Protection Issues for Under-Impedance relay used as starting supervision for large synchronous motors

P. Marini

Abstract--**Some petrochemical plants (low density polyethylene type) always require the use of big synchronous motors to feed large power compressors (typically from 10 to 30 MW).**

In certain supply network conditions, it could happen that the motor undergoes a critical starting which takes several tens of seconds to be completed. "Critical" means that the starting time is higher than the time the rotor can withstand in blocked condition: therefore, it is necessary to assess the actual motor rotation to be sure that the motor is being self-ventilating during its acceleration and can survive the critical starting.

By means of numerical simulations, it is demonstrated that the solution of using an under-impedance relay (ANSI code 21) for starting supervision, as is proposed in technical literature since many years, gives some troubles for the correct and safe protection of the starting of the motor, with respect to the most common solution of adopting a supervision switch relay (ANSI code 14) based on rotor speed measurement.

Keywords: **Under impedance, blocked rotor protection, synchronous motor, critical starting, starting supervision.**

I. INTRODUCTION

THE application of synchronous motors which drive machines like extruders or compressors, has become in the latest years a common practice for polypropylene chemical plants, especially for large power applications, typically from 10 MW to 30 MW, [1]. In particular, the most common solution for the motor starting adopted in industrial plants is the direct starting across the line: at this aim the motor is designed with a very low inrush current ranging from 350% to 450% of rated current, and with a minimum starting voltage at motor terminals ranging from 70% to 80% of rated voltage.

Depending on the total inertia of motor plus driven machine and on the resistant torque of the driven mechanical load, it could happen that the motor accelerates with a critical starting time being higher than its blocked rotor withstand time: this means that, should the rotor be blocked just during the starting, it will surely burn if the motor is not promptly disconnected from the supply [2].

In the technical literature the application of an under-impedance relay (ANSI code 21) is suggested to protect the motor during starting [3], [4], [5].

The novelty of this work consists in highlighting the intrinsic limits of the under-impedance relay when used for the purpose of starting supervision of motors having a critical starting time.

Since the synchronous motor under study is already provided with an under-impedance protection relay function being active only during normal running operation against phase faults which could occur inside the motor stator windings, the main purpose of this work is to investigate if a separate under-impedance function of same relay could be effectively used also to protect blocked rotor conditions happening during starting transient events.

A. System Data

The electrical scheme of a typical industrial plant, in which a synchronous motor is used to drive a large power compressor, is shown in Fig. 1.

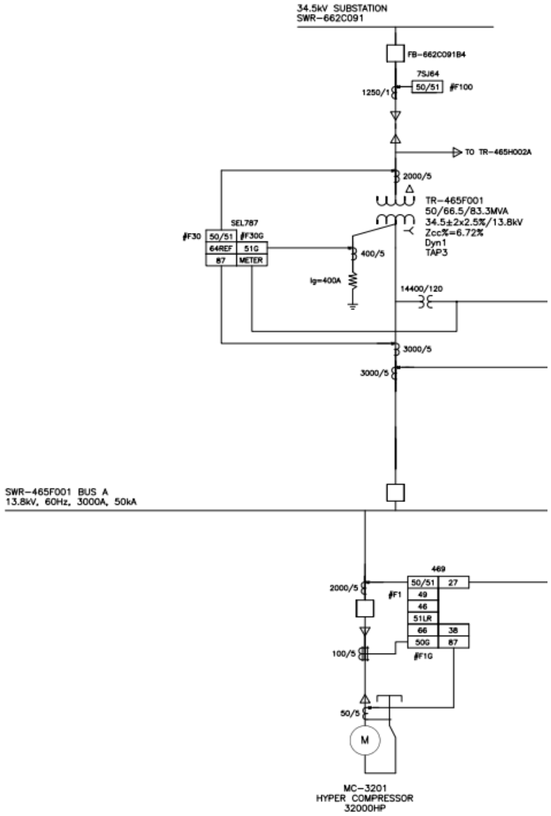


Fig. 1. Single-line diagram of the industrial electrical system

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

Paolo Marini is with the Department of Electrical Engineering, Maire Tecnimont Group, Milan, Italy (e-mail: p.marini@tecnimont.it).

Paper submitted to the International Conference on Power Systems Transients (IPST2023) in Thessaloniki, Greece June 12-15, 2023

B. *Modeling*

For the aim of numerical simulation by ATP (Alternative Transient Program) [6], the electrical network is simplified and modeled as shown in Fig. 2, following the general guidelines presented in [7].

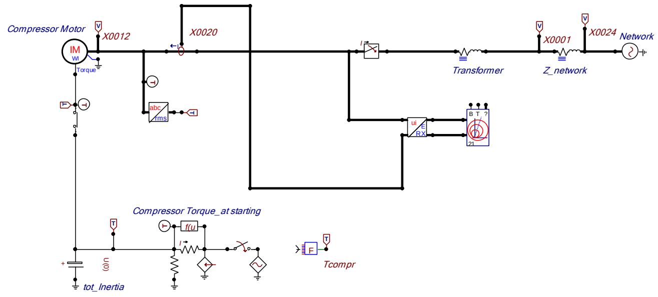


Fig. 2. EMTP-ATP model of the electrical system

All equivalent impedances of the network components are referred to the motor rated voltage level, as described in detail into 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 asynchronous starting of the synchronous motor, which is equipped with a starting damper cage, is modeled by means of ATP universal induction machine model (UMIND) based on d-q reactance Park's theory [7], by entering the input data in the Windows graphical interface of ATP (Windsyn) [6], which performs an equivalent motor circuit parameter fitting which best suits the manufacturer's data: locked rotor and breakdown torques, locked rotor and rated stator currents, rated efficiency, rated power factor and rated slip. The model has been validated by comparing the resulting starting time with the one provided by the motor manufacturer and the results are shown in the Appendix.

The under-impedance relay (ANSI code 21) is represented and parameterized by means of the model (W1RELAY21C) being available in the library of the Windows graphical interface of ATP (Windsyn) [6].

Current and voltage transformers which feed the under-impedance relay are not modeled and they are considered as ideal components: therefore, the quantities shown in the following simulation graphs refer to primary circuit values and not to secondary circuit ones.

II. PRE-ANALYSIS AND DISCUSSION

Before performing numerical simulations, few theoretical topics from existing technical literature are first analyzed and discussed.

A. *Permissible locked rotor time*

It is well known from technical literature [8], [9], that every motor has its own thermal withstand capability referred to the condition when the rotor is blocked due to some mechanical fault on the shaft coupling between motor and driven machine. This thermal withstand capability depends case by case on the specific design made by the motor manufacturer who usually provides the locked rotor limits already referred to the stator winding currents, as enlisted here after:

$I_{LR\_75\%U\_hot}$	blocked rotor current at 75% rated voltage (minimum starting voltage) in hot-state thermal condition (motor already running before locked rotor)
$T_{LR\_75\%U\_hot}$	blocked rotor time corresponding to $I_{LR\_75\%U\_hot}$
$I_{LR\_75\%U\_cold}$	blocked rotor current at 75% rated voltage (minimum starting voltage) in cold-state thermal condition (motor at ambient temperature before locked rotor)
$T_{LR\_75\%U\_cold}$	blocked rotor time corresponding to $I_{LR\_75\%U\_cold}$

$$I_{LR\_75\%U\_hot} < I_{LR\_75\%U\_cold} \quad \text{(valid in general)} \quad (1)$$

$$T_{LR\_75\%U\_hot} < T_{LR\_75\%U\_cold} \quad \text{(valid in general)} \quad (2)$$

The locked rotor limits are also depicted in Fig. 3.

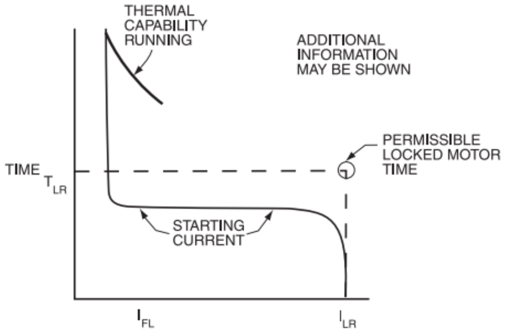


Fig. 3. Typical motor-starting and capability curves (IEEE Std. 242)

B. *Historical protection method by impedance relay*

The historical method of using an under-impedance relay to supervise a motor starting event is represented in Fig. 4.

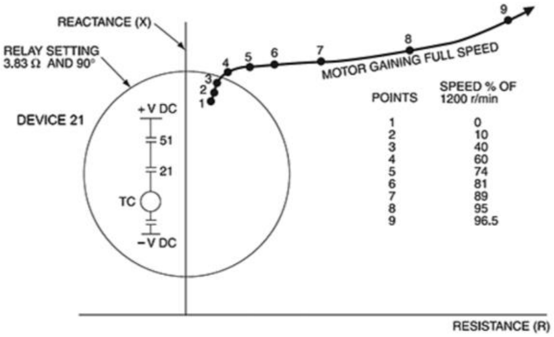


Fig. 4. Protection of high-inertia motor using an impedance relay

As can be seen, each point of the impedance locus during the motor starting corresponds to a certain percentage of speed gained during acceleration. In the example represented in Fig. 4, the most critical point is the number 3 which corresponds to 40% of rated speed: this means that if the motor speed remains under this limit the motor is considered in locked condition and the under-impedance relay will issue a trip after a certain time in order to prevent damage to rotor winding/cage.

C. Case Studies

Three types of transients are simulated and compared: the first case is when the motor experiences a mechanical rotor jam just during its acceleration; the second case is when the rotor is locked only after the starting while the motor is already running; the third case is the normal starting without any mechanical fault on the shaft. In all cases the locus of the motor impedance is studied.

III. RESULTS

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

A. Blocked rotor condition during starting

A locked rotor condition during starting is simulated by injecting on the shaft an extra load torque step approximately equal to three times the rated motor torque, ten seconds later after the initiation of motor starting: the scope is to increase the load torque enough such as to slow down the speed thus causing the motor to stall.

The resulting motor angular speed is shown in Fig. 5.

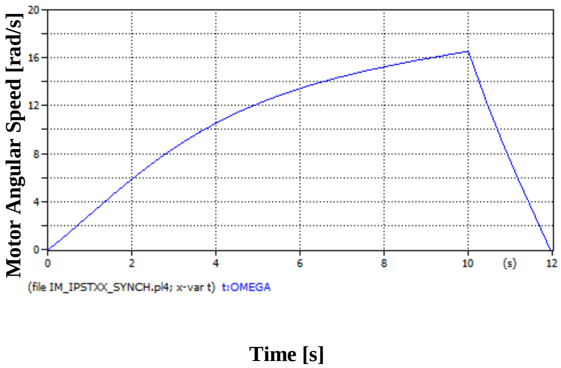


Fig. 5. Motor angular speed during a stalling condition while starting

As can be seen, the speed starts to decrease 10 seconds after the initiation of motor starting: therefore, the locked rotor condition during starting can be considered starting at 10 s.

The motor impedance vs. time is plotted in Fig. 6: the phase impedance initially increases up to 10 s when it begins to decrease because the motor is going into stalling condition.

The motor impedance inside the *R/X* chart of the under-impedance relay is shown in Fig. 7: the phase A is chosen as reference. The motor has a locked rotor impedance equal to 1.93 ohm, while the radius of the relay circular locus is set to 2.35 ohm (120% of motor locked rotor impedance). As can be seen, the impedance remains within the circle of the *R/X* chart and therefore 11 seconds after the initiation of starting, the impedance relay trips the motor, since the motor can withstand the locked rotor condition only for 12 seconds as per manufacturer design. The behavior of the impedance relay is the correct one and the motor is safely disconnected before any rotor damage could occur.

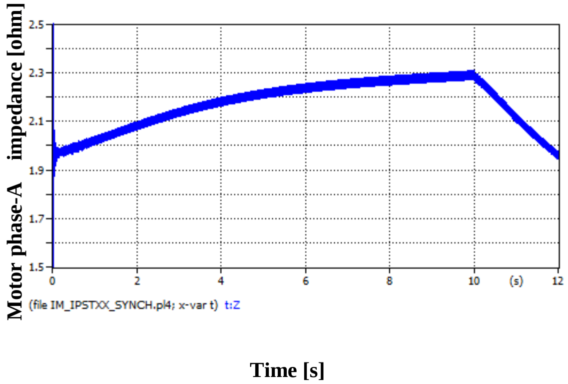


Fig. 6. Motor phase impedance vs. time (locked rotor during starting)

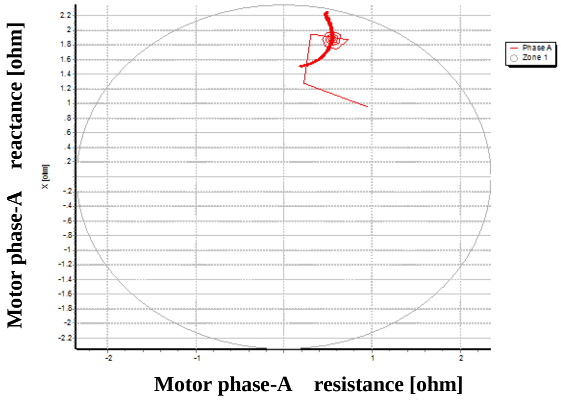


Fig. 7. Motor phase impedance inside *R/X* chart of Under-Impedance Relay (locked rotor during starting)

B. Blocked rotor after starting while motor running

Now the blocked rotor condition is realized after the motor is started, by injecting an extra torque load on the shaft as done in the previous case study.

The resulting motor angular speed is shown in Fig. 8.

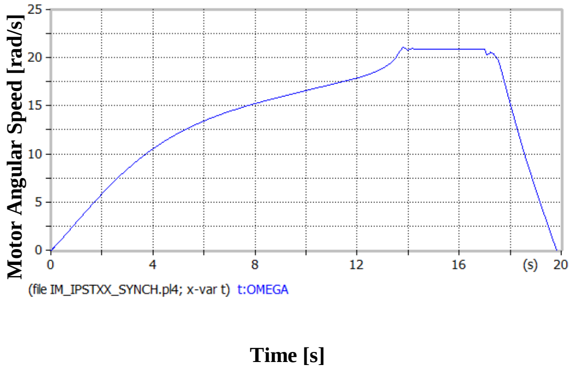


Fig. 8. Motor angular speed during a stalling condition after starting

The motor takes almost 16 seconds to complete the start, and then at 17 seconds the extra load torque is applied to make the motor to slow down and stall.

The motor impedance vs. time is plotted in Fig. 9.

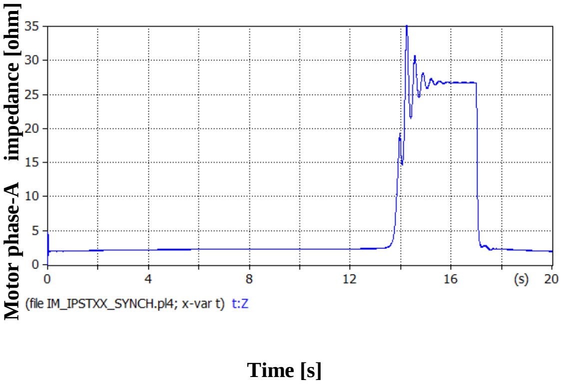


Fig. 9. Motor phase impedance vs. time (locked rotor during running)

At 20 seconds, 3 seconds after the locked rotor condition occurs, the motor impedance reaches again the value of 1.93 ohm which is the same as the impedance at the initial instant of motor starting.

The motor impedance inside the *R/X* chart of the under-impedance relay is shown in Fig. 10: the phase A is chosen as reference.

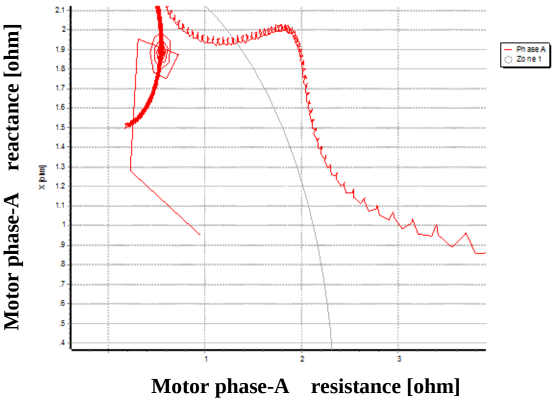


Fig. 10. Motor phase impedance inside *R/X* chart of Under-Impedance Relay (locked rotor during running)

Therefore, also in this case the impedance relay (ANSI code 21) is able to issue a trip because the motor impedance enters the relay circular zone which is set to 2.35 ohm (120% of motor locked rotor impedance) with a maximum trip delay time of 11 seconds.

C. *Normal starting condition without rotor jam*

Finally, the normal starting without any mechanical fault condition is studied.

The motor impedance vs. time is plotted in Fig. 11, and an enlarged view of the same impedance is shown in Fig. 12. At 11 seconds after the initial instant of starting, the motor impedance is still within the tripping impedance threshold of 2.35 ohm and therefore the under-impedance relay will issue a trip in 11 seconds although there is no rotor jam.

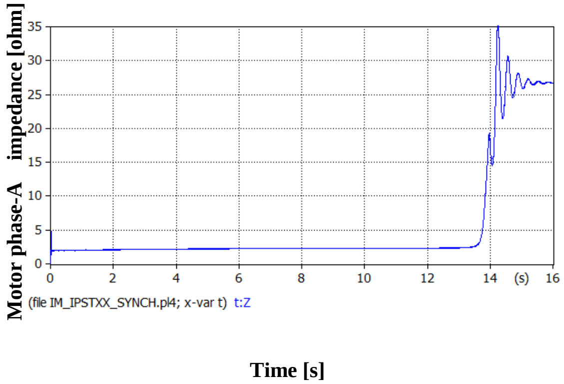


Fig. 11. Motor phase impedance vs. time (normal starting)

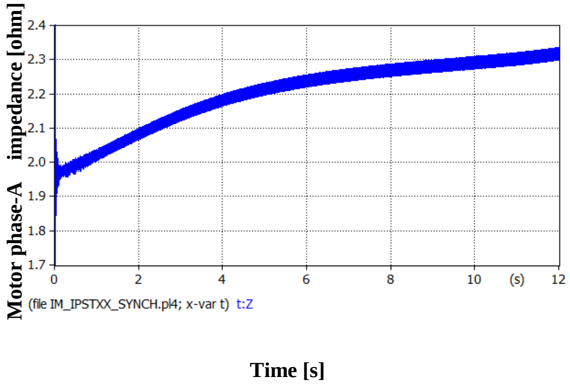


Fig. 12. Motor phase impedance vs. time – Enlarged view (normal starting)

The motor impedance angle vs. time is shown in Fig. 13: the phase A is chosen as reference. The characteristic angle of the impedance is around 75 degrees (1.31 rad) during the starting.

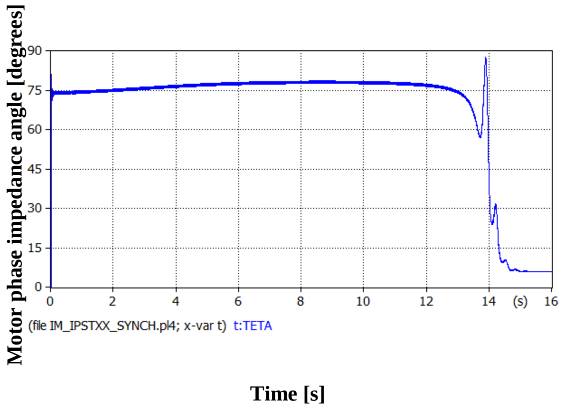


Fig. 13. Motor phase impedance angle vs. time (normal motor starting)

The motor impedance inside the *R/X* chart of the under-impedance relay is shown in Fig. 14: the phase A is chosen as reference.

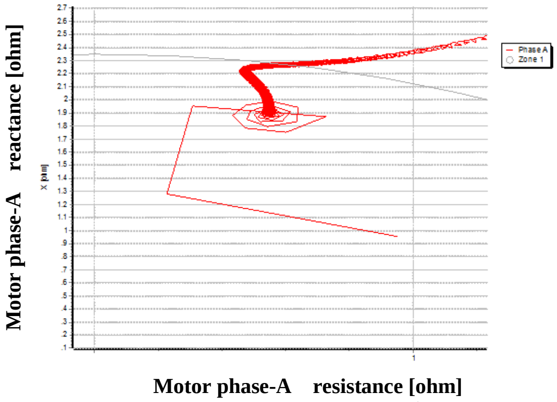


Fig. 14. Motor phase impedance inside *R/X* chart of Under-Impedance Relay (normal motor starting)

D. *Alternative protection method by speed monitoring*

Since the impedance relay (ANSI code 21) is not capable of discriminating between a normal starting condition and a locked rotor condition, it is better to perform the motor starting supervision by means of the rotor speed measurement.

The motor manufacturer provided the safe steps of acceleration which guarantee the correct rotor ventilation during the starting: it is sufficient that at least one of the acceleration steps is not reached to make the speed switch relay to trip the motor feeder.

Speed-Switch relay settings (ANSI code 14):

- 1st step of acceleration
  30% of rated speed to be reached within 4 s

- 2nd step of acceleration
  60% of rated speed to be reached within 7 s

- 3rd step of acceleration
  95% of rated speed to be reached within 15 s

The motor speed simulated during starting and shown in Fig. 15, confirmed that the above speed monitoring settings do not hinder the normal starting of the motor when there is no rotor jam.

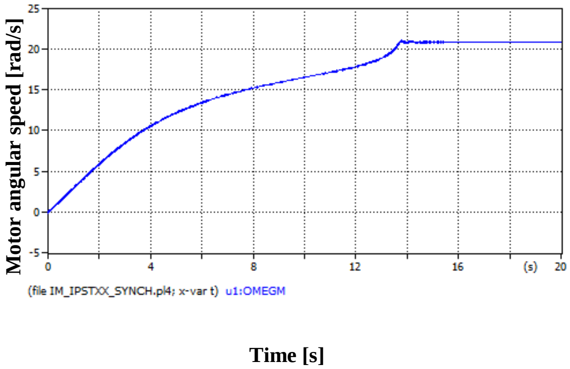


Fig. 15. Motor angular speed vs. time (normal motor starting)

IV. CONCLUSIONS

Large synchronous motors which are started directly across the line are designed usually with damper windings, placed inside the rotor pole shoes, which serve the purpose of a cage for the asynchronous starting. However, this damper cage cannot have inherently the same thermal withstand robustness as the squirrel cage normally designed for induction motors, and when a motor drives a mechanical load with high resistant torque or high inertia, as well as when a motor is started at very low voltage at its terminals, it can easily happen that the starting time becomes critical since it is higher than the time which can be withstood by the rotor in blocked condition.

The historical solution existing in technical literature of using an under-impedance relay for supervising the motor starting resulted to be non-effective for correctly distinguishing between the normal starting and the blocked rotor condition for the following reasons:

- the setting of the under-impedance relay locus in the *R/X* chart has always to take into account the measuring errors for the impedance detection due to the accuracy class of current and voltage instrument transformers which feed the impedance relay [10]: at this aim, the radius of the impedance circle is usually chosen equal to 120% of the locked rotor impedance of the motor, considering 10% accuracy for current transformer plus 3% accuracy for voltage transformer, plus a further safe margin;

- the motor impedance does not vary significantly during the normal motor starting compared to the event of blocked rotor (both locked rotor during starting and locked rotor during running), and an undue trip can occur during a normal starting although there is no real rotor jam, because the motor impedance locus does not exit the under-impedance circle before the trip issued by the impedance relay.

In case of a critical starting time, the most sure and safe method to assess the correct motor rotation during its acceleration is to use a speed switch relay (ANSI code 14) which operates based on the rotor speed monitoring. Since the synchronous motor is normally already equipped with a speed encoder mounted on the shaft, which is necessary to monitor that the full speed rotation is reached just before the motor be excited and pulled into step, it is quite convenient to send the speed measurement to the multifunction relay used for the motor feeder protection.

The under-impedance relay (ANSI code 21) could be instead applied for the purpose of detecting a blocked rotor condition during motor running and only after motor starting (equivalent to the ANSI function 51R – rotor jam during running): at this aim during each motor starting event the under-impedance has to be inhibited for all the time being necessary for the completion of the motor starting, and then it is activated only after the motor is running and synchronized to the supply grid.

This work may be further improved by testing also the behavior of the impedance relay (ANSI code 21) in a real time digital simulator environment, as well as investigating whether other protection functions (like for example the thermal overload ANSI code 49) can be used as alternative way to protect the motor during starting condition.

V. APPENDIX

A. *Electrical Network Component Data*

TABLE I
SUPPLY NETWORK

Equipment	Parameters
Network Supply to the Captive / Unit transformer for synchronous motor	34.5 kV rated voltage
	60 Hz rated frequency
	1040 MVA Min. 3-ph. short circuit power
	17.4 kA symmetrical (RMS) Min. 3-ph short circuit current
	X/R ratio 10

TABLE II
CAPTIVE/UNIT TRANSFORMER

Equipment	Parameters
Captive / Unit Transformer dedicated to the supply of 13.8 kV Compressor Motor	50 MVA rated power
	34.5 kV / 13.8 kV rated voltage ratio
	Dyn1 Vector group
	60 Hz rated frequency
	Z_t = 12% (ref. to 50 MVA) Short circuit impedance
	X/R ratio 10

For the simulation of the circuit model shown in Fig. 2, transformer and supply network impedances are calculated referred to the motor rated voltage (13.8 kV) and to the transformer base power (50 MVA). In the calculation, the impedance is approximated to the reactance due to *X/R* = 10:

Reference Base impedance Z_{REF}:

$$Z_{REF} = \ [(13.8\,kV)^2/(50\,MVA)\ ] \ = 3.809 \text{ ohm} \qquad (3)$$

Network impedance Z_N:

$$Z_N = \ (1\,p.u.)\cdot\left(\frac{50\,MVA}{1040\,MVA}\right) \ = 0.0481 \text{ p.u.} \qquad (4)$$

Z_N is the per unit impedance of the supply network

$$X_N = \ Z_N \cdot Z_{REF} \ = 0.183 \text{ ohm} \qquad (5)$$

X_N is the reactance of the supply network

$$R_N = \ X_N/10 \ = 0.0183 \text{ ohm} \qquad (6)$$

R_N is the resistance of the supply network

Transformer impedance Z_T:

$$X_T = \ (0.12\,p.u.)\cdot(Z_{REF}) \ = 0.457 \text{ ohm} \qquad (7)$$

X_T is the reactance of the captive/unit transformer

$$R_T = \ X_T/10 \ = 0.0457 \text{ ohm} \qquad (8)$$

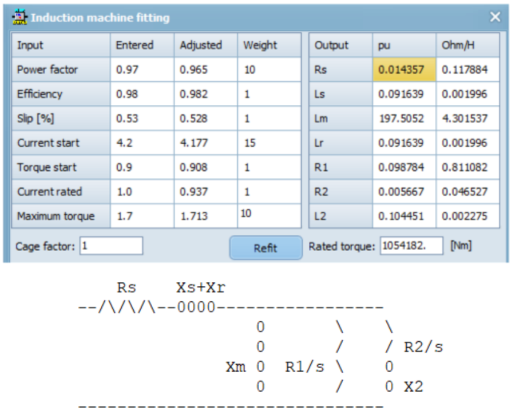
R_T is the resistance of the captive/unit transformer

TABLE III
SYNCHRONOUS MOTOR PARAMETERS (DIRECT ON LINE STARTING)

Manufacturer's Data	Parameters
Rated Power	22000 kW (30000 hp)
Rated Voltage (r.m.s. line to line)	13800 V
Rated Frequency	60 Hz
Full load stator current (FLC)	970 A
Locked Rotor current (LRC)	LRC = 420% FLC at 100% rated voltage
Rated power factor	0.97 p.u.
Rated Efficiency	0.98 p.u.
Rated Speed	20.94 rad/s (200 r.p.m.)
Minimum starting voltage	75% of rated voltage
Starting Time (at minimum starting voltage)	16 s
Locked Rotor withstand time (at minimum starting voltage, in hot thermal conditions)	12 s
Rated Torque at rated speed	1054182 N*m
Breakdown Torque at 100% rated voltage (Asynchronous starting)	170% Rated Torque
Locked Rotor Torque at 100% rated voltage (Asynchronous starting)	90% Rated Torque
Moment of Inertia of motor referred to rated speed	136200 kg*m^2
Moment of Inertia of compressor referred to rated speed	2000 kg*m^2
Rotor type for asynchronous starting	Damper winding cage

B. *Validation of motor model for direct on line starting*

The equivalent circuit for the asynchronous direct on line starting of the synchronous motor is obtained through the parameter fitting feature available in ATPDraw software [6]:



Input	Entered	Adjusted	Weight
Power factor	0.97	0.965	10
Efficiency	0.98	0.982	1
Slip [%]	0.53	0.528	1
Current start	4.2	4.177	15
Torque start	0.9	0.908	1
Current rated	1.0	0.937	1
Maximum torque	1.7	1.713	10

Output	pu	Ohm/H
Rs	0.014357	0.117884
Ls	0.091639	0.001996
Lm	197.5052	4.301537
Lr	0.091639	0.001996
R1	0.098784	0.811082
R2	0.005667	0.046527
L2	0.104451	0.002275

Cage factor: 1

Rated torque: 1054182. [Nm]

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    Rs    Xs+Xr
--/\/\/\--0000-----------------
                  0       \    \
                  0       /    / R2/s
               Xm 0  R1/s \    0
                  0       /    0 X2
-------------------------------
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Fig. 16. Parameter fitting for the equivalent circuit of asynchronous starting

The load torque of the driven compressor is modeled with the following polynomial expression as a function of speed:

$$T_{load\,p.u.} = 8 - 27.5\,w + 71.5\,w^2 - 40\,w^3 \qquad (9)$$

where:

w = rotor speed (in per unit of rated speed)

$T_{load\,p.u.}$ = resistant torque of driven compressor, in per unit of the rated motor torque at full speed

The results of the motor starting are shown in the following figures: the simulations confirm the starting time of about 16 seconds when the minimum starting voltage is 75% of rated voltage at motor terminals, as stated by the motor manufacturer.

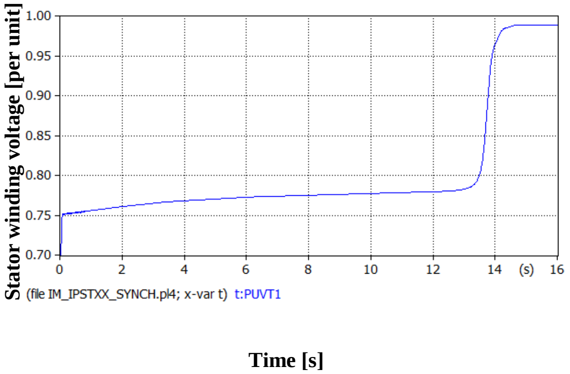

Fig. 17. Voltage at motor terminals during starting

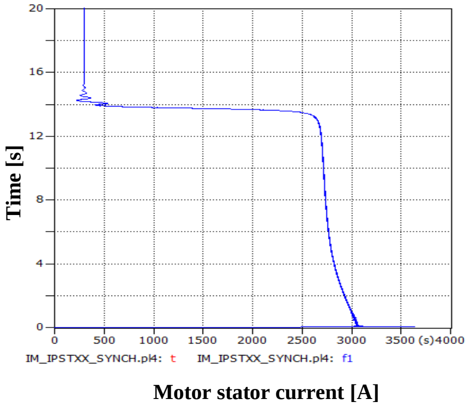

Fig. 18. Motor starting time vs. starting current (stator winding current)

C. Settings of Under-Impedance Relay (ANSI code 21)

The settings of the under-impedance relay are shown graphically in the circular locus of the following figure.

The circle is centered in the origin of the *R/X* chart and has a radius of 2.35 ohm. The characteristic reference impedance of the line (in our application line means motor) is taken equal to X_L = 1.93 ohm (reactance) and R_L = 0.419 ohm (resistance):

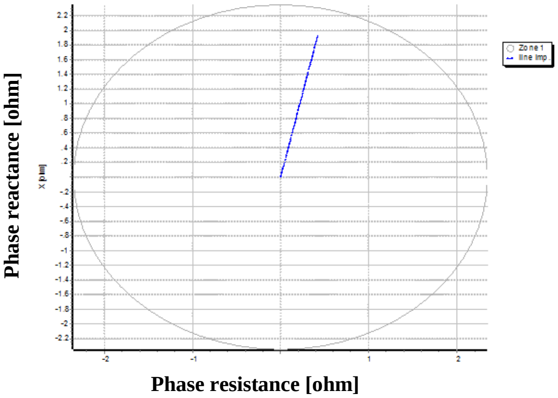

Fig. 19. Setting of *R/X* chart for Under-Impedance Relay (ANSI code 21)

VI. ACKNOWLEDGMENT

The author gratefully acknowledges the Electrical Department of Maire Tecnimont Group, for the consultation of the available technical literature.

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