TEMPORARY HARMONIC DISTORTION CAUSED BY A REDUCED VOLTAGE SOFT-STARTER

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Abstract - Some petrochemical plants require always the use of squirrel cage induction motors to feed large power compressors (typically from 2 to 10 MW).
In case of very low minimum short circuit power available from the medium voltage network which supplies the motor, one method to decrease further the motor locked rotor current in order not to exceed the limits on minimum transient busbar voltages, is to apply a soft-starter equipment based on thyristor control, which regulates the voltage at motor terminals during the starting phase.
Anyway, although the soft-starter operates only during the limited time period of the motor starting, it has the drawback of generating current harmonics towards the supply network, with the consequence that the voltage harmonic distortion at supply busbars exceeds the required limits as per applicable standards.
Simulations are carried out by means of EMT based software in order to assess the temporary harmonic distortion and the easiest remedy to solve this issue is described.

Index Terms - Thyristor converter, reduced voltage, soft-starter, harmonic distortion, power quality.

I. INTRODUCTION

The application of reduced voltage soft-starter equipment, based on thyristor valve bridge [1], [2], [3], has become in the latest years a common practice for chemical plants when it is necessary to control the locked rotor current during the starting of the motor, especially for large power applications, typically from 1 MW to 10 MW. The most common application in industrial facilities is to reach a starting current within a range from 250% to 450% of rated locked rotor current, by lowering enough the voltage at motor terminals during the starting [4].

The novelty of this work consists in highlighting that also soft-starting equipment used for temporary motor starting condition can cause significant harmonic voltage disturbances to the medium voltage supply grid at the point of common coupling of the industrial facility: indeed, nowadays most industrial customers and distribution system operators require power quality metering also on medium voltage switchgears, thereby the harmonic voltage distortion cannot be neglected even during transients events lasting only some tens of seconds, as was instead done as common industry practice in the past.

A. System Data

The electrical scheme of a typical industrial plant, in which a large induction motor is supplied by a medium voltage switchgear feeding also other user loads, is shown in Fig. 1.

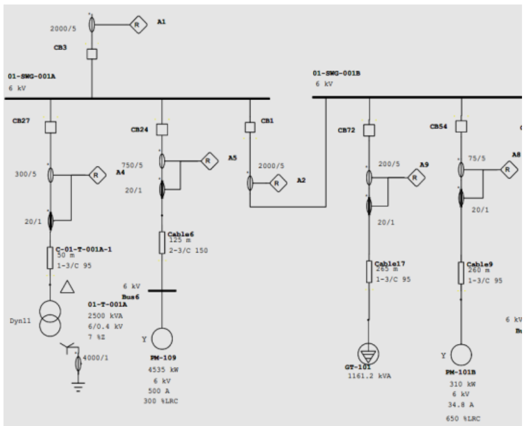


Fig. 1 Typical simplified single-line diagram of industrial facility

The basic scheme of the motor soft-starter is shown in Fig. 2, and it is realized with a thyristor bridge (two thyristors in back-to-back connection on each phase conductor).

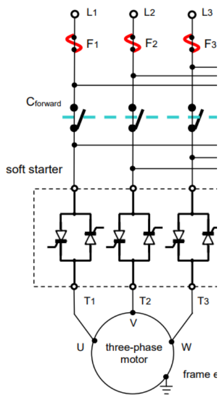


Fig. 2 Typical scheme of reduced voltage thyristor-based motor soft-starter

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

B. *Modeling*

For the aim of numerical simulation by EMT software [5], the electrical network is simplified and modeled as shown in Fig. 3, following the general guidelines presented in [6].

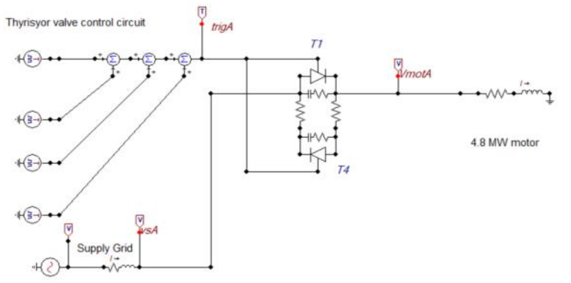


Fig. 3 EMT model for the aim motor soft starting simulations (simplified 1-phase representation of the complete 3-phase model)

All equivalent impedances of the network components are referred to the motor rated operating voltage level (6 kV), as described in detail into the Appendix: the equivalent impedance of the supply network is derived from the corresponding value of available minimum short circuit power at the point of common coupling between the industrial plant and the supply grid.

The network supply short circuit impedance is modeled as R-L components, since the network is mainly inductive and the charging shunt capacitance of cables can be neglected due to the short electrical length (less than 500 m as total length)

The motor is modeled by means of its locked rotor impedance during starting at rated voltage, as R-L components: it is not necessary to use a more detail electro-mechanical model since the scope of the simulation is to get the harmonic current spectrum injected by the soft-starter towards the supply network.

The AC-to-AC soft-starter converter is modeled as a six-thyristor bridge configuration, each thyristor being provided with its parallel R-C snubber to avoid voltage spikes.

In the reality the soft-starter measures the motor locked rotor current during starting and modifies the RMS value of its output voltage in such a way to guarantee an almost constant value of reduced locked rotor current as established by the user: for the aim of simulation, this type of closed-loop voltage control with current measurement as feedback is emulated as an open-loop control by setting a certain fixed degree for the firing angle to the thyristor valves and then by shifting of the enough amount the phase angle of the supply grid with respect to the firing angle of the thyristor, in order to get the desired value of output voltage during the soft-starting period.

II. PRE-ANALYSIS AND DISCUSSION

Few theoretical topics from existing technical literature [4], are first analyzed and discussed.

A. *Maximum allowable motor starting power*

It is first necessary to understand why it is needed to lower further the locked rotor current of the motor during its starting.

From the short circuit power divider rule, the minimum busbar voltage during motor starting can be evaluated by:

$$U_{6kVmin} = S"k_{min} / (S"k_{min} + S"k_{mot}) \text{ per unit} \qquad (1)$$

where

U_{6kVmin}	minimum voltage, in p.u. (per unit), at 6 kV supply busbar during 6 kV motor starting
$S"k_{min}$	minimum short circuit power at 6 kV supply grid, in MVA
$S"k_{mot}$	motor starting power, in MVA

By imposing the requirement for the transient minimum voltage at supply busbars:

$$U_{6kVmin} \geq 0.90 \text{ per unit} \qquad (2)$$

it is then possible to get from (1) the maximum limit of motor starting power such as to comply with (2):

$$S"k_{mot} \leq (1 - U_{6kVmin}) / U_{6kVmin} * S"k_{min} \qquad (3)$$

B. *Need of reduced voltage soft-starter*

By using the value of minimum value of short circuit power available at 6 kV supply grid (120 MVA) and by applying the relationship (3), the maximum starting power of the motor which can be applied in order to comply with the minimum voltage at 6 kV busbars (0.90 p.u.), amounts to:

$$S"k_{mot} \leq 13.3 \text{ MVA} \qquad (4)$$

The necessary motor starting current results equal to:

$$I_{start} = S"k_{mot} / S_{mot} \qquad (5)$$

$$= 13.33 \text{ MVA} / 5.52 \text{ MVA} = 2.4 \text{ per unit}$$

where

$S"k_{mot}$	motor starting power, in MVA
S_{mot}	motor apparent power, in MVA

Since the 6 kV motor has a LRC – locked rotor current (at 100% rated voltage) – being equal to 4.5 per unit of nameplate current, it is apparent that in order to lower the starting current from 4.5 per unit to 2.4 per unit, a soft-starter equipment is needed which applies a voltage at motor terminals equal to:

$$U_{start} = I_{start} / LRC \qquad (6)$$

$$= 2.4 \text{ per unit} / 4.5 \text{ per unit} = 0.53 \text{ per unit}$$

where

U_{start}	motor terminal voltage during soft starting regulation
I_{start}	actual starting current of the motor due to soft-starter regulation
LRC	locked rotor current of the motor when it is started directly-on-line with 100% voltage at its terminals.

C. *Case Studies*

Three types of transients are simulated and compared:

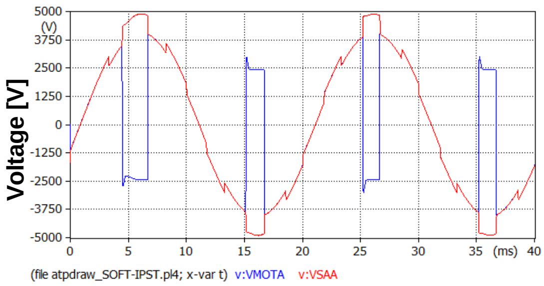
- 1st case: motor soft-starting without any capacitor bank for power factor improvement;
- 2nd case: motor soft-starting with one capacitor bank being already in service just before the starting occurs;
- 3rd case: motor soft-starting with two capacitor banks being already in service just before the starting occurs.

III. RESULTS

The results of numerical simulations are shown graphically in the following figures.

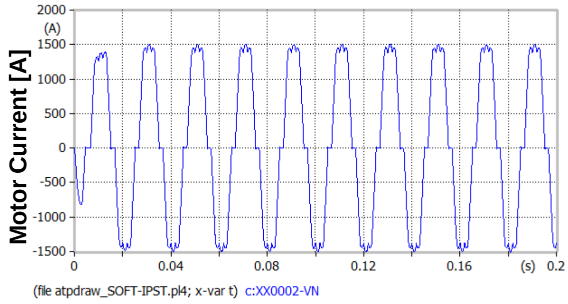
A. *Harmonic distortion without capacitor banks*

The supply voltage and the output voltage are shown in Fig. 4, while the motor current is shown in Fig. 5.



Time [10^{-3} * s]

Fig. 4 Supply voltage and soft-starter voltage during motor soft-starting

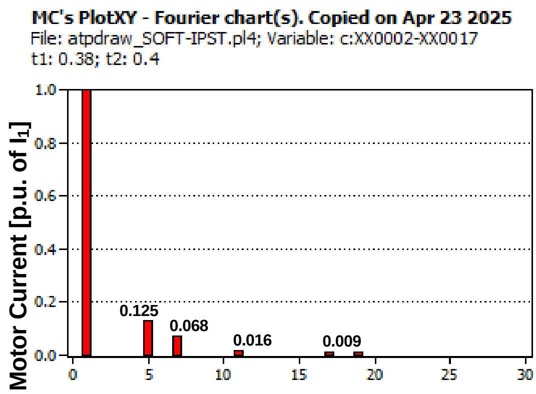


Time [s]

Fig. 5 Motor current during soft-starting

It is quite evident that the supply and motor voltages are much more distorted with respect to the motor current, since the current distortion is partially filtered by the motor leakage inductance.

The harmonic spectrum of the motor current is shown in Fig. 6. As can be seen, the individual harmonic orders are those typical of a 6-pulse thyristor-rectifier converter (5th, 7th, 11th, 17th, 19th); the total harmonic distortion for current (THD_I) amounts to 14.4% which also falls within the typical range (10% to 40%) of THD_I for 6-pulse thyristor-rectifier converters.



Harmonic order

Fig. 6 Harmonic spectrum of motor current during soft-starting in per unit of fundamental current (THD_I = 14.4%)

The individual harmonic orders of the supply voltage and the relevant total harmonic distortion (THD_V) are shown in Fig. 7.

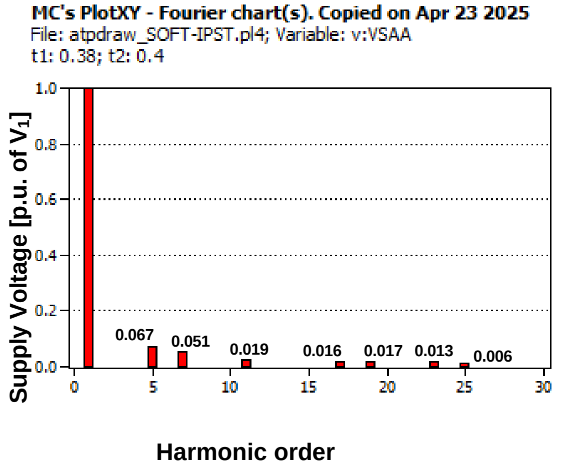


Fig. 7 Harmonic spectrum of supply voltage during motor soft-starting in per unit of fundamental voltage (THD_V = 9.01%)

The total harmonic distortion of the supply voltage amounts to 9% which exceeds the limit of 5% foreseen by the applicable IEEE standards [7], for all the duration of the transient starting which lasts approximately 25 seconds as per information from soft-starter manufacturer.

A frequency scan is performed to check the harmonic impedance of the supply network, as shown in Fig. 8.

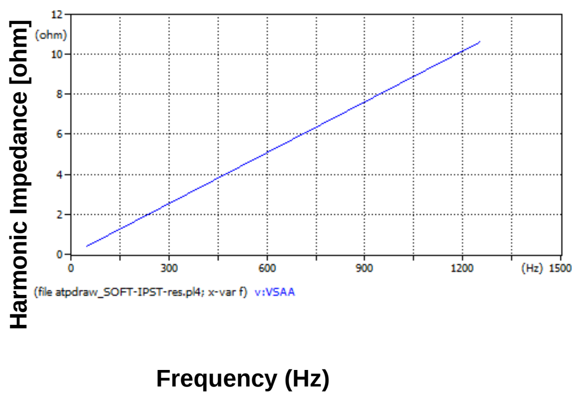


Fig. 8 Harmonic impedance of the supply network (operation without any capacitor bank)

As can be seen, the supply network impedance increases proportionally with the rise of frequency since the network behaves mostly as an inductive impedance (the effect of capacitance of the supply cables is neglected due to their very short length).

Therefore, some countermeasures are necessary to avoid that the customer of the industrial facility is subjected to some penalties coming from the DSO-distribution system operator.

Anyway, the industrial facility is already provided with capacitor banks at 6 kV voltage level, for the aim of compensating the power factor at the point of common coupling between the industrial facility and the supply distribution grid.

The ratings of the available power factor improvement capacitor banks are shown in Fig. 9.

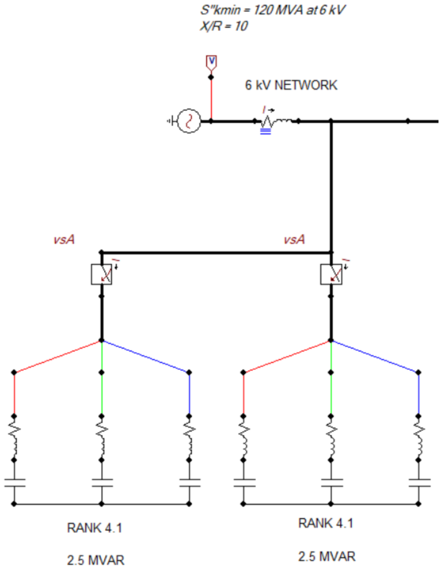


Fig. 9 Available capacitor banks on 6 kV distribution switchgear

The capacitor banks are of the de-tuned filter type [8], and they are equipped with series reactors which serve the purpose of both inrush current limiters and harmonic blocking filters: de-tuned type filter means that the L-C filter is tuned lower than the most significant expected harmonic order, therefore lower than 5th harmonic order in the case study.

Hence a possible remedial action can be to switch-on one or both capacitor banks just before the motor is started.

B. Harmonic distortion with one capacitor bank

One capacitor bank (2.5 MVAr) is switched-on before the motor is started.

The individual harmonic orders of the supply voltage and the relevant total harmonic distortion (THD_V) are shown in Fig. 10.

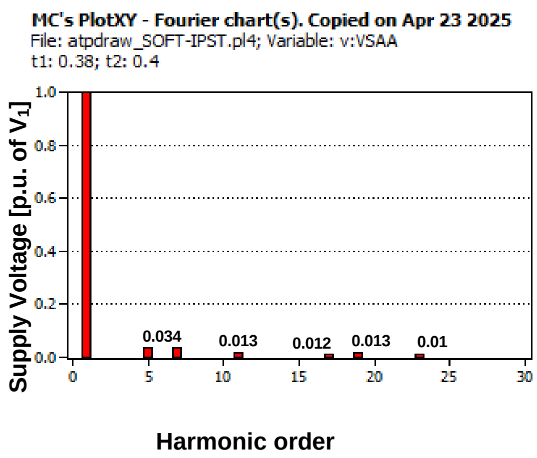
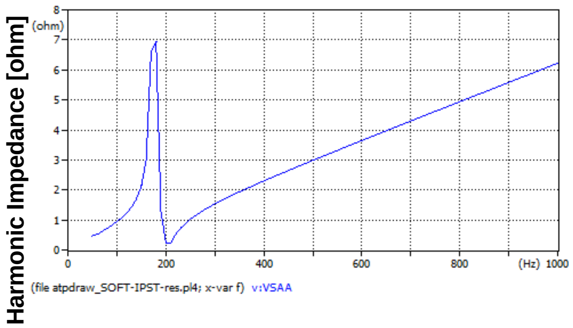


Fig. 10 Harmonic spectrum of supply voltage during motor soft-starting and one capacitor bank in service, in per unit of fundamental voltage (THD_V = 5.57%)

As can be seen, the allowable limit of 5% for the voltage total harmonic distortion is again exceeded.

A frequency scan is performed to check the harmonic impedance of the supply network, as shown in Fig. 11.

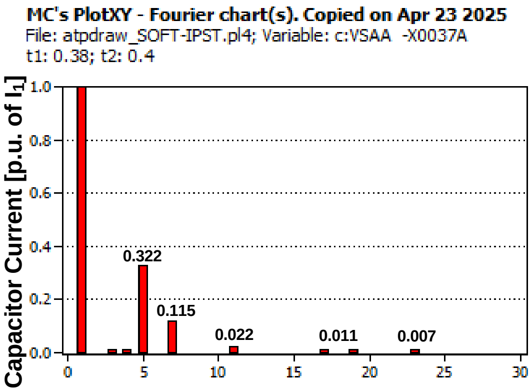


Frequency (Hz)

Fig. 11 Harmonic impedance of the supply network (operation with only one capacitor bank)

As can be seen, the operation of one capacitor bank working in parallel to the supply network creates a resonance in the impedance pattern placed around 180 Hz (3.6 times the fundamental frequency). The impedance magnitudes from the 5th harmonic order and above are a bit lower than the operating condition without any capacitor: it is why the voltage harmonic distortion of the 2nd case study results lower than the 1st case study.

It is also interesting to check if the capacitor bank is subject to any overload condition due to the harmonic currents injected by the soft-starter equipment. The harmonic spectrum of the capacitor current is shown in Fig. 12.



Harmonic order

Fig. 12 Harmonic spectrum of capacitor current during soft-starting in per unit of fundamental current (THD_I = 34.4%); only one capacitor bank into service

The total harmonic distortion for the current (THD_I) flowing inside the capacitor bank amounts to 34.4%. This means, according to the definition of THD_I as per reference standard [7], that the RMS value of the total current (fundamental plus harmonics) flowing inside the capacitor can be calculated as follows:

$$I_{RMS} = I_1 * \sqrt{[\,1 + THD_I^2\,]} \qquad (7)$$

$$= 254 \text{ A (1.06 times the rated current)}$$

where

I_{RMS}	RMS value of current
I_1	rated operating fundamental current of the capacitor bank (240 A corresponding to 2.5 MVAr)
THD_I	total harmonic distortion for current (0.344).

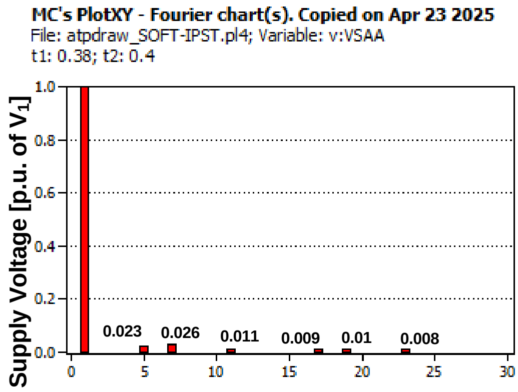
Since the capacitor bank is designed for a continuous voltage of 1.2 times the busbar operating voltage, it can deliver up to 1.44 times (1.2 times squared) the rated operating power (3.6 MVAr) and therefore it can absorb up to 1.44 times the rated operating current (346 A). Therefore, no overload occurs for the capacitor and series reactor of the capacitor bank.

C. Harmonic distortion with two capacitor banks

Also the second capacitor bank (2.5 MVAr) is switched-on before the motor is started.

The individual harmonic orders of the supply voltage and the relevant total harmonic distortion (THD_V) are shown in Fig. 13.

Now the limit of 5% for voltage total harmonic distortion is satisfied thanks to the harmonic filtering effect provided by the de-tuned capacitor banks.



Harmonic order

Fig. 13 Harmonic spectrum of supply voltage during motor soft-starting in per unit of fundamental voltage (THD_V = 3.98%); both capacitor banks into service

A frequency scan is performed to check the harmonic impedance of the supply network, as shown in Fig. 14.

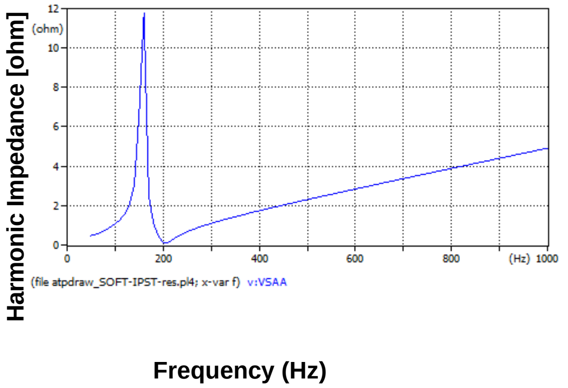


Fig. 14 Harmonic impedance of the supply network (operation with both capacitor banks)

As can be seen, the operation of two capacitor banks working in parallel to the supply network lowers the resonance point in the impedance pattern to 160 Hz (3.2 times the fundamental frequency) and the resonance peak is higher than the scenario with only one capacitor. The impedance magnitudes from the 5th harmonic order and above are a bit lower than the previous operating condition with only one capacitor: it is why the voltage harmonic distortion of the 3rd case study results lower than the 2nd case study.

It is again worth checking if each capacitor bank is subject to any overload condition due to the harmonic currents injected by the soft-starter equipment. The harmonic spectrum of the current of each capacitor bank is shown in Fig. 15.

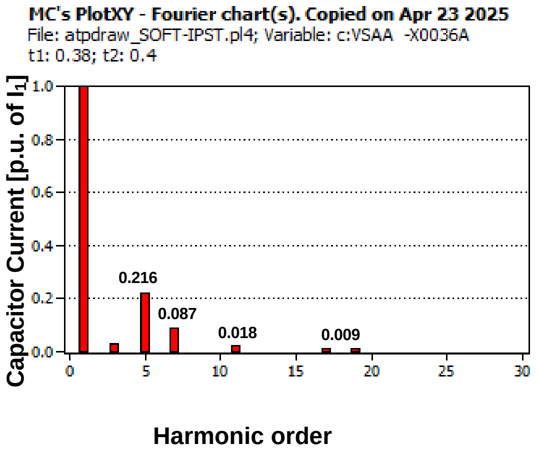


Fig. 15 Harmonic spectrum of each capacitor current during soft-starting in per unit of fundamental current (THD_I = 23.6%); both capacitor banks into service

The total harmonic distortion for the current (THD_I) flowing inside the capacitor bank amounts to 23.6%. This means, according to the definition of THD_I as per reference standard [7], that the RMS value of the total current (fundamental plus harmonics) flowing inside the capacitor can be calculated as follows:

$$I_{RMS} = I_1 * \sqrt{[\, 1 + THD_I^2 \,]} \qquad (8)$$

$$= 247 \text{ A (1.03 times the rated current)}$$

where

I_{RMS}	RMS value of current
I_1	rated operating fundamental current of the capacitor bank (240 A corresponding to 2.5 MVAr)
THD_I	total harmonic distortion for current (0.236).

Since each capacitor bank is designed for a continuous voltage of 1.2 times the busbar operating voltage, it can deliver up to 1.44 times (1.2 times squared) the rated operating power (3.6 MVAr) and therefore it can absorb up to 1.44 times the rated operating current (346 A). Therefore, no overload occurs for the capacitor and series reactor of each capacitor bank.

IV. CONCLUSIONS

A medium voltage soft-starter made of thyristor valves is an AC-to-AC power converter which regulates only the voltage but not the frequency and it can be viewed as an electronic version of the electro-mechanical starting method of motors by means of an autotransformer [4]. Therefore, similarly as starting autotransformers, soft-starter equipment can be used successfully for those motor applications without excessive load inertia or without too high load resistant torques whereby it is allowable to start safely the motor even with a low terminal voltage ranging typically from 50% to 80% of rated nameplate voltage. Nowadays, the preference by most industrial customers for soft-starter in place of autotransformer is due mainly to the high reliability of the electronic control instead of electromechanical control.

In terms of converter topology, soft-starter equipment is also simpler than an adjustable speed drive based on voltage source converter [2]: indeed, soft-starter does not need an input multi-winding transformer since its thyristor valves can work directly at the supply voltage of the motor (ranging from 2.3 kV up to 10 kV). The drawback of this simplicity implies that soft-starter equipment injects generally much more harmonic currents towards the supply network, than what does an adjustable speed drive based on voltage source converters.

Considering that soft-starter equipment is used mainly for weak supply network having low short circuit power values, the resulting voltage harmonic distortion caused by soft-starter can be quite significant and exceed easily the tolerable limits foreseen by applicable standards.

The temporary harmonic pollution caused by soft-starter equipment can be easily handled considering that most industrial facilities are provided nowadays with capacitor banks for the aim of power factor improvement at the point of common coupling between the industrial facility and the distribution system operator. Such capacitor banks are most often provided also with series reactors and therefore can behave also as harmonic filters.

Therefore, the easiest remedial action to attenuate the harmonic distortion of soft-starter is to switch-on the capacitor banks just before the motor starting occurs. The energization transient of capacitor bank lasts typically few hundreds of milliseconds [8]: therefore, capacitors could be manually switched-on also when the industrial facility is in no-load or with very low load operating conditions, without compromising the target power factor at the point of common coupling since the power factor measuring is generally updated every 15 minutes, while the capacitor banks switching transient plus the subsequent motor soft-starting transient take only few tens of seconds.

The switching of capacitor banks even at no-load conditions, just before the motor is started, is not expected to be a real concern in terms of temporary supply busbar overvoltage (less than 5% steady state overvoltage is usually acceptable) provided that the total power of capacitor banks be less than 5% of the minimum short circuit power of the grid bus to which the capacitors are connected: for example, capacitor banks with total power of 5 MVAr are suitable because equal to 4% of the minimum short circuit power of 120 MVA.

Each capacitor bank is selected as a de-tuned L-C filter type: therefore, it is generally designed for a continuous voltage up to 1.2 times the supply operating voltage and can provide 1.44 times (proportionally to the square of the voltage) the rated operating capacitive power. This design voltage criterion gives a safe margin also against any possible overload of the capacitor and reactor of the L-C filter since the filter is designed to carry a continuous current up to 1.44 times the rated operating current.

V. REFERENCES

[1] A. M. Trynadlowski, *Modern Power Electronics*, John Wiley & Sons, 2016.

[2] B. Wu, M. Narimani, *High-Power Converters and AC Drives*, John Wiley & Sons, 2017.

[3] B. R. Pelly, *Thyristor Phase-Controlled Converters and Cycloconverters*, John Wiley & Sons, 1971.

[4] IEEE Std 3002.7 IEEE Recommended Practice for Conducting Motor-Starting Studies and Analysis of Industrial and Commercial Power Systems.

[5] H. W. Dommel, *EMTP Theory Book*, Microtran Power System Analysis Corporation, Vancouver, Canada, 1992.

[6] *Alternative Transient Program (ATP) - Rule Book*, Canadian/American EMTP User Group, 1987-92.

[7] IEEE 519 IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems (EMC).

[8] IEC 61642 Industrial a.c. networks affected by harmonics - Applications of filter and shunt capacitors.

VI. APPENDIX

A. Electrical Network Component Data

TABLE A-I
SUPPLY NETWORK

Equipment	Parameters
Equivalent Network at the Point of Common Coupling for the industrial facility	6 kV rated voltage
	50 Hz rated frequency
	120 MVA Max. 3-phase short circuit power
	11.5 kA Symmetrical (RMS) Min. 3-phase short circuit current
	X/R = 10 reactance to resistance ratio

TABLE A-II
SQUIRREL CAGE INDUCTION MOTOR

Manufacturer's Data	Parameters
Rated Power	4800 kW
Rated Voltage (r.m.s. line to line)	6000 V
Rated Frequency	50 Hz
Full load stator current (FLC)	535 A
Rated Apparent Power	5520 kVA
Locked Rotor current (LRC)	LRC = 450% FLC LRC = 4.5 p.u. at 100% rated voltage
Locked rotor power factor	0.10 p.u.
X/R ratio at locked rotor	10
Rated power factor	0.90 p.u.
Rated Efficiency	0.965 p.u.
Rated Speed	155.7 rad/s (1487 r.p.m.)
Direct-on-line Starting Time at 100% voltage	5 s
Direct-on-line Starting Time at 80% voltage	12 s
Starting Time at 53% voltage (Soft-Starter regulation)	25 s
Driven Load application	Pump

TABLE A-III
CAPACITOR BANK

Equipment	Parameters
Capacitor	U_N = 6 kV rated operating voltage
	f_N = 50 Hz rated frequency
	Q_N = 2.5 MVAr rated operating power
	C = 221.05 µF capacitance/phase
	X_C = 14.4 ohm capacitive reactance/phase
	U_R = 7.2 kV rated maximum voltage
	Q_R = 3.6 MVAr rated maximum power
Series Reactor	L_L = 2.75 mH inductance/phase
	X_L = 0.863 ohm inductive reactance/phase
	R_L = 0.0173 ohm reactor resistance/phase
	$r = \sqrt{(X_C/X_L)} = 4.1$ harmonic tuning factor of the L-C filter
	Air-core type
	I_R = 346 A rated maximum current

For the simulation of the circuit model shown in Fig. 3, the supply grid impedance and the locked rotor impedance of the motor are calculated on the basis of input data shown in Table A-I and Table A-II:

<u>Network impedance Z_N:</u>

$Z_N = (6\ \text{kV})^2 / 120\ \text{MVA} = 0.3\ \text{ohm}$ (A-1)
Z_N is the impedance of the supply network

$X_N \approx Z_N = 0.3\ \text{ohm}$ (A-2)
X_N is the reactance of the supply network
Z_N can be approximated to X_N, since $X_N / R_N = 10$

$R_N = X_N / 10 = 0.03\ \text{ohm}$ (A-3)
R_N is the resistance of the supply network

<u>Motor Locked Rotor impedance Z_{LR}:</u>

$Z_M = (6\ \text{kV})^2 / 5.52\ \text{MVA} = 6.52\ \text{ohm}$ (A-4)
Z_M is the rated impedance of the motor (full load)

$Z_{LR} = (1 / 4.5) * 6.52\ \text{ohm} = 1.45\ \text{ohm}$ (A-5)
Z_{LR} is the locked rotor impedance of the motor

$X_{LR} \approx Z_{LR} = 1.45\ \text{ohm}$ (A-6)
X_{LR} is the locked rotor reactance of the motor
Z_{LR} can be approximated to X_{LR}, since $X_{LR} / R_{LR} = 10$

$R_{LR} = X_{LR} / 10 = 0.145\ \text{ohm}$ (A-7)
R_{LR} is the locked rotor resistance of the motor

B. Soft-starter control logics

The soft-starter equipment works therefore as an AC-to-AC converter which can lower the RMS value of output voltage with respect to the RMS value of the input supply voltage, by means of the firing control of the thyristor valves.

The principle of control logics for the firing angle of the thyristor valves is represented in Fig. A-I, Fig. A-II, while the principle of this voltage regulation is shown in Fig. A-III.

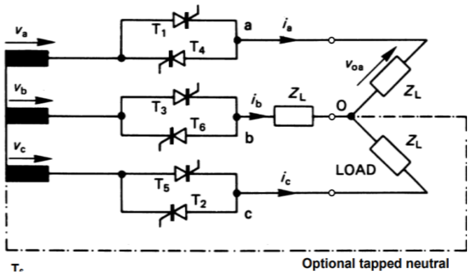


Fig. A-I Simplified representation of soft-starter thyristor valves

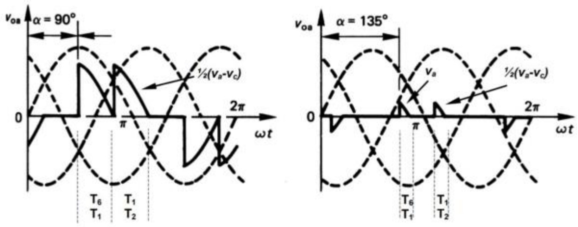


Fig. A-II Example of output voltage waveform for two different firing angles

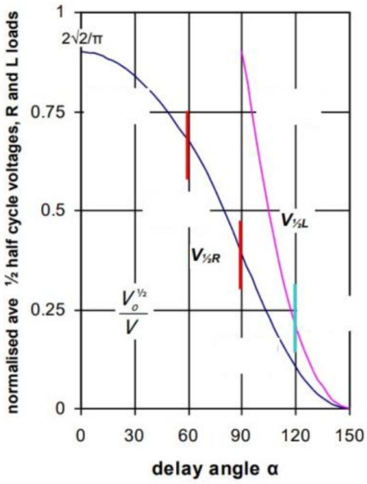


Fig. A-III Output RMS voltage of soft-starter vs. thyristor firing angle

VII. VITA

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