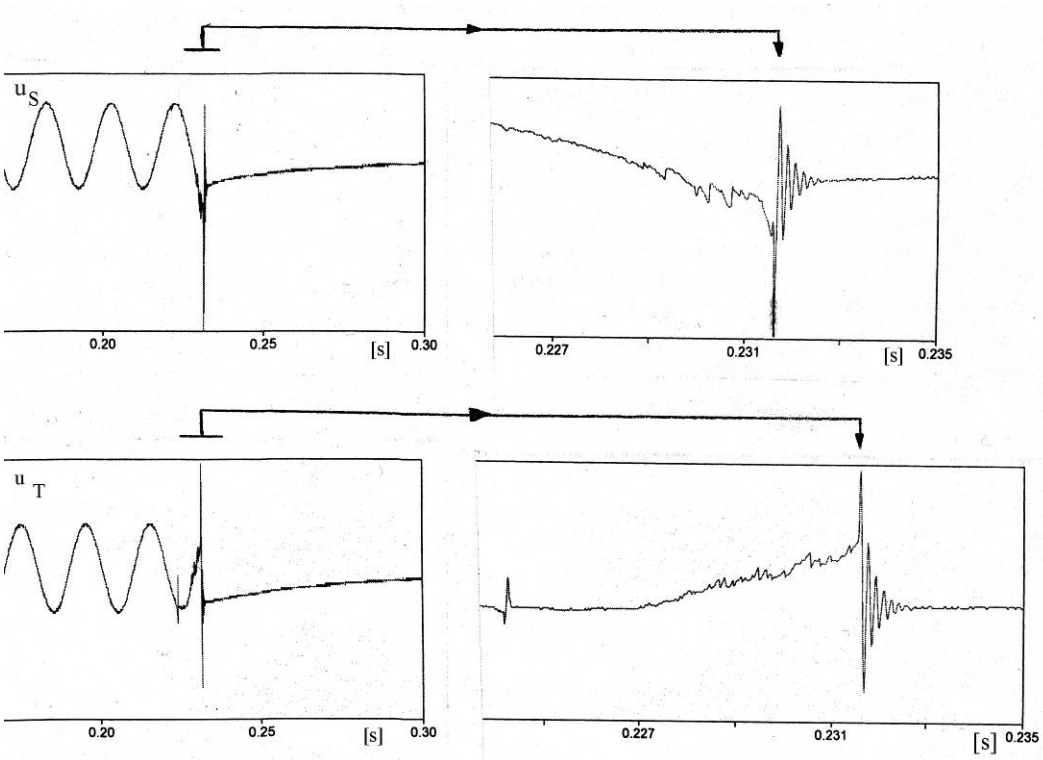

Fig. 4. Transient phase-to-phase voltages u_S and u_T on the stator winding insulation of the 6kV, 500kW motor at its switching-out during acceleration.

The impulse withstand voltage to earth of the motor stator winding according to the draft of the IEEE Working group [2] (insulation aging during exploitation is taken into consideration) is:

$$U_p=1{,}25\sqrt{2}\,(2U_n+1)\ \text{kV}$$

(U_n - motor rated voltage in kV).

Expressed in relative units, for motors having rated voltage U_n=6 kV it amounts 4.7 p.u.. It is also the lowest margin for

the insulation withstand voltage given by the Working group 13.02. CIGRE [3].

V. ANALYSIS OF INVESTIGATION RESULTS

Experimental investigations on 6 kV industrial networks have shown that overvoltages, appearing on the stator winding insulation of high-voltage motors at earth fault occurrence and switching operations of minimum oil circuit-breakers, have frequencies up to several kHz. As such, they can be classified to overvoltages with slow rise-time. According to [2], the withstand voltage of the stator winding insulation for such overvoltages should be at least 4.7 p.u.. By analysis of overvoltages determined by experimental investigations, it is observed that, overvoltages, appearing at switching-out the motor during acceleration, have the values which are close to withstand voltage values. The reason for such high overvoltages is current cutting, in the course of oil circuit-breaker opening operation, before passing through its natural zero value. This phenomenon is particularly expressed at older types of minimum oil circuit-breakers. Minimum oil circuit-breakers of more contemporary production, at switching-out, cut the current at lower values, and consequently, the overvoltages are lower. The overvoltages appearing at switching-out the motor during acceleration, considerably stress the stator winding insulation and their appearance should be limited or restrained. All remaining overvoltages, which appear at earth fault occurrence and at switching-in and switching-out of motors in normal operation, are not that high as to require the measures for their limitation. It only shall be provided that in the 6 kV network do not appear ferroresonant oscillations which may last for hours, if not eliminated by changes occurring in the network (switching-in or switching-out of some cable line with motor or 6 kV/0.4 kV transformer, earth-fault etc.).

VI. CONCLUSIONS

On the basis of the results analysis of investigations of overvoltages on the stator winding insulation of high-voltage motors in the 6 kW networks of industrial plants, the conclusion can be drawn that some of them are significantly stressed and even endangered. In order to reduce dielectric stresses of stator windings insulation of high-voltage motors it is necessary to undertake the following:

a) Prevent the motor switching-in by means of certain restrains, if all conditions for putting into operation of facilities driven by them are not met.
b) Overcurrent protections of motors shall be set in such a way that strong currents appearing during motor acceleration do not activate them.
c) If the measure under /a/ cannot be realized, and switchings-out of the motor in acceleration occur, it is necessary to protect the stator windings insulation to earth by surge arresters. They can be mounted at the entrance of the motor cable line and even better, if feasible, at motor terminals.
d) Prevent the appearance of ferroresonance by introducing the resistor of about 20 ohms resistance at the ends of the broken delta secondary windings of the voltage transformers set in the measurement cell.
e) Determine as soon as possible the earth-fault spot, when it appears. Eliminate it as soon as possible, taking care not to produce damage in the production procedure.
f) Avoid switchings-in and switchings-out of circuit-breakers of cable lines with high-voltage motor, except switching-out that one on which an earth fault occurred. By such operations of circuit-breakers, excessively higher overvoltages can appear than those registered by investigations.

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