

# INVESTIGATIONS ABOUT SELF-EXCITATION FOR LARGE INDUCTION MOTOR

Copyright Material PCIC energy  
Paper No. PCIC energy EUR26\_01

Paolo Marini  
Tecnimont  
Via G. De Castillia 6/A 20124  
Milano, Italy  
p.marini@tecnimont.it

**Abstract** - In polypropylene petrochemical plants large power induction motors (e.g. rated 9 to 20 MW), fed by a dedicated unit transformer, are normally used to drive extruder machines required by this type of industrial process. Most of the times the requirements from distribution grid operator about power factor improvement are quite demanding such as it becomes necessary to feed also capacitor banks from the same switchgear which supplies the motor.

In case of a sudden opening of the switchgear incomer circuit breaker due to an inadvertent wrong operation procedure by plant personnel, it could happen that the motor remains temporarily connected to the capacitor during the coasting-down transient of the motor: the phenomenon of motor self-excitation due to the ferro-resonance between the magnetizing inductance of the motor and the bank capacitance can occur with the consequent damage and failure of the capacitor bank insulation.

EMT software simulations are carried out to understand under which operating conditions the phenomenon of self-excitation of the induction motor can happen when the power factor compensation exceeds the magnetizing current of the motor.

**Index Terms** - Capacitor, ferro-resonance, induction motor, self-excitation, temporary overvoltage.

## I. INTRODUCTION

The need of power factor improvement in industrial facilities is becoming in the latest years more and more demanding: in most cases the historical compensation value of power factor equal to 0.9 lagging is no longer sufficient, while most MV distribution system operators (DSOs) require a compensation value equal to at least 0.98 lagging [1].

For large power machines which are fed directly across the line from the supply grid, the recourse to an induction motor is often the preferred choice by many industrial users since induction machines are more robust than synchronous machines in terms of withstanding against supply voltage dips and supply voltage interruptions. However, differently from the synchronous motor, the induction motor requires the compensation of its power factor and this means that capacitor banks have to be fed from the same switchgear which supplies the induction motor.

The novelty of this work consists in the way a root cause analysis is carried out to understand why some capacitor banks failed during the de-energization event of an induction motor together with paralleled capacitors: the operating conditions which could trigger the phenomenon

of self-excitation of the induction motor [2], [3] are discussed and suitable countermeasures are suggested in order to prevent the occurrence of such phenomenon in future.

## A. System Data

The electrical distribution scheme of a typical industrial plant, in which an induction motor is used to drive a large power extruder machine, is shown in Fig. 1.

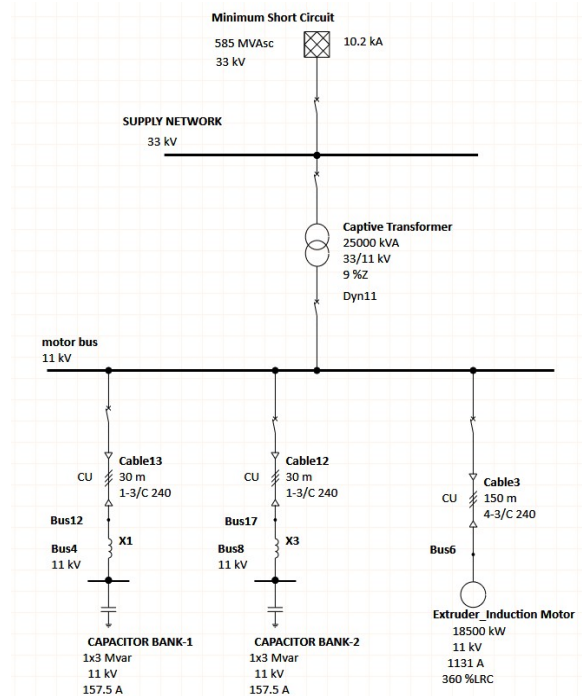


Fig. 1 Single-line diagram of the industrial electrical system

Main electro-mechanical parameters, for each network component, are reported in the Appendix.

## B. Modeling

For the aim of numerical simulation by EMT software [4], the electrical network is simplified and modeled as shown in Fig. 2 and Fig. 3, following the general guidelines presented in [5].

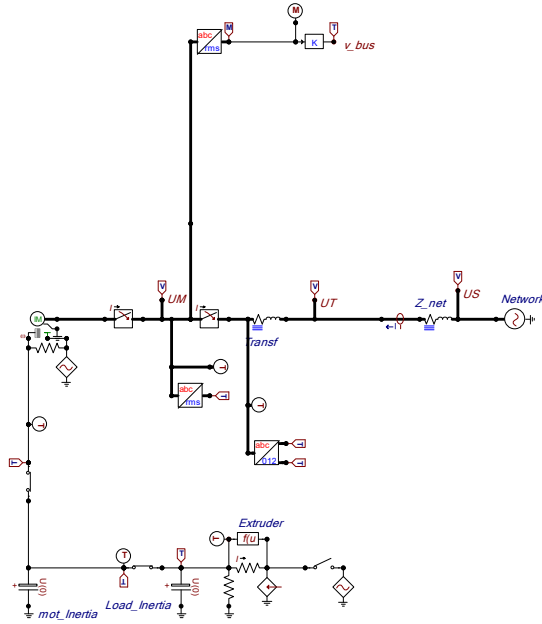


Fig. 2 EMT model of the induction motor

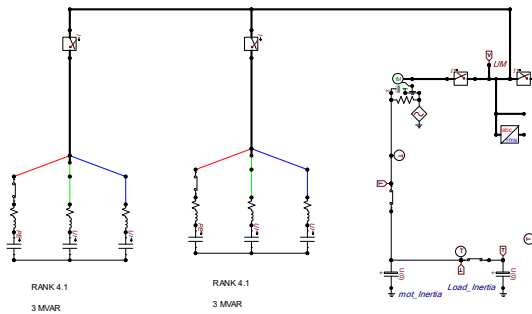


Fig. 3 EMT model of the capacitor banks

All equivalent impedances of the network components are referred to the motor rated voltage level, as described in detail in the Appendix: the transformer short circuit impedance and the supply network short circuit impedance are modeled as R-L components. 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 series impedance (R-L components) and the charging shunt capacitance of cables (C component) can be neglected due to the short electrical length (less than 250 m as total length).

The squirrel cage induction motor is modeled based on d-q reactance Park's theory [4], by entering in the Windows graphical interface of EMT software [5] the parameter (stator / rotor resistances and inductances) of the equivalent circuit provided by the motor manufacturer. Mechanical coupling and driven machine are represented by an electrical equivalent circuit connected to the motor windings circuit. The saturation of the magnetic core is

modeled as a two-slope characteristic based on saturated inductance values received by the motor manufacturer.

Each one of the two capacitor banks for the aim of power factor improvement is represented by a three-phase model: each phase being made of a capacitance, and a series reactor for the purpose of limiting the inrush current during capacitor energization.

## II. PRE-ANALYSIS AND DISCUSSION

A simplified analysis, based on the information received by the personnel of the industrial plant, is carried out before performing EMT numerical simulations to understand the reasons why the capacitor banks got damaged.

### A. Power factor improvement of the induction motor

The total compensating reactive power of the capacitor banks is selected according to the following equation:

$$Q_C = P_m / \eta * (\tan \Phi_1 - \tan \Phi_2) \quad (1)$$

where

$P_m$  motor rated power (18.5 MW)

$\eta$  motor full load efficiency (0.965)

$\tan \Phi_1$  tangent of power angle corresponding to motor power factor (0.89 lagging) without any correction

$\tan \Phi_2$  tangent of power angle corresponding to improved required power factor (0.98 lagging).

By applying the equation (1) with the above input data, the required capacitive reactive power results equal to 6 MVar, which is then split into two banks with 3 MVar each.

### B. Description of the event

During maintenance activities, the personnel of the industrial facility performed the following actions:

- the 11 kV motor was first unloaded by its driven machine up to 10% of rated torque;
- then, the 11 kV switchgear incomer circuit breaker was opened to de-energize both the motor and the capacitors at the same time.

Few seconds after the opening of the switchgear incomer circuit breaker, the same personnel witnessed the following events:

- the rupture of the case of both capacitor banks occurred;
- after the inspection of the faulted capacitor banks, the personnel actually acknowledged the failure of the frame-to-ground insulation inside the affected capacitor banks.

### C. Interpretation of the accidental event

It is well known from technical literature [6], [7], [8], that induction machines could be triggered into self-excitation operation due to shunt capacitances connected to the stator winding.

Therefore, a possible explanation of the insulation failure being experienced for both capacitor banks could be sought for the temporary resonance condition occurring between the motor magnetizing inductance and the paralleled capacitance of the power factor improvement banks. The simplified electrical circuit of the parallel resonance is shown in Fig. 4.

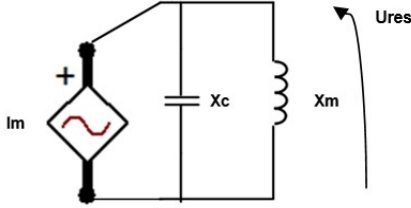


Fig. 4 Equivalent circuit of parallel resonance

Indeed, by injecting the motor magnetizing current “ $I_m$ ” into the paralleled capacitor reactance “ $X_c$ ” and motor magnetizing reactance “ $X_m$ ”, the temporary overvoltage across the reactances can be estimated as follows.

$$U_{res} = I_m / (1 / X_c - 1 / X_m) \quad (2)$$

where

$U_{res}$	resonance overvoltage
$I_m$	motor magnetizing current (242 A)
$X_c$	capacitors reactance ( $X_c = [11\text{kV}]^2 / 6 \text{ MVar} = 20.17 \text{ ohm}$ )
$X_m$	motor magnetizing reactance (25 ohm).

By applying the equation (2) with the above input data, the resonance overvoltage “ $U_{res}$ ” amounts to 25.3 kVrms which means an overvoltage of 2.3 per unit when the overvoltage is expressed in per unit of the supply rated operating voltage of 11 kVrms.

The manufacturer of the capacitor banks provided the following design overvoltage limits:

TABLE I  
MOMENTARY OVERVOLTAGE LIMITS FOR CAPACITORS

Duration	Multiplying Factor Times Rated RMS Voltage
6 cycles (120 ms)	2.2
15 cycles (300 ms)	2.0
1 second	1.7
15 seconds	1.4
1 minute	1.3
30 minutes	1.25

It is quite apparent from the above table that the resonance overvoltage could exceed easily the withstand

limit of the capacitor bank and this could explain in principle the reason why the insulation of the capacitor banks failed while de-energizing motor and capacitors together.

The motor is also exposed to the same resonance overvoltage during the coasting-down period of the motor itself. As per the reference IEC standard [9], the motor is designed to withstand the following voltage limit:

$$U_w = 2 * U_n + 1 \text{ kVrms} = 25 \text{ kVrms} \quad (3)$$

where

$U_w$	power frequency withstand voltage for induction motor (1 minute duration)
$U_n$	highest rated voltage of the motor (110% of 11 kVrms = 12 kVrms).

The withstand voltage limit of 25 kVrms (2.27 per unit) is slightly exceeded by the resonance overvoltage (25.3 kVrms corresponding to 2.3 per unit). Anyway, no damage to motor stator winding insulation was found by the facility personnel during the inspection of the motor.

### D. Case Studies

The temporary resonance overvoltage evaluated in the previous section was only a preliminary simplified approach to grasp the origin of the overvoltage transient event. However, more detailed EMT simulations are needed in order to assess both the magnitude and the time duration of the resonance overvoltage such as to confirm why the failure of the frame-to-earth insulation of capacitor banks occurred.

The self-excitation transient event of the induction motor is triggered by de-energizing the motor in almost no-load condition while keeping the shunt capacitor banks connected to the motor. Two scenarios are simulated:

- Self-excitation considering a linear magnetizing inductance of the motor.
- Self-excitation taking into account the effect of the saturation of the magnetizing inductance of the motor.

## III. RESULTS

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

### A. Self-excitation with linear magnetizing inductance

After having first initialized the circuit model (motor started and running in very low load condition, and both capacitor banks being energized in parallel to the motor), the incomer circuit breaker of the 11 kV supply switchgear is opened at the time instant  $t = 9$  s. The resulting overvoltage at motor and capacitor terminals is shown in Fig. 5, while the motor speed is shown in Fig. 6.

As can be seen, the resonance voltage lies between 4 p.u. and 5 p.u. for more than 1.5 seconds (from time instant of 10.5 s up to time instant of 12 s): hence, it is well beyond the withstand limits of capacitor banks given by the manufacturer in Table I.

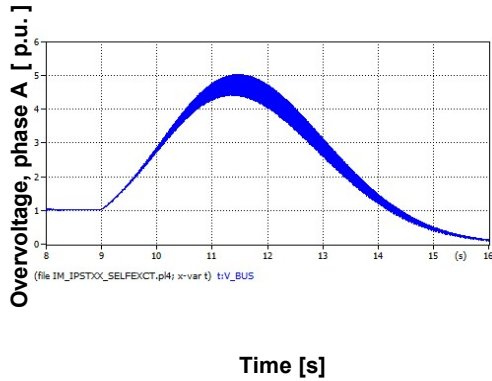


Fig. 5 Resonance overvoltage (phase A, per unit of rms value) during the self-excitation transient of the induction motor (linear magnetizing inductance)

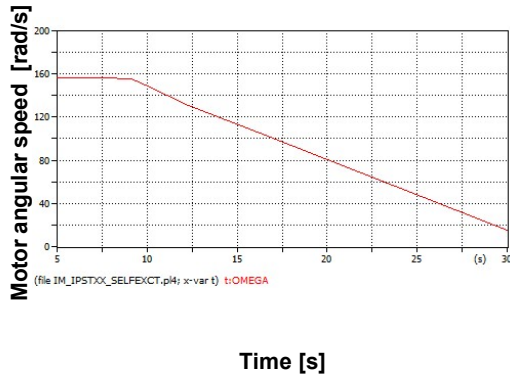


Fig. 6 Motor angular speed (rad/s) during the coasting-down of the induction motor

However, the calculated resonance overvoltage could have been overestimated since the magnetizing inductance of the motor has been considered purely linear. It is useful to perform the same simulation by considering also the magnetic saturation of the motor core, since magnetic saturation could generally provide some damping effect against the resonance overvoltage.

#### B. Self-excitation with the effect of magnetic saturation

The resulting overvoltage at motor and capacitor terminals is shown in Fig. 7 and Fig. 8 (enlarged view).

As can be seen, the saturation of motor magnetizing inductance provides some damping effect to the resonance overvoltage which is now lower than the previous case study with linear magnetizing inductance. Anyway, the resonance overvoltage is again beyond the withstand limits allowed by the manufacturer of the capacitor banks and this explains the reason for the capacitor failure: the transient voltage exceeds 1.7 p.u. for approximately 2 seconds, as well as it exceeds 2 p.u. for approximately 1 second.

The highest value of the resonance voltage reaches 2.2 per unit: it is lower than 2.3 per unit which is the withstand limit allowed for the motor insulation. This

explains why the motor was not affected by the overvoltage transient event.

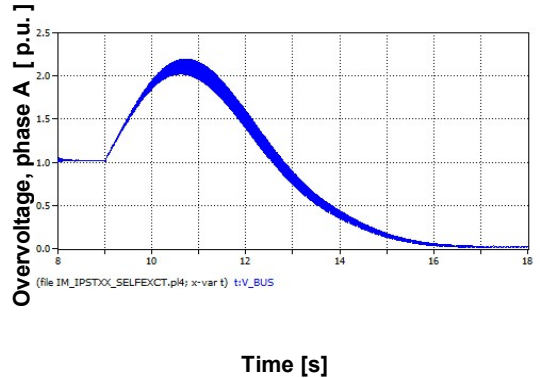


Fig. 7 Resonance overvoltage (phase A, per unit of rms value) during the self-excitation transient of the induction motor (saturated magnetizing inductance)

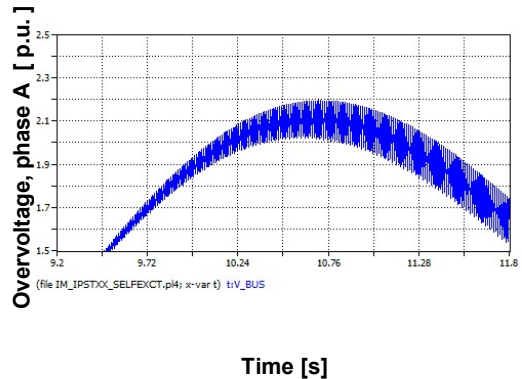


Fig. 8 Enlarged view of the resonance overvoltage (phase A, per unit of rms value) during the self-excitation transient of the induction motor (saturated magnetizing inductance)

## IV. CONCLUSIONS

Whenever a capacitor bank is fed from the same supply switchgear as that of a large induction motor, many industrial users are already aware that, should the capacitor overcompensate more than 90% of the no-load motor magnetizing current, the phenomenon of self-excitation of the motor could occur if the motor is working in no-load and it is left connected to the capacitor during its deceleration.

In order to avoid that the induction motor self-excitation transient be triggered, the customer of the industrial facility standardized the following normal operating procedure, shown also in Fig. 9 for the energization of the motor and in Fig. 10 for the de-energization of the motor.

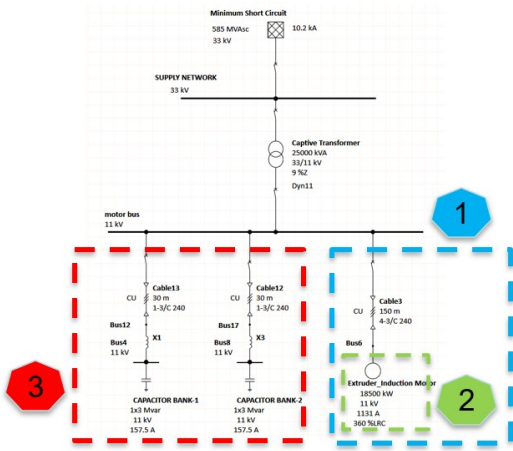


Fig. 9 Normal operating procedure during energization of the motor

During energization of the motor (reference to Fig. 9):

- 1) first the motor is started;
- 2) then the motor is fully loaded by the driven machine;
- 3) finally, the capacitor banks are energized with the motor already working at full load.

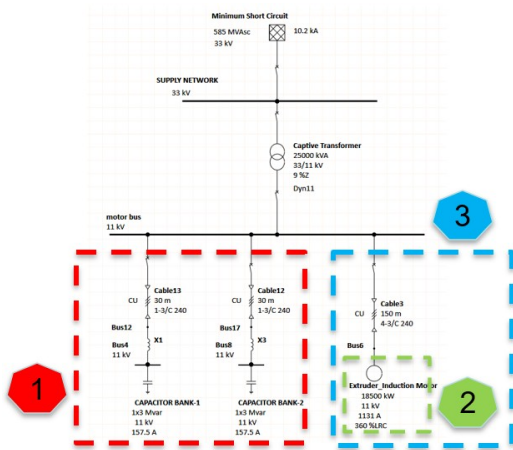


Fig. 10 Normal operating procedure during de-energization of the motor

During de-energization of the motor (reference to Fig. 10):

- 1) first the capacitors banks are switched-off;
- 2) then the motor is unloaded by the driven machine;
- 3) finally, the motor is switched-off at no-load or very low load operating condition.

However, in the fault scenario being analyzed here, the personnel of the industrial facility did not follow exactly the above de-energization procedure, while the following sequence of events instead occurred, as shown also in Fig. 11:

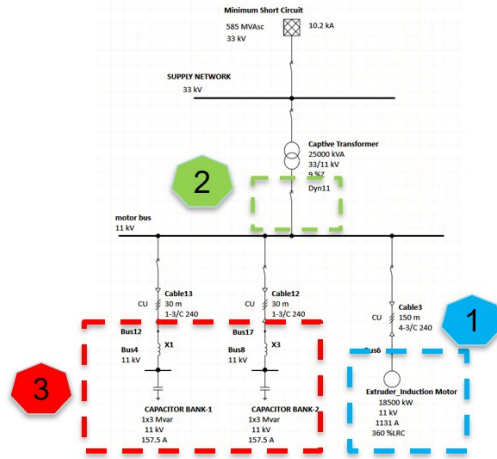


Fig. 11 Wrong operating procedure actually occurred

Wrong operating procedure (reference to Fig. 11):

- 1) the motor was first unloaded by its driven machine;
- 2) then, instead of switching-off the capacitor banks before switching-off the motor, the switchgear incomer circuit breaker was opened to de-energize both the motor and the capacitors at the same time: in this way the capacitor banks were able to trigger the self-excitation of the induction motor working in no-load condition during the motor coasting-down transient;
- 3) the voltage at the switchgear busbar which was feeding motor and capacitor suddenly increased beyond the voltage withstand limit of the capacitor banks and immediate insulation failure of capacitor banks happened. The overvoltage protection relay of the capacitor bank feeder (ANSI 59) [10], [11], fed by the instrument voltage transformer installed on the 11 kV busbar, was set only with one tripping threshold (120% of rated voltage for a delay of 10 seconds) and was not able to promptly clear the transient overvoltage which reached 200% of rated voltage in less than 2 seconds.

In order to avoid similar events in future, the following remedial actions were applied, independently of any standardized procedure which should normally be followed by the site personnel:

- a new fast tripping threshold for the overvoltage relay (ANSI 59), fed by the instrument voltage transformer installed on the main 11 kV busbar, is set for the protection of the capacitor feeder:

$$U_{>>} = 140\% \text{ of rated voltage} \quad (4)$$

$$t_{>>} = 0.1 \text{ s time delay} \quad (5)$$

where

$U_{>>}$  overvoltage relay tripping threshold

$t_{>>}$  overvoltage relay tripping delay time

- as shown in Fig. 12, every time when the incomer circuit breaker is opened intentionally or is tripped for any reason, an inter-trip signal is given from the incomer circuit breaker to each outgoing feeder breaker of the capacitor bank, such as to avoid the paralleling condition between capacitor and motor during the coasting-down of the motor in no-load condition.

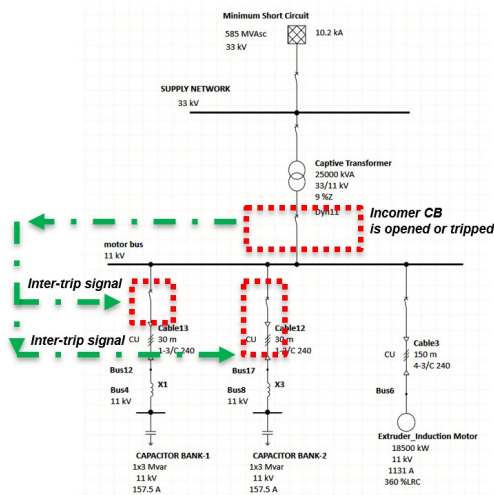


Fig. 12 Inter-trip signal to avoid self-excitation of the motor

## V. REFERENCES

- [1] W. Hofmann, J. Schlabbach, W. Just, *Reactive Power Compensation, a practical guide*, John Wiley & Sons, 2012.
- [2] C. F. Wagner, "Self-Excitation of Induction Motors," *AIEE Transactions*, vol. 58, February 1939.
- [3] T. G. Martinich, M. Nagpal, A. Bimbhra, "Analysis of Temporary Over-Voltages from Self-Excited Large Induction Motors in the Presence of Resonance – Case Studies," in *Proc. IPST 2013 – International Conference on Power Systems Transients in Vancouver, Canada*.
- [4] H. W. Dommel, *EMTP Theory Book*, Microtran Power System Analysis Corporation, Vancouver, Canada, 1992.
- [5] *Alternative Transient Program (ATP) - Rule Book*, Canadian/American EMTP User Group, 1987-92.
- [6] E. D. Bassett, F. M. Potter, "Capacitive Excitation for Induction Generators," in *Proc. 1935 – A.I.E.E Summer Convention in Ithaca, N. Y.*
- [7] D. Seyoum, M. F. Rahman, "The dynamic characteristics of an isolated self-excited induction generator driven by a wind turbine," in *Proc. IEEE Industry Application Conference – 37<sup>th</sup> IAS Annual Meeting in Pittsburgh, USA*, October 2002.
- [8] CIGRE Working Group C4.46, "Evaluation of Temporary Overvoltages in Power Systems due to Low Order Harmonic Resonances," *Technical Brochure TB 913*, August 2023.
- [9] IEC 60034-1 Rotating electrical machines – Part 1: Rating and performance.
- [10] IEEE C37.99 IEEE Guide for Protection of Shunt Capacitor Banks.
- [11] IEC 60871-3 Shunt capacitors for a.c. power systems having a rated voltage above 1000 V – Part 3: Protection of shunt capacitors and shunt capacitor banks.

## VI. APPENDIX

### A. Electrical Network Component Data

TABLE A-I  
SUPPLY NETWORK

Equipment	Parameters
Network Supply to the Captive / Unit transformer for induction motor	33 kV rated voltage
	50 Hz rated frequency
	585 MVA Min. 3-phase short circuit power
	10.2 kA Symmetrical (RMS) Min. 3-phase short circuit current
	X/R = 10 reactance to resistance ratio

TABLE A-II  
CAPTIVE / UNIT TRANSFORMER

Equipment	Parameters
Captive / Unit Transformer dedicated to the supply of 11 kV Extruder motor	25 MVA rated power
	33 kV / 11 kV rated voltage ratio
	Dyn11 vector group
	50 Hz rated frequency
	$Z_t = 9\%$ (ref. to 25 MVA) short circuit impedance
	$X/R = 20$ reactance to resistance ratio

For the simulation of the circuit model shown in Fig. 2, transformer and supply network impedances are calculated referred to the motor rated voltage (11 kV) and to the transformer base power (25 MVA). In the calculation, the impedance is approximated to the reactance due to  $X/R = 10$  for supply network and  $X/R = 20$  for captive transformer:

Reference Base impedance  $Z_{REF}$ :

$$Z_{REF} = (11 \text{ kV})^2 / 25 \text{ MVA} = 4.84 \text{ ohm} \quad (\text{A-1})$$

Network impedance  $Z_N$ :

$$Z_N = 1 \text{ p.u.} * (25 \text{ MVA} / 582 \text{ MVA}) = 0.0430 \text{ p.u.} \quad (\text{A-2})$$

$Z_N$  is the per unit impedance of the supply network

$$X_N = Z_N * Z_{REF} = 0.207 \text{ ohm} \quad (\text{A-3})$$

$X_N$  is the reactance of the supply network

$$R_N = X_N / 10 = 0.0207 \text{ ohm} \quad (\text{A-4})$$

$R_N$  is the resistance of the supply network

Transformer impedance  $Z_T$ :

$$X_T = 0.09 \text{ p.u.} * Z_{REF} = 0.436 \text{ ohm} \quad (\text{A-5})$$

$X_T$  is the reactance of the captive/unit transformer

$$R_T = X_T / 20 = 0.0218 \text{ ohm} \quad (\text{A-6})$$

$R_T$  is the resistance of the captive/unit transformer

TABLE A-III  
INDUCTION MOTOR DATA

Manufacturer's Data	Parameters
Rated Power	18500 kW
Rated voltage (r.m.s. line to line)	11000 V
Rated frequency	50 Hz
Number of poles	4
Rated slip	0.5%
Full load stator current (FLC)	1131 A
No load stator current ( $I_0$ )	242 A
Locked Rotor current (LRC)	LRC = 360% FLC at 100% rated voltage
Rated power factor	0.89 p.u.
Rated Efficiency	0.965 p.u.
Rated torque at rated speed	118000 N*m
Moment of inertia of motor referred to rated speed	1500 kg*m <sup>2</sup>
Moment of inertia of extruder referred to rated speed	300 kg*m <sup>2</sup>
Resistant extruder torque at starting and at low load operation	10% of rated torque

The equivalent circuit during running operation of the induction motor is provided by the motor manufacturer and it is represented in Fig. A-1 with relevant numerical parameters listed in Table A-IV:

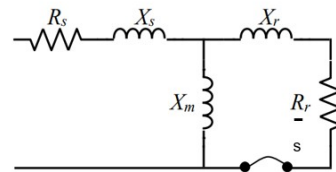


Fig. A-1 Equivalent circuit of induction motor

TABLE A-IV  
INDUCTION MOTOR EQUIVALENT CIRCUIT PARAMETERS

Manufacturer's Data	Parameters
Stator resistance ( $R_s$ )	0.027856 ohm
Stator leakage reactance ( $X_s$ )	0.69115 ohm
Rotor leakage reactance ( $X_r$ )	0.69115 ohm
Rotor resistance ( $R_r$ )	0.292444 ohm
Magnetizing reactance ( $X_m$ )	25 ohm

The saturation characteristic of the magnetic core of the motor is modeled in EMT software [4], [5], as represented in Fig. A-2 on the basis of numerical parameters provided by the motor manufacturer and enlisted in Table A-V:

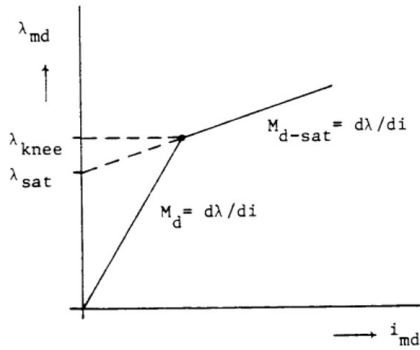


Fig. A-2 Saturation characteristic of motor magnetic core (symmetrical behavior between d-axis and q-axis)

TABLE A-V  
INDUCTION MOTOR MAGNETIZATION PARAMETERS

Manufacturer's Data	Parameters
unsaturated magnetization inductance (M <sub>d</sub> )	0.079489 H
saturated magnetization inductance (M <sub>d-sat</sub> )	0.0676 H
Flux-linkage at the saturation knee point $\lambda_{knee}$	19.222 Wb

TABLE A-VI  
CAPACITOR BANK

Equipment	Parameters
<b>Capacitor:</b> improves the motor power factor	11 kV Rated operating voltage
	3 MVar Rated operating reactive power
	158 A Rated operating current
	C = 78.9 μF Capacitance per phase
	X <sub>c</sub> = 40.34 ohm Reactance per phase
<b>Series reactor:</b> limits the capacitor inrush current	L = 7.703 mH Inductance per phase
	X <sub>L</sub> = 2.42 ohm Reactance per phase
	R <sub>L</sub> = 0.0484 ohm Series resistance per phase
	X <sub>L</sub> / R <sub>L</sub> = 50 Quality factor
	Air-core reactor type

## VII. VITA

**Paolo Marini** is Electrical Network Studies Group Leader in Tecnimont, Italy.

Mr. Paolo Marini received his Master of Electrical Engineering degree in 2005. In 2006 he joined the Department of Electrical Engineering of Tecnimont Company based in Milan, Italy. He is an Individual Member of the International Council on Large Electric Systems (CIGRE), an Individual Member of IEEE Industry Applications Society (IAS), and an Industrial Member of the Italian Electrotechnical Committee (CEI), Technical Sub-Committee CT2 "Rotating Machines".

[p.marini@tecnimont.it](mailto:p.marini@tecnimont.it)