LARGE MOTOR STATOR WINDING FAILURE DUE TO LIGHTNING TRANSFERRED OVERVOLTAGES

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Abstract - In polypropylene petrochemical plants high power motors are normally used to drive extruder or compressor machines required by this type of industrial process. Each motor of such a big size is usually fed by a dedicated supply captive transformer which often is directly connected to a high voltage overhead line.
In case of lightning stroke hitting the overhead line, a surge voltage impinging on high voltage transformer windings can be transferred to the motor side due to the electrostatic and electromagnetic coupling of transformer windings, with the risk of endangering the motor stator winding to frame insulation as well as the stator winding inter-turn insulation.
The effectiveness of installing surge arresters at motor terminals is evaluated by EMTP modeling and then comparing the resulted over-voltages to the impulse withstand limits given by IEEE standards for rotating machines.

Index Terms — Lightning overvoltage, metal oxide surge arrester, surge capacitor, transferred surge.

I. INTRODUCTION

The application of high power induction or synchronous motors (typical rated power between 9 MW and 30 MW), which drive machines like extruders or compressors, has become in the latest years a common practice for polypropylene chemical plants.

In order to be started direct-on-line, the large power motor usually requires the supply by a dedicated captive transformer where the primary winding is fed at high voltage (typically between 69 kV and 230 kV) by the transmission network system operator (TNSO). Sometimes, the primary winding of the captive transformer is directly fed by an overhead line which is then potentially exposed to the risk of direct lightning strokes due to line shielding failures or line back-flash failures. It is historically well known in the technical literature [1] that rotating machinery connected directly or electrically close to overhead lines is more vulnerable to surges than many other type of apparatus.

A fault incident event which happened in an industrial plant is discussed: an unexpected ground fault occurred inside the frame of a large synchronous motor with quite apparent damages to the insulation of the stator windings.

The novelty of this work consists in the way a root cause analysis is carried out in order to find the origin of the fault event: an explanation in terms of lightning overvoltage transmitted from the overhead line to the motor windings is derived by means of numerical simulations performed with EMTP-ATP software.

Finally, some remedial corrective actions are suggested in order to prevent in future the damage due to this type of fault event.

A. System Data

The electrical distribution scheme of a typical industrial plant, in which a large synchronous motor (27.5 MW rated power at 11 kV) is applied, is shown in Fig. 1. The motor is necessary to drive a gas compressor needed by the chemical plant based on the technology of LDPE – low density polyethylene. The motor is fed by a 220/11 kV captive transformer which receives the supply by a 220 kV overhead line.

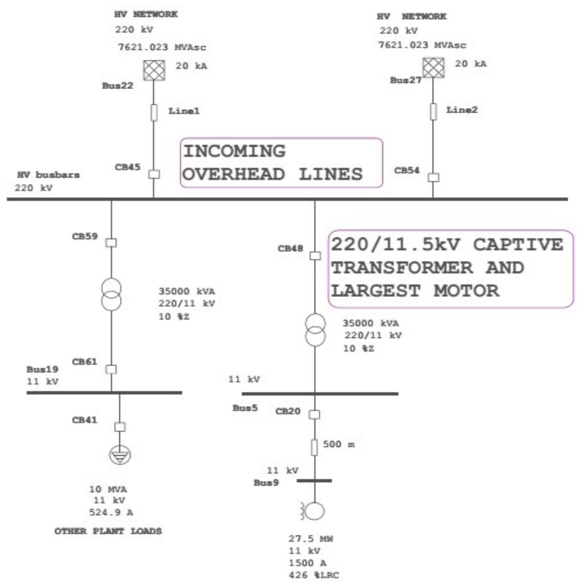

Fig. 1 Single-line diagram of the industrial electrical system

Main electrical parameters for the network components are reported in the Appendix.

B. Need for Electromagnetic (EMT) Modelling

In order to study lightning overvoltages, a simple RMS-type modelling, which is usually used for short circuit studies or for transient stability studies, is not sufficient in this case, because in general the lightning phenomena occur within few microseconds and not between tens of milliseconds and some seconds, and it is therefore necessary to model the surge impedance characteristic of the network components involved.

In particular here the phenomenon of transferred lightning overvoltage between the primary and secondary transformer windings is studied, hence it is necessary to model all the stray capacitances of transformer windings.

For the above reasons it was decided to use an EMT based software like EMTP-ATP. Other EMT software equivalent to EMTP-ATP can in general be used for such kind of studies, like PSCAD-EMTDC or EMTP-RV which are also well known worldwide nowadays.

C. *Modelling*

For the aim of numerical simulation by ATP (Alternative Transient Program) [2], the electrical network is simplified and modeled as shown in Fig. 2, following the general guidelines presented in [3].

All equivalent impedances of the network components are referred to the motor rated voltage.

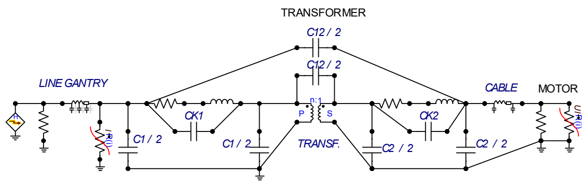

Fig. 2 EMTP-ATP model of the electrical system

The motor captive transformer is modeled by means of a capacitive network due to the electrostatic surge transfer from primary to secondary winding, and by its leakage inductance and turns ratio due to the electromagnetic surge transfer from primary to secondary winding [4], [5], [6]. Since the neutral point of the primary high voltage wye-connected winding is solidly grounded, it is assumed that the coupling between the three-phase windings does not influence significantly the calculation of the phase-to-ground voltage according to experience get from technical literature [7]. This simplifying assumption allows to consider only the single-phase equivalent circuit of one winding for studying the lightning surge wave process.

The lightning surge current on the high voltage system is modeled using an exponential surge function (Heidler current source generator), on the basis of data from the transmission network system operator (TNSO) of the 220 kV network who performed the study of insulation coordination considering the lightning striking location close to the industrial plant substation (few hundreds of meters): the type of simulated lightning strike is a shielding failure of the incoming 220 kV supply overhead line, without the presence of insulator string flashover. The probability of lightning back-flashover events was considered null by TNSO due the good tower foot resistance of the overhead line (approximately 10 ohm):

- back-flashover happens when the lightning hits the earth wire among transmission towers or one transmission tower, then the potential of the tower increases beyond the withstand voltage (critical flashover voltage) of insulators and a flashover across the line insulators finally occurs. Thanks to the good value of tower foot resistance (10 ohm) the critical flashover overvoltage of line insulators is not exceeded.
- shielding failure means that the lightning hits directly the line conductors and a consequent overvoltage wave then travels along the line conductors.

The surge arresters on both high voltage and medium voltage levels are modelled with non-linear resistors (graphical symbol by a red line through in Fig. 2) based on data sheet from relevant manufacturer: this means that the voltage vs. current characteristic of the resistor is not a straight line as is shown in Fig. A-IV and Fig. A-V into the Appendix.

The last span between two consecutive towers of the supply high voltage overhead line is modelled by a line element having a certain characteristic surge impedance, while the medium voltage cable from the captive transformer to the motor is modeled by a single pi-grec impedance element.

The surge impedance of the motor is estimated on the basis of inductance and capacitance parameters provided by motor vendor, by means of procedure from technical literature [4].

II. PRE-ANALYSIS AND ASSUMPTIONS

Before performing numerical simulations, a few theoretical assumptions are first discussed for the aim of getting a likely explanation of the fault event.

A. *Description of the events*

The synchronous motor driving the largest compressor motor in the industrial chemical plant as shown previously, experienced stator winding failure to ground while in operation, which was detected and cleared promptly by the earth fault motor protection relay, causing an inadvertent plant shutdown.

After the motor inspection by plant personnel with the assistance of motor manufacturer, it was clear that the coil failure to ground was due to a turn-to-turn insulation breakdown which then evolved rapidly to the breakdown of the ground-wall insulation, with the final result of a stator to ground fault event.

The single phase-to-earth fault damaged mainly the stator coil winding, without causing the melting of the stator iron core, thanks to the fact the earth fault was cleared quickly (less than 200 ms) and considering that the neutral point of the secondary winding of the captive transformer was high-resistance grounded to a quite low value (20 A) which can be withstood for twenty seconds by the stator iron core.

B. *Interpretation of the incidental event*

After deep investigation by plant personnel and motor manufacturer technicians about the root cause analysis of the incident event, it was highly suspected that the origin of the fault had to be searched externally to the management of the industrial plant, that is, in an external cause not depending on incorrect maintenance activities.

The transmission network system operator (TNSO), owner of both the 220 kV supply line and of the 220/11 kV motor captive transformer, was inquired about the lightning strike activity in the zone where the plant is installed, and a high lightning flash activity was actually confirmed (lightning flash density equal to almost 150 thunderstorm days/year). TNSO confirmed the occurrence of several events of lightning flashes hitting the line conductors (shielding failure) due to the triggering of surge arrester counters installed at the primary high voltage side of the 220/11 kV captive transformer.

A plausible explanation for the motor stator winding failure is that the lightning overvoltage originating on the 220 kV incoming line traveled towards the captive transformer: here, the magnitude of the surge was partially suppressed by the surge arresters installed to protect the high voltage winding of the transformer, but a residual overvoltage was still transferred through the transformer to the motor windings causing the breakdown of the stator ground-wall insulation.

C. Case Study

The most representative lightning stroke current, from the TNSO who was responsible for the insulation coordination for the 220 kV overhead line, is injected into the line, and the resulting over-voltages impinging on the captive transformer and on the motor are analyzed.

In fact, the impact of a lightning stroke directly on a phase conductor can be seen as a current injection on the phase conductor: the current divides itself into two equal parts at the point of impact, and the two generated voltages travel in both directions along the line away from the point of strike.

A flashover will generally occur if the critical flashover overvoltage $U_{50\%}$ (i.e. the overvoltage having 50% probability to cause line insulator flashover) of the line insulation is exceeded. For a stroke at the midspan between two consecutive towers, the critical stroke current magnitude I_c that will cause flashover is given by:

$$I_C = 2 * (U_{50\%} / Z_c) \qquad (1)$$

where:

I_C	critical lightning stroke current (peak vakue)
$U_{50\%}$	critical flashover voltage (CFO) of line insulation
Z_C	surge impedance of line phase conductor

Taking Z_C = 500 ohm, $U_{50\%}$ = 1250 kV (line-ground), it results I_C = 5 kA (peak value).

III. RESULTS

The results of numerical simulations are shown graphically in the following figures. Lightning over-voltages (instantaneous peak values), are chosen as the most significant magnitudes in order to evaluate the impact of the 220 kV system lightning stroke current on the 11 kV distribution system.

A. Overvoltage calculation

The lightning overvoltage at overhead line tower and the overvoltage at the primary bushings of the captive transformer are shown in the following Fig. 3.

The phase A is taken as reference for all the plots.

As can be seen, the overvoltage peak value at 220 kV tower is around 1050 kV (line-ground), and it is within the lightning impulse withstand level for which the line insulators are designed (1250 kV, line-ground), therefore no back-flashover takes place. The line overvoltage, travelling towards the captive transformer, is then chopped by surge arresters in order to protect the primary transformer windings: the actual overvoltage peak value of 415 kV (line-ground) is less than the transformer design withstand level (950 kV, line-ground).

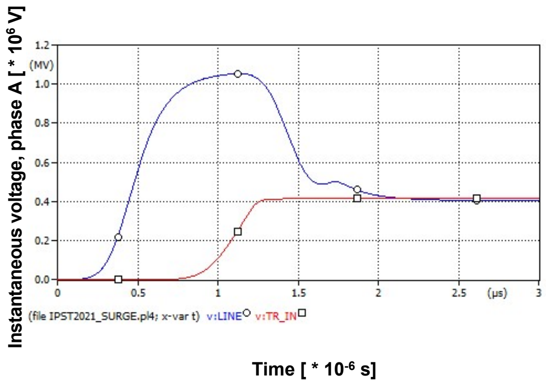

Fig. 3 Lightning overvoltages on 220 kV side (line and transformer)

In the next figure, the overvoltage being transferred from the primary winding to the secondary winding of the captive transformer is shown.

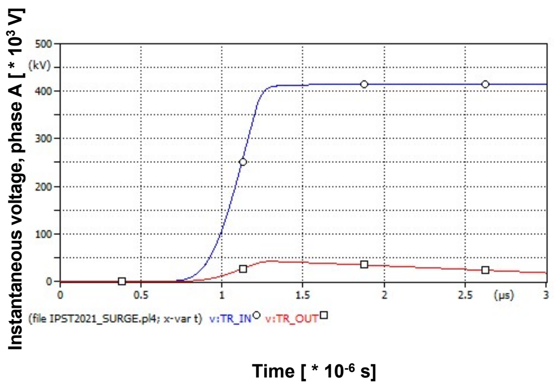

Fig. 4 Lightning overvoltages on 220 kV and 11 kV transformer windings

The overvoltage on transformer primary winding, whose peak value is 415 kV (line-ground), is quite attenuated on the secondary winding side, where it reached the peak value of 41.5 kV (line-ground) which is within the lightning impulse level of transformer secondary winding (75 kV, line-ground). However, the overvoltage transferred on the 11 kV distribution system, although it is not dangerous for transformer windings, could still impact the insulation of downstream motor equipment.

In the next figure, the overvoltage occurring at motor terminals is shown, taking into consideration the effect of the supply cable between captive transformer and motor. The cable helps lowering the rate of rise of the incoming surge, thanks to the cable capacitance.

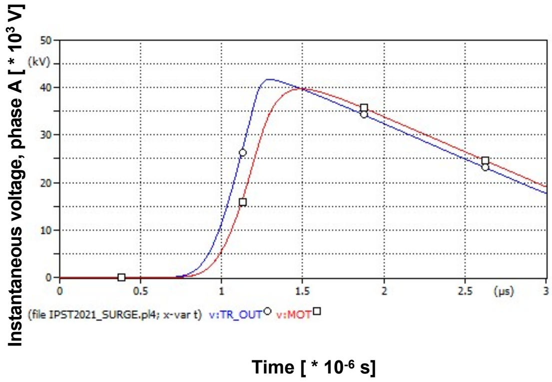

Fig. 5 Lightning overvoltages on transformer and motor 11 kV windings

As can be seen, the motor overvoltage reaches the peak value of 40 kV (line-ground).

B. Comparison with IEEE impulse withstand envelopes

The insulation of motor stator winding was manufactured and type-tested in factory according to the applicable IEC standard for impulse voltage withstand levels [9]. However, the same IEC standard does not consider the effect of ageing on the impulse voltage withstand levels.

For the above reasons, the overvoltage calculated at motor terminals is compared with the voltage withstand envelopes taken from IEEE standard [8], as shown in Fig. 6.

There are two types of withstand envelope in IEEE standard. The former (IEEE-1 in Fig. 6) having the greatest magnitude is the standard withstand envelope: the characteristic point at 0.1 $*10^{-6}$ s is 3.5 p.u. (per unit of √2/√3*line-line voltage), which means 32 kV (line-ground) for a system having 11 kV rated voltage and which corresponds to the withstand value foreseen by IEC standard for the rated steep-front-impulse voltage withstand [9]. The latter (IEEE-2 in Fig. 6) refers to the alternative withstand envelope, which is used for testing coils in machines that are not likely to see high-magnitude fast-fronted surges.

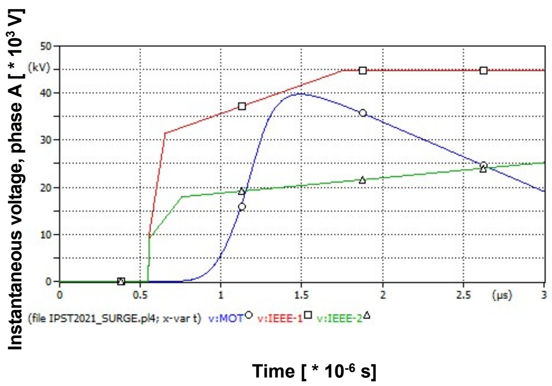

Fig. 6 Overvoltages on 11 kV motor windings vs. IEEE withstand envelopes

As can be seen, the overvoltage at motor terminals is within the standard (3.5 p.u.) envelope normally applied to test a newly manufactured stator coil, but it exceeds significantly the alternative withstand envelope.

Considering that the motor has been operating for more than ten years in an industrial environment and therefore is not new, the standard (3.5 p.u.) withstand envelope is deemed no longer a reliable reference to judge the impulse voltage withstand quality of the motor insulation.

The alternative withstand envelope is instead exceeded in the zone having front times greater than 1.2 * 10^{-6} s, just where it is likely that a stress to groundwall insulation can occur [8].

C. Installation of surge arresters at motor terminals

The application of surge arresters installed at motor terminals can be a valid remedy to prevent excessive voltage surges to stator winding insulation [10].

In the next figure, the overvoltage at motor terminals, after the installation of the surge arrester, is shown.

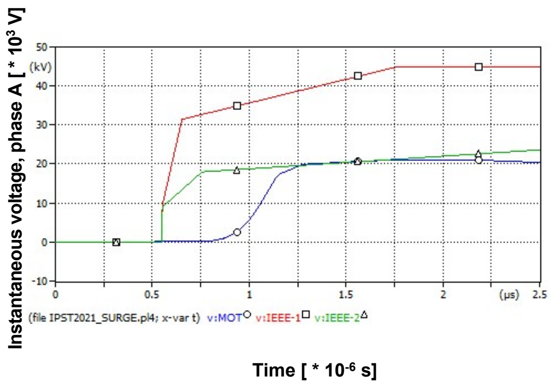

Fig. 7 Overvoltages on 11 kV motor windings vs. IEEE withstand envelopes

In this case, the overvoltage at motor terminals is safely within also the most conservative IEEE voltage withstand envelope (IEEE-2 in Fig. 7).

IV. CONCLUSIONS

The surge arresters installed at the primary bushings of a motor captive transformer are necessary in order to chop the incoming lightning overvoltage originating on the supply overhead line such as to protect the transformer windings insulation, but they are not sufficient to prevent that a residual overvoltage be still transferred to the motor windings.

The overvoltage impinging on motor stator winding is for sure not so harmful as the scenario of a motor being directly fed by an overhead line; anyway this surge, whose magnitude is a bit attenuated by the transformer impedance as well as by the surge arresters installed at high voltage primary windings of the transformer, can damage the groundwall insulation of the motor.

IEEE standards recommend that the insulation of a motor being already in service since a long time be tested at only 75% of the standard impulse test voltage applied to newly designed equipment [8]. In fact, for a motor being already running for many years, and especially used with a continuous service duty into an industrial polluted environment, it is more likely that the motor insulation may have lower strength with respect to the new design condition and could be impacted by transferred lightning over-voltages, as it actually happened in the case study where this problem was not faced at all neither during the commissioning of the industrial plant nor during the first ten years of motor operation.

In order to prevent similar surge events in the future, it was decided to install the following devices at motor terminals (detail data are shown in the Appendix):

- a metal oxide surge arrester, necessary in order to further reduce the surge amplitude at machine terminals within acceptable limits for both the turn-to-turn and groundwall insulation;

- a R-C surge suppressor device (also named sometimes R-C snubber or R-C filter) used to lower enough the rate of rise of the incoming surge voltage at motor terminals, due to its well known effect of flattening the surge wave slope; this was a conservative and additional safety choice [10], since simulations showed that the capacitance of motor feeding cable was already sufficient for this aim thanks to the quite long motor supply cable;

- both the above components were installed near to the motor terminal box and designed for the same area being classified as hazardous for the risk of explosion where the motor was installed.

V. REFERENCES

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[10] D. Paul, S. I. Venugopalan, "Power Distribution System Equipment Overvoltage Protection," *IEEE Transactions on Industry Applications*, vol. 30, No. 5, September/October 1994.

VI. APPENDIX

A. *Electrical Network Component Data*

TABLE A-I
CAPTIVE TRANSFORMER

Equipment	Parameters
Transformer dedicated to the supply of the largest compressor 11 kV motor	35 MVA rated power
	50 Hz rated frequency
	220 / 11 rated voltage ratio
	Z_T = 10% short circuit impedance (referred to rated power)
	L_T = 1.101 mH inductance/phase (at 11 kV)
	R_T = 0.01153 ohm resistance/phase (at 11 kV)

The equivalent circuit for the overvoltage surge transfer is shown in Fig. A-I, with relevant manufacturer parameters shown in Tab. A-II:

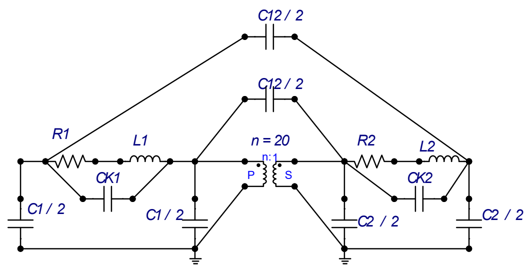

Fig. A-I Circuit model of the captive transformer for surge transfer study

TABLE A-II
SURGE TRANSFER PARAMETERS OF CAPTIVE TRANSFORMER

Parameter	Numerical value
Primary turn-to-turn capacitance C_{K1}	1425 pF
Secondary turn-to-turn capacitance C_{K2}	7640 pF
Primary-to-Secondary capacitance C_{12}	1570 pF
Primary phase-to-ground capacitance C_1	2080 pF
Secondary turn-to-turn capacitance C_2	1040 pF
Turns Ratio n	20
Primary winding resistance R_1	2.306 ohm
Secondary winding resistance R_2	0.005765 ohm
Primary winding leakage inductance L_1	220.4 mH
Secondary winding leakage inductance L_2	0.551 mH

TABLE A-III
SYNCHRONOUS MOTOR DATA

Manufacturer's Data
27500 kW rated power
11000 V rated voltage (r.m.s. line to line)
1654 A full load stator current (FLC)
400% of FLC locked rotor current
0.90 rated power factor
0.97 rated efficiency
42.5 nF phase-to-ground capacitance
3.057 mH (locked rotor inductance)

From the above manufacturer data, the surge impedance Z_s of the motor is estimated from the following equation, as per technical literature [4], and it results equal to Z_s = 403 ohm:

$$Z_s = 3/2 * \sqrt{(L/C)} \qquad \text{(A-1)}$$

where:

Z_s	surge impedance of the motor
L	locked rotor motor inductance
C	motor phase-to-ground capacitance

TABLE A-IV
CABLE

Equipment	Parameters
cable feeder from captive transformer to synchronous motor	500 m length
	240 mm^2 cross section
	3-core aluminum conductors 4 parallel runs/phase
	X_c = 0.1 ohm /km reactance / phase / km
	C_c = 0.2 *10^{-6} F/km capacitance / phase / km

TABLE A-V
OVERHEAD LINE

Equipment	Parameters
220 kV last span of incoming overhead line supplying the motor captive transformer	Z_L = 500 ohm Line surge impedance
	v = 3*10^8 m/s Propagation velocity
	R_L = 0.06 ohm/km Line resistance

The equivalent circuit model for the lightning stroke current, hitting the last span of the overhead line, is shown in the below figure, with following corresponding equation for the Heidler current generator [2]:

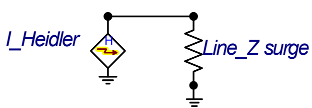

Fig. A-II ATP circuit model of the lightning stroke current on 220 kV system

$$I_{Heidler} = Amp \cdot \frac{(t/T_f)^n}{\left(1 + (t/T_f)^n\right)} \cdot e^{(-t/tau)} \qquad \text{(A-2)}$$

where:

$I_{Heidler}$	Heidler current source
t	time variable
Amp	5000 A (current amplitude)
T_f	1.488 * 10^{-6} s (front duration)
tau	75 * 10^{-6} s (stroke duration)
n	5 (rate of rise factor)

The lightning stroke current waveform resulting from the previous equation is shown in the next figure:

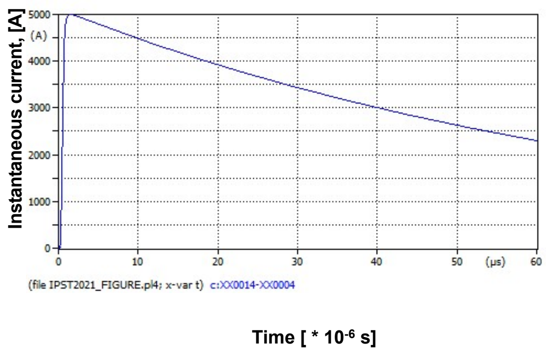

Fig. A-III Lightning stroke current waveform on 220 kV line phase conductor

TABLE A-VI
220 kV SURGE ARRESTER DATA

Equipment	**Parameters**
Metal Oxide Surge Arrester installed at the 220 kV bushings of Captive Transformer	U_R = 192 kV Rated Voltage (phase-to-ground)
	U_C = 154 kV Maximum Continuous Voltage (phase-to-ground)
	I_R = 20 kA Rated discharge current
	U_s = 488 kV discharge voltage (at rated discharge current I_R)
	IEC Class 4

TABLE A-VII
CIRCUIT MODEL OF 220 kV SURGE ARRESTER
(TYPE 92 RESISTOR IN ATP)

Current (A)	**Voltage (V)**
2500	400000
5000	424000
10000	455000
20000	488000

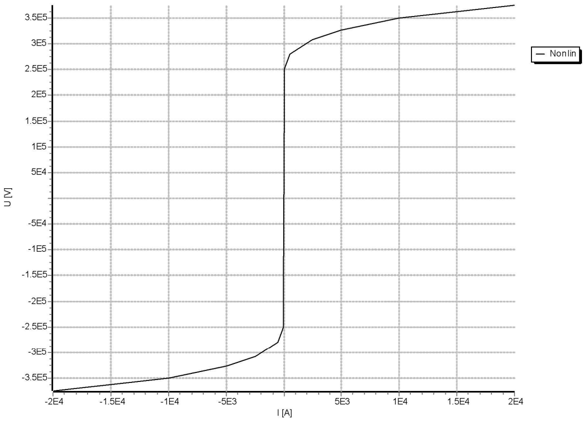

Fig. A-IV Voltage vs. current characteristic of 220 kV surge arrester modelled in EMTP-ATP

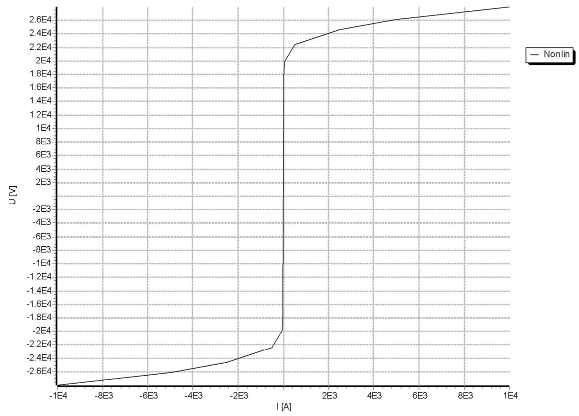

Fig. A-V Voltage vs. current characteristic of 11 kV surge arrester modelled in EMTP-ATP

TABLE A-VIII
11 kV SURGE ARRESTER DATA

Equipment	Parameters
Metal Oxide Surge Arrester installed at the 11 kV terminals of compressor motor	U_R = 11.3 kV Rated Voltage (phase-to-ground)
	U_C = 9 kV Maximum Continuous Voltage (phase-to-ground)
	I_R = 5 kA Rated discharge current
	U_s = 26.1 kV discharge voltage (at rated discharge current I_R)
	IEC Class 2

TABLE A-IX
CIRCUIT MODEL OF 11 kV SURGE ARRESTER
(TYPE 92 RESISTOR IN ATP)

Current (A)	Voltage (V)
500	22400
2500	24600
5000	26100
10000	27980

TABLE A-X
R-C SUPPRESSION DEVICE

Equipment	Parameters
R-C suppression device installed at the 11 kV terminals of compressor motor	C = 0.25 * 10^{-6} F Capacitance (per phase)
	R = 50 ohm Resistance (per phase)
	U_R = 12 kV Rated Voltage (phase-to-phase)

VII. VITA

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