Switching Transient Analysis during Motor Starting with Flux Compensated Magnetic Amplifier

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Abstract - This paper presents the results from the analysis of an incident in an industrial MV network during starting a large motor with Flux Compensated Magnetic Amplifier (FCMA). Initial field investigation and measurement campaign were conducted on site to identify the cause. The issue could be related to the switching overvoltage during the bypassing phase with vacuum circuit breaker (VCB).
Modelling and simulations are made with EMTP/ATP software, which allows describing the system in the very details. Results are compared with measurements with good match to better explain how the event would unfold. Demonstration of the performance of the mitigation solution are provided.

Index Terms — Motor starting, FCMA, switching overvoltage, troubleshooting.

I. INTRODUCTION

The case discussed in this paper is that of an Air Separation Unit with an N2 liquefier located in France (at Feyzin).

The N2 compressor was running for years with a DOL (Direct On Line) starting method induction motor.

A project of debottlenecking was decided and the N2 compressor motor was replaced with a more powerful spare motor. The rated power of the spare motor was 8,8MW while that of the original motor was 7,5MW. Calculations showed that the DOL method was no longer acceptable (even with the 7,5MW motor, the voltage drop during starting was at the limit of what was acceptable).

Different starting methods were investigated and compared as soft starter, autotransformer, inductance and finally FCMA (Flux Compensated Magnetic Amplifier) was selected.

At the motor starting, the voltage drop managed by the FCMA module is maximum and generated only by the starting current passing through the FCMA module coils. On this project, the Energy recovery system was also implemented.

Autotransformer starting method is usually preferred in this type of plant as more simple than a soft starter (no electronic skill needed) and less expensive (lower TCO).

The main advantage of FCMA compared with the Autotransformer is that no additional circuit breaker has to be added (when the electrical room did not provide free space).

The criteria to be considered when doing the choice of the starting device:

a. Limiting starting current
b. Maximum voltage drop imposed on the HV network
c. Existing loads running during start-up
d. Starting torque needed (linked to compressor curve)
e. Starting time
f. Maximum temperature rising for the rotor and stator windings

The start-up induces electro-mechanical and thermal stresses on the motor, so:

a. The starting time shall be as short as possible
b. The number of consecutive start-ups shall be limited in time.

Nevertheless, the appropriateness of this starting mode is conditioned to the following constraints evaluated during the design stage:

- maximum voltage drop authorized on the HV network,
- maximum voltage drop tolerated on MV busbar to prevent any stalling or disruption on other connected loads (ΔU=13 to 20% depending on upstream network min/max short circuit power).,
- the motor inrush current and torque capabilities at reduced voltage versus compressor starting torque
- The minimum angular acceleration, overall starting time allowed by compressor designer to reduce any shaft natural frequency and vibrations.

II. PROS AND CONS FCMA VS AUTOTRANSFORMER

Despite the fact that AutoTransformer is generally the preferred solution, FCMA presents the below advantages:

- reduced layout (compact solution and less circuit breakers needed)
- best TCO compared with electronic solutions along with reliability and lower maintenance
- easiness of operation
- higher torque in the end of the starting sequence

Disadvantages:

- starting time is higher, (as the system is maintaining a constant starting current during the time where the speed and voltage increase slowly).

- Lack of transparency of the design
- Dry type coils versus oil transformer: easier to repair an oil transformer than a dry coil

III. STUDIED CASE

A. Network Configuration - Incident

In the studied case, the 8.8 MW motor is powered from a 6.6 kV panel switchboard. To reduce the impact on the network voltage during motor starting, the technical solution selected in this case consists of using a Flux Compensated Magnetic Amplifier (FCMA).

FCMA uses the principle of opposition of two sinusoids flux: the first one is supplied by the main source (6.6 kV), while the second comes from the motor neutral start-point through an autotransformer. The motor windings are supplied by a reduced voltage, incurring the reduction of starting current.

Contrary to conventional motor starting with standard autotransformer, this is not the line voltage which is decreased but it is the neutral voltage which is increased.

The autotransformer of the FCMA has its third winding connected in delta configuration where a capacitor bank is added between the phases in closed circuit to compensate for the reactive power demanded by the motor during starting period.

Fig. 1 provides a simplified single line diagram illustrating the operation of the system.

Following a maintenance operation, the motor was restarted. Firstly, the operator opened the Bypass-CB, then he closed the SS-CB, then closed the Main-CB to supply the motor with reduced voltage. When the motor speed had achieved its nominal value, the operator opened the SS-CB, then closed the Bypass-CB to supply the motor with full voltage.

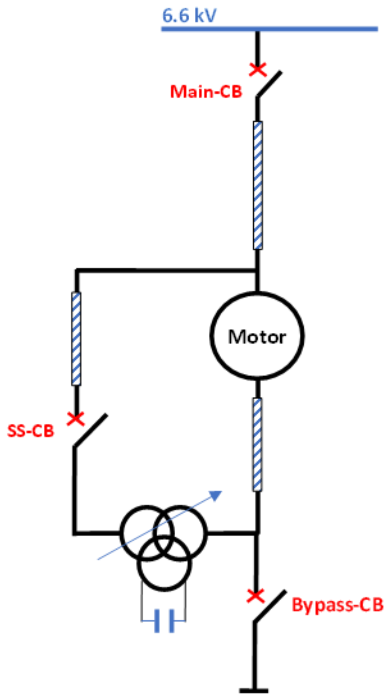


Fig. 1 Single Line Diagram

The incident came at the opening of SS-CB. An insulation issue occurred and damaged the FCMA.

Onsite investigation had been carried on the FCMA and results showed the damage in the first windings which is typically linked to the overvoltage issues. A RC-snubber was proposed to add to the primary side of the FCMA. Measurements had been done after to verify the performance of the mitigation solution.

This paper describes the analyses performed on the event. The system is modeled in EMTP-ATP with the simulation of the above switching operation sequence to reproduce the event and explain how it would unfold. Simulation results are compared and showed a good match with onsite measurements.

B. System Modeling

1) *Model of motor*

Universal Machine model UM3 is used to model the 8.8 MW motor. The mechanical load is represented by a nonlinear current-dependent resistance. Model parameters are evaluated based on manufacturer's data for nominal and starting conditions.

Fig. 2 shows the theoretical behavior of the motor with nominal load during starting period under nominal ideal voltage source. In case of running a direct online start-up, the starting current is expected 5.3 times of rated current and stating time is 5s.

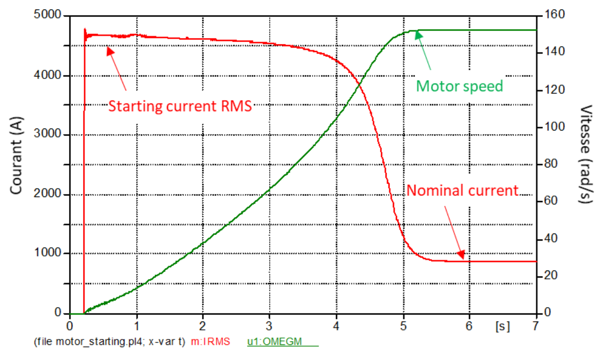


Fig. 2 Motor starting with ideal voltage source

2) *Model of FCMA*

Model of FCMA is given in Fig. 3.

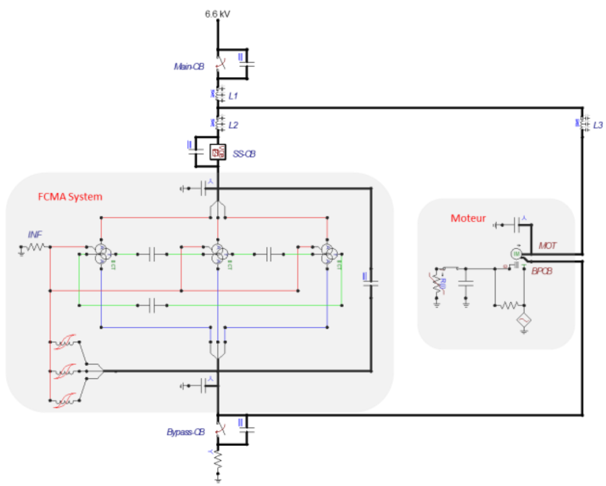


Fig. 3 Modelling of FCMA system

The key element in the FCMA system is the internal three-winding autotransformer.

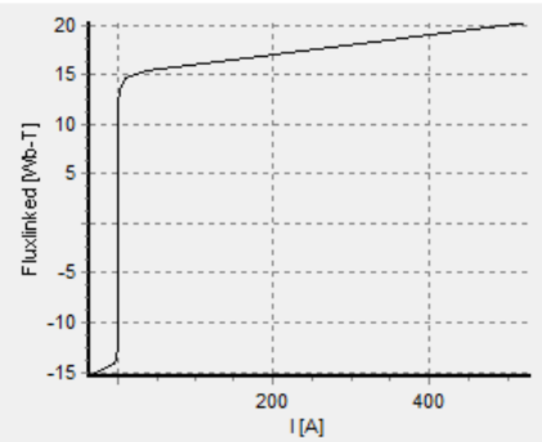
The FCMA autotransformer is modelled by using 3 single-phase BCTRAN model with external iron-core non-linear inductance represented by piecewise-linear type 96-elements connected to the secondary winding terminals in a star configuration.

The authors have chosen this representation for several reasons. This model allows modelling the special coupling between phases of the FCMA autotransformer, especially for adding the capacitor in the third winding in closed loop. Another advantage is the ease of residual flux initialization for transformer energization simulation. Major drawback of this model is that it misjudges the losses, and consequently, the equivalent resistive damping of the circuit and rate of the inrush current decay, which can be seen at the end of inrush current shown in Fig. 4.

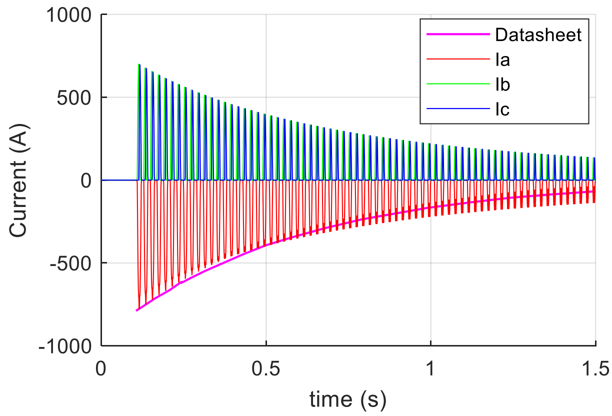
Model verification has been conducted and simulation results are compared to datasheet values.

Firstly, the FCMA autotransformer impedance is measured by short-circuit test and no-load test simulations and compared to datasheet values given at rated condition. Secondary, the saturation characteristics can be verified by simulation of the energization of the FCMA autotransformer with an ideal voltage source and with maximum of residual flux at inrush instant, as given in Fig. 4.

Lumped capacitance to ground is added at all terminals of the FCMA autotransformer and between windings to represent its behaviors at high frequency domain. Their values are not available however, assumed values could be taken based on the IEEE Std. C37.011-1994.



Magnetizing characteristic



Simulation of the transformer energization

Fig. 4 Modelling of the FCMA internal autotransformer magnetizing characteristic

3) *Model of circuit breaker*

In this system, the Main-CB is a SF6 circuit breaker (CB), the SS-CB and Bypass-CB are circuit breakers with vacuum breaking technology (VCB).

Medium voltage CB is known for its capability to interrupt the current before it crosses the natural zero. This phenomenon refers to the "current chopping". For SF6 CB, the chopping current depends on the breaking environment and the capacitances at its both sides. For VCB, the current chopping level relies on material of contacts, which is represented in this case, by a normal statistic distribution with mean of 5A and standard deviation of 10%.

SF6 CB can be modelled by a switch with a lumped capacitance between contacts. A detailed and appropriate model for SS-CB will be used to represent phenomena related to interrupting current in vacuum described in [1], such as current chopping, restriking, virtual current chopping, and voltage escalation. Model has been developed and validated with tests performed in laboratory, illustrated in Fig. 5.

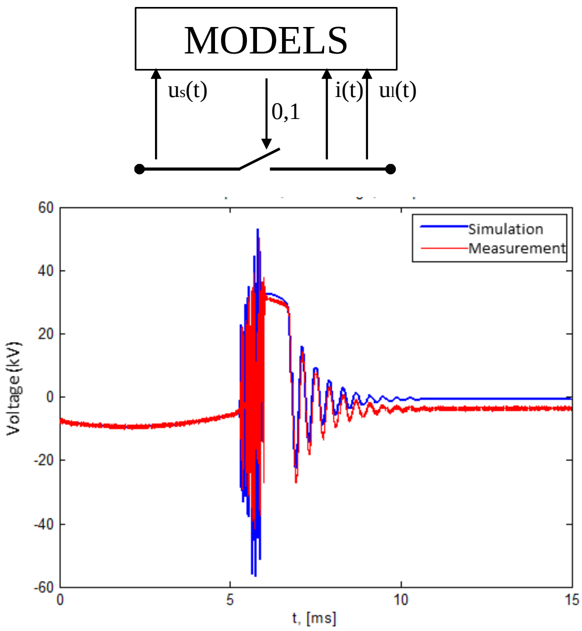


Fig. 5 Model of VCB – simulation vs. tests results

The Bypass-CB is operated to close therefore it can be modelled simply by a switch with a lump capacitance between contacts.

IV. INVESTIGATION ON MOTOR STARTING WITH FCMA

The motor starting procedure with FCMA is reconducted. The simulation is set initially with SS-CB closed and Bypass-CB opened.

A. Motor Starting Phase

The sequence starts by closing Main-CB. The 6.6 kV voltage from the grid is applied to the line side of the motor and the primary side of the FCMA autotransformer. The secondary voltage feeds the neutral of the motor.

Fig. 6 shows simulation results for acceleration of motor from stand still to full speed with nominal load.

During the starting period, the line voltage and neutral voltage are in phase.

The FCMA autotransformer ratio is adjusted to build up the potential at the neutral point of the motor, consequently, reduce the potential difference between line and neutral voltage.

As a result, the voltage applied along the motor windings is estimated to 2.36 kVrms (35.7% of nominal voltage) as given in Fig. 7, while in the 6.6 kV grid side, only a drop of 10% of nominal voltage can be observed. With this reduced voltage, the motor starting current is limited to 2708 Arms (3830 A peak) which corresponds to 3.1 times of rated current. The starting time is estimated to 23 seconds compared to 5 seconds in direct online starting mode.

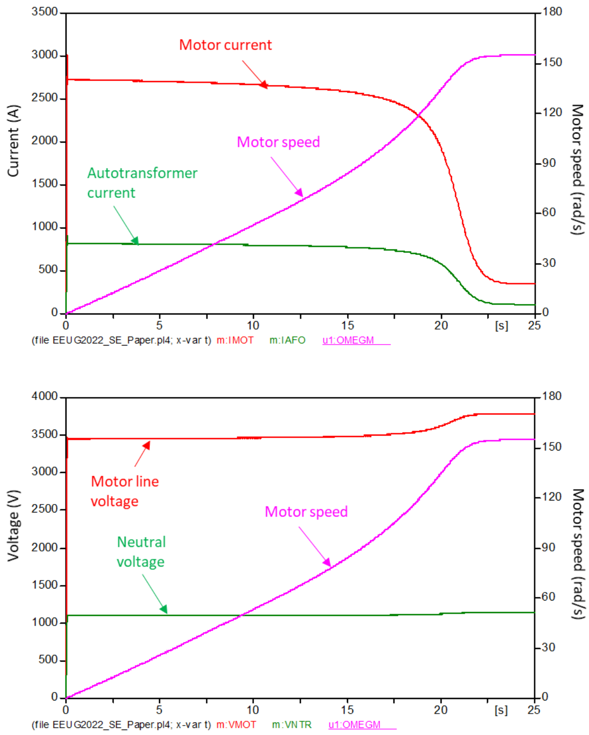


Fig. 6 Current and Voltage rms values in FCMA system during motor starting

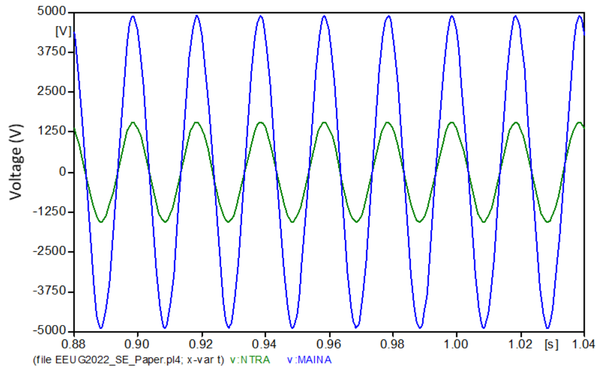


Fig. 7 Instantaneous potential difference between line and neutral voltage

Simulations results are compared and show a good match with onsite measurement. The current passing through SS-CB is estimated by simulation to 817 Arms and measured to the same value as reported in Fig.8.

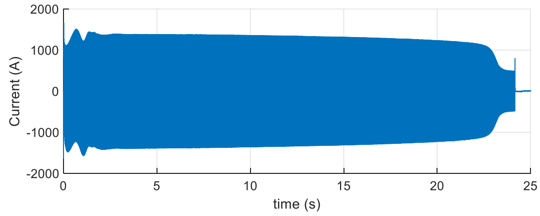


Fig. 8 Current passing through SS-CB – On-site measurement

B. By-pass Phase

Once the motor speed reaches to nominal value, it is time to bypass the FCMA autotransformer to re-establish the normal operation of the motor. This can be realized by opening the SS-CB, then closing Bypass-CB.

We observe two transient oscillations during this phase:

At the opening of SS-CB, the FCMA autotransformer losses the supply from 6.6 kV. The neutral point of the motor is connected to the secondary of the transformer which behaves as an inductance in series in the circuit. Due to the important variation of flux, the FCMA autotransformer goes to saturation region. This manifests in a typical form of magnetizing current which can be clearly observed onsite measurement in Fig. 9 and simulation results in Fig. 10.

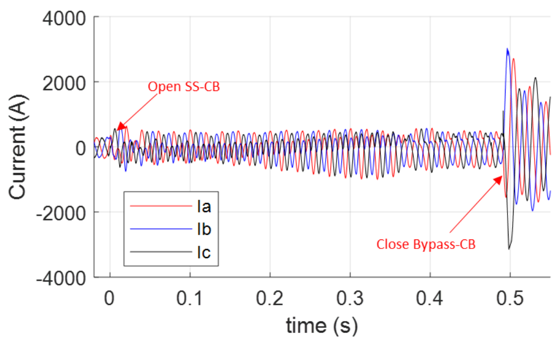


Fig. 9 Zoom on the current in motor - measurement

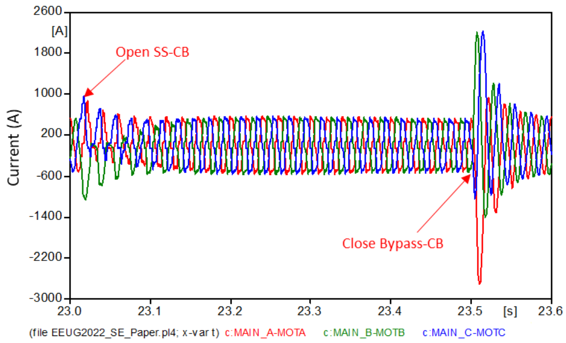


Fig. 10 Zoom on the current in motor - simulation

A disturbance can also be remarked on the neutral voltage in measurement in Fig. 11 and simulation results in Fig. 12.

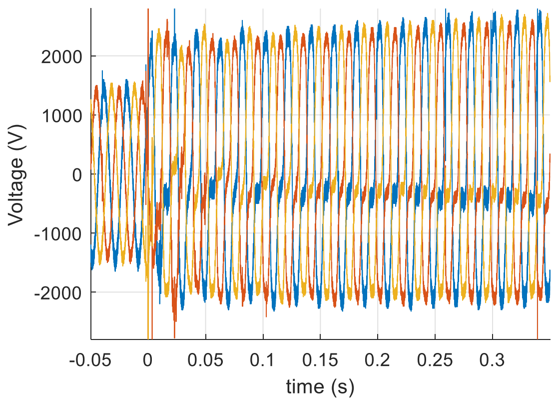


Fig. 11 Zoom on voltage at neutral point - measurement

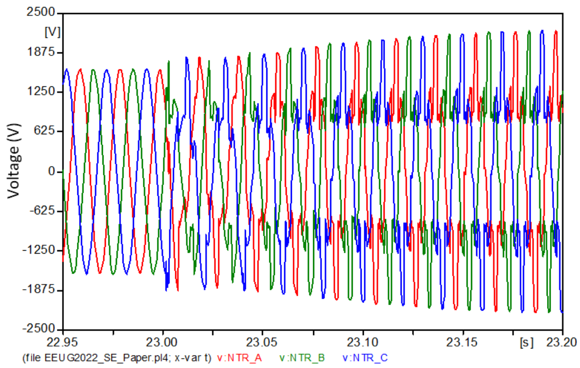


Fig. 12 Zoom on voltage at neutral point - simulation

Comparison between measurements and simulation results shows a slight difference in the amplitudes of observed parameters: The simulated peak current is 1125 A vs. 700 A measured; the peak voltage at neutral point is 1985 V in simulation vs. 2050 V measured.

This comes from :

- the modeling of the hysteresis with assumption on the characteristics of iron-core material and autotransformer design parameters
- the estimation of remanent flux at switching off of SS-CB.

The transient oscillation related to FCMA autotransformer saturation lasts until the closing of Bypass-CB, which marks the clear separation between the FCMA and the motor. The neutral point is disconnected to FCMA. This can be clearly seen in Fig. 13 and consistent with onsite record.

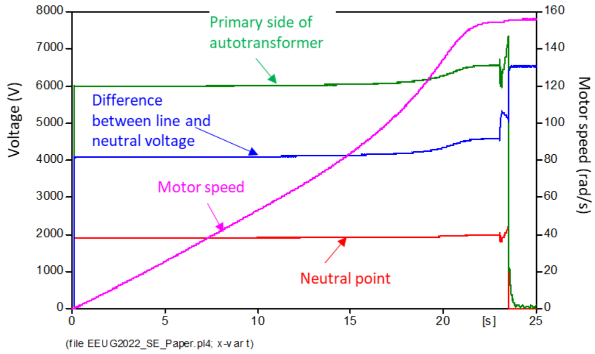


Fig. 13 Evolution of voltage at different point in the system during motor starting

C. Zoom on the opening of SS-CB

The current passing through the SS-CB is small and very inductive. A phase shift of almost 90° between current and voltage can be observed in Fig.14. At the opening of SS-CB, the current amplitude is 113 Arms (160 A peak). This is typical circumstance that arises the occurrence of dangerous overvoltage while switching off with VCB.

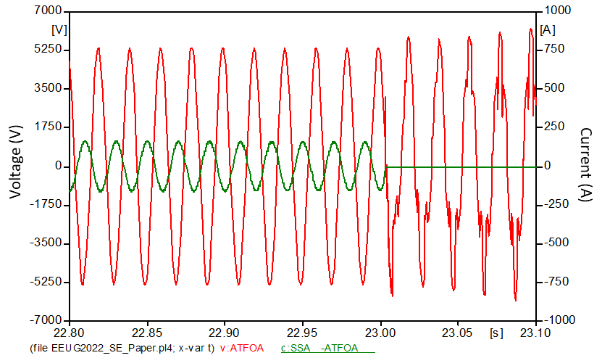


Fig. 14 Zoom on current passing through SS-CB at opening

In practice, when the SS-CB is ordered to open, VCB interrupts the first phase which crosses zero and restriking can occur when contact separation takes place near current zero. The time between the beginning of contact separation and the instant at which the current goes below the chopping level has a decisive impact on both amplitude and rate of rise of the generated overvoltage.

It can take two forms:

- Case 1: When the VCB is ordered to open, the contacts are gradually opening up, so as the dielectric strength. When the current falls below the chopping level, the dielectric strength has increased enough to withstand the Transient Recovery Voltage (TRV) occurred at effective current interruption and successfully extinguished the generated arc. As a result, VCB can interrupt the current without arc reignition, Fig. 15**Erreur ! Source du renvoi introuvable.**. A transient oscillation can be seen on the voltage without risk of dangerous overvoltage, as shown in Fig.16.

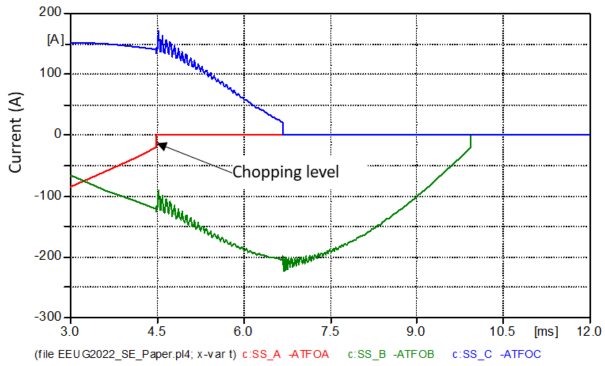


Fig. 15 Case 1:Current passing through SS-CB at opening

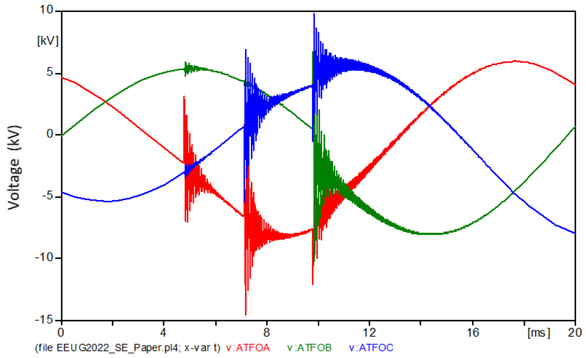


Fig. 16 Case 1: Voltage at the primary side of FCMA autotransformer

- Case 2: At the current interruption, if the gap between contacts is too small and dielectric strength has not developed enough to withstand TRV, VCB will fail to extinguish the generated arc. Reignition occurs. As a result, the network capacitances on both sides of the breaker discharge over the network inductance, causing a high frequency (HF) oscillating current (typically 100 – 200 kHz) through the VCB, as given in Fig. 17. When this HF current falls near zero, VCB has the capability of quenching HF current and new TRV is generated. If the separating contacts have not yet gained sufficient dielectric strength, there will be a new reignition. This sequence may be repeated several times with steeper and higher TRV amplitude, as illustrated in Fig. 18. The reignition is stopped when the contact gap is high enough to quench arc.

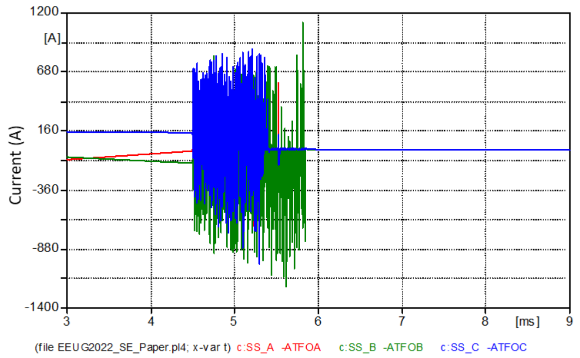


Fig. 17 Case 2: Current passing through SS-CB at opening

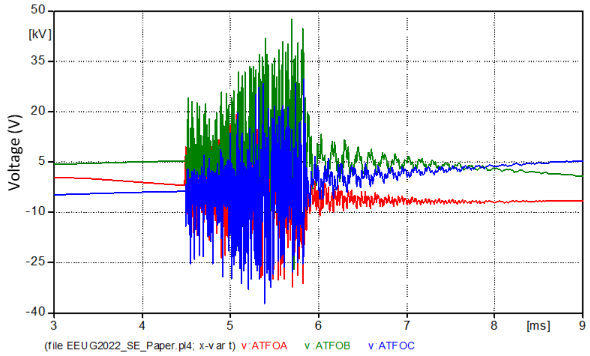


Fig. 18 Case 2: Voltage at the primary side of FCMA autotransformer

In the second case, although the VCB is designed to withstand the generated overvoltage, the overvoltage spreads along equipment in the circuit would be high enough to exceed their withstand capability leading to significant decrease for the interturn insulation strength.

Fig. 18 reports the overvoltage observed at the FCMA autotransformer's primary side. The maximum prospective peak overvoltage can reach to 47 kV, exceeding its standard rated frequency overvoltage withstand (28.3 kV peak) and in the limit of the basic insulation level (BIL = 40 or 60 kV peak).

In this installation, the motor starting is not rare. The probability of occurrence of such dangerous voltage could be not negligible and weaken gradually the insulation of equipment. It could result finally in insulation issue and that is the cause of the FCMA autotransformer damage in this incident.

D. Mitigation solution

Mitigation solution for overvoltage related to switching with VCB is well-known. A RC snubber is proposed to add to the FCMA autotransformer primary side. In the next figure, the performance of the solution is shown.

No overvoltage has been observed during onsite measurements after adding the RC snubber.

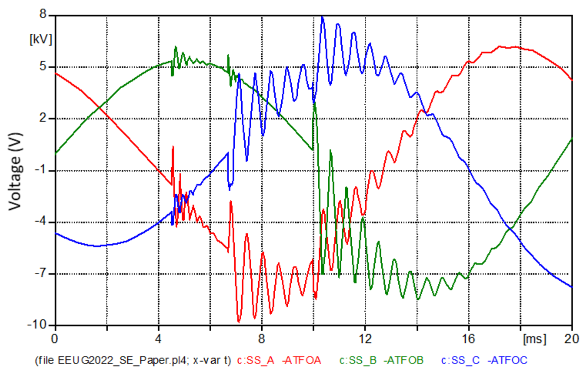


Fig. 19 Voltage at the primary side of FCMA autotransformer with presence of RC snubber

V. ON-SITE MEASUREMENT: LESSONS LEARNED

On customer site, and especially in a MV electrical network, it could be difficult to meet all the necessary conditions to perform an accurate measurement. The installation of the measuring devices and sensors must be as non-intrusive as possible. The number of recording sequences is also often limited so as not to interfere with the process. However, the measurement remains a good solution to identify a root cause of an issue, to quantify it or to check the effectiveness of corrective actions implemented.

For this application, it was also key to clearly identify the operation sequence and to select the measurement location accordingly. Overvoltage phenomenon - if not sufficiently damped since the mitigation solution had already been installed - was expected to appear at the opening of the vacuum circuit breaker (SS-CB in Fig. 1), on the FCMA side, at the end of the motor starting sequence. In addition, it also seems realistic to observe an overvoltage occurring on the neutral side of the motor, especially when the Bypass-CB (see. Fig. 1) opens, when the neutral voltage becomes floating. As a result, two sets of voltage sensors have been installed.

For transient phenomenon measurement, inductive voltage transformers installed in the switchgear cannot be used because they filter out the transient overvoltage: capacitive voltage divider probes are more appropriate to measure it. For this application a 1:1000 voltage probe able to withstand 40kV peak overvoltage (BIL of 6.6kV materiel) has been installed as shown in Fig. 20.

Fig. 20 Installation of capacitor voltage divider probes on customer site

Particular care is taken for the installation and wiring to avoid any risk of arcing between the probes and the MV busbar, as the insulation distances could be reduced by adding measurement probes. A proper wiring also avoids any induction loop phenomenon with the probes wires to occur.

In order to have an overview of motor starting, current sensors have been installed downstream the SS-CB circuit breaker and on the motor neutral side.
By measuring these two currents, it was also possible to calculate the total line current, thus avoiding the installation of an additional set of current probes which would limit the memory recording.

Flexible Rogowski probes has been used because they have the expected accuracy for the phenomenon observed and they are easy to install around MV insulated cables, especially when there are several cables in parallel.

Fig. 21 Installation of Rogowski current sensors around MV cables.

After installing voltage and current probes, the last step is to parameter the recording device: it a compromise between the sampling frequency and the recording time. For this application, both high sampling frequency (VCB restriking phenomenon expected) and high recording time (starting time of around 25s) was required. As we have the possibility to perform two consecutive motor startings, it was decided to record only the circuit breakers opening and closing sequence with a high frequency acquisition (10MHz) for the first starting and to record the complete starting sequence with a lower sampling frequency for the second start.

Once measurements are performed, the analysis must be done with criticism. For instance, a measurement noise can be confused with overvoltage. Sometimes the noise is easily identifiable. This is the case for noise occurring in steady state, or when the transient voltage magnitude and phase are similar on all voltage channels. When measurement is realized in a noisy environment, it is possible to perform a first test with voltage probes installed but not connected to the MV network: this gives a noise signature that could be ignored when the probes will be connected. Knowing well the expected phenomenon is also key to properly filter the signal when needed. The use of simulation models can also be a good way to predict the measurement that will be obtained.

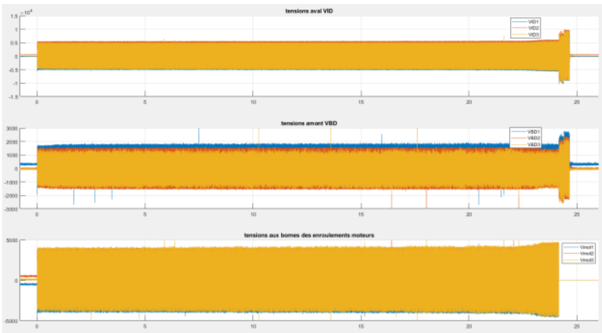


Fig. 22 Measurement noise observed in steady state.

For this measurement campaign, a phase rotation inversion and non-zero crossing current have been observed during more than 1 second as shown in the next figure:

Fig. 23 Non-zero crossing current measured

It was clear that it was not physical phenomenon. The phase rotation inversion comes from the inversion of the “A” and “C” labels inside the switchboard. For the second issue, the origin was found and digitally compensated afterwards: the current across the Rogowski sensor was higher than the measuring range of the sensor. The signal was positively and negatively clipped but with a small difference between the positive and negative clipping levels. The corresponding integrated signal has a DC component increasing over the time. At the end of the starting, the current decreases and became lower than the false DC component. The signal is then not centered on 0.

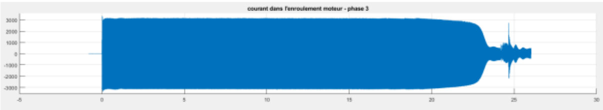


Fig. 23 Current signal after numerical filtering

The measurement campaign does not show any significant overvoltage. The measurements show that motor starting last around 23s. The voltage drop on the main busbar side varies from 11% at the beginning of the motor starting to 5.5% at the end of the motor starting. Thanks to the elevation of the neutral voltage, the FCMA reduces the voltage across the motor winding to around 37% of the rated voltage. The line current was limited to around 1.6 In during the motor starting.

VI. CONCLUSIONS

Contrary to conventional motor starting with an autotransformer, FCMA is not used to reduce the motor line voltage but to increase the neutral voltage. It therefore reduces the voltage applied to motor windings and starting current. The FCMA autotransformer is the key element. It has a special configuration, especially the third winding where capacitors can be added to compensate the reactive power required during motor starting. Modeling such a system is a challenging task.

EMTP ATP model of the motor and FCMA system has been developed. Simulations were carried out to reproduce with accuracy the phenomena of interest. The results obtained by simulation are consistent with on-site measurements.

The simulation analysis highlights the sequence of events on site that led to the damage to the FCMA system. This provides clear physical explanations of the issue, how the incident occurred and provides appropriate mitigation solution. The effectiveness of the mitigation solution is also demonstrated.

VI. REFERENCES

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II. VITA

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