Immunity to voltage dips for synchronous motors

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Abstract-- **In latest years the use of synchronous motors to feed large power compressors (e.g. 5 to 30 MW) in petrochemical plants (especially of Low Density Polyethylene type) is becoming more and more a widespread industrial practice, especially because their operation avoids the installation of large power capacitor banks that would be otherwise necessary to satisfy the requirements for plant power factor improvement.**

The recourse to a synchronous motor poses however some problems in terms of its transient stability since, with respect to an induction motor of similar power, it is more sensitive to voltage dips on supply network, with the risk of falling easily out of step.

In this paper, a typical electrical distribution from an industrial plant is taken into consideration and several voltage dip magnitudes, which could arise from events like short circuits, sudden application of large power loads or partial loss of generating power, are simulated: the aim is to put in evidence under which conditions cases of instability could arise.

Simulations are carried out by means of EMTP-ATP program: synchronous machine model is based on the d-q electrical equations using parameters from motor manufacturer.

Design data from motor manufacturer regarding voltage dip ride thorough capabilities are used as comparison with the results obtained from ATP program and useful conclusions are derived in terms of choice of the electrical protection system schemes which give synchronous motors a better immunity to voltage dips.

***Keywords*: Voltage dips, transient stability, synchronous motors, out of step, abnormal oscillations.**

I. INTRODUCTION

THE use of large power synchronous motors (typical rating between 5 MW and 30 MW), has become in several industrial plants a valid alternative to the more traditional induction motors of similar power, due to their inherent high value of operating power factor which helps reducing the plant global demand of reactive power, thus permitting to avoid the recourse to traditional large size static capacitor banks.

However, a synchronous machine is very sensitive to dips on stator winding voltages, due to abnormal transient disturbances that can occur in the electrical distribution system, and consequently can lose easily its synchronism with the supply power system: the electro-mechanical transient phenomenon being here considered is commonly identified under the names transient stability [1], [3], or large-disturbance rotor angle stability [6]: it is a short term phenomenon which involves large excursions of machine rotor angle and is influenced by the nonlinear relationship between active power (P) and rotor angle (δ). The time frame of interest for transient stability phenomena is usually in the order of 3 to 5 seconds following a disturbance.

The most common events giving rise to serious network voltage dips are phase to phase short circuits, which can really cause a supply voltage collapse to near zero, or sudden re-accelerations of huge amount of motor loads following a switchgear busbar load transfer, which usually cause less severe voltage dips of partial magnitude with respect to the effect of short circuit events. The meaning of supply voltage dips or supply voltage short interruptions is as per definition of international standards about electromagnetic compatibility in industrial environments [7].

The aim of this work is to analyze which combinations of voltage dip magnitude and corresponding time duration could give rise to instability conditions for a synchronous motor in an industrial plant.

II. SYSTEM DATA AND MODELING

A. System Data

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

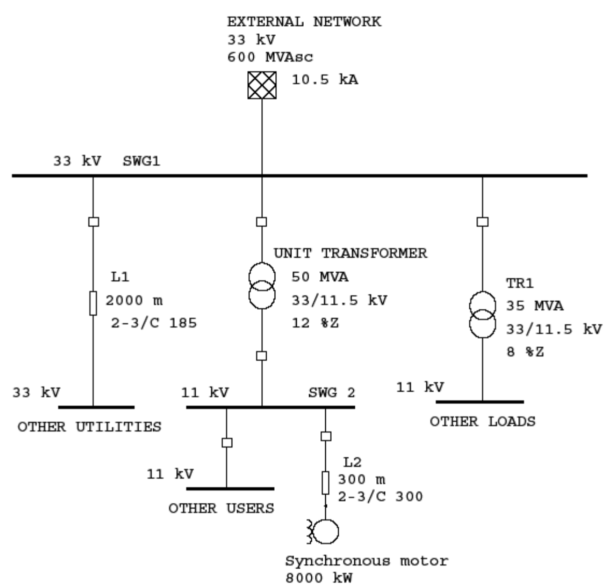

Fig. 1. Single-line diagram of the industrial electrical system

Main electro-mechanical parameters, for each network

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component, are reported in the Appendix.

B. Modeling

For the aim of numerical simulation by ATP (Alternative Transient Program) [5], the electrical network is simplified and modeled as shown in Fig. 2, following the general guidelines presented in [4].

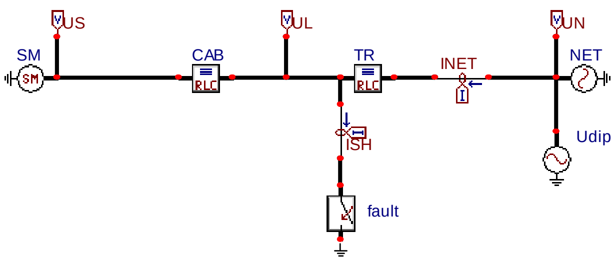

Fig. 2. ATP model of the electrical system

All equivalent impedances of the network components are referred to the motor rated voltage level and, due to the symmetry of the disturbances (3-phase symmetrical voltage interruptions or 3-phase symmetrical voltage dips), the resulting equivalent network is referred to the line to neutral voltages (star equivalent circuit).

Cable and unit transformer are modeled as constant impedances, since they are electrically short line and for the aim of the electro-mechanical transient under study a more detailed model is not necessary; the equivalent impedance of the supply network is negligible with respect to the impedances of transformer and motor.

The motor is modeled by means of ATP model type SM59 for synchronous machines [5], based on d–q reactance Park's theory and with no transient control system (TACS) and no magnetic saturation being taken into account. Machine saturation affects transient stability by reducing the magnitude of transient reactances [1], but it is preferable in stability studied to use a conservative value, i.e. the higher un-saturated transient reactance. Due to the short term phenomena of network voltage dips and due to the machine being designed as a motor instead of a generator, the excitation system is assumed as a constant during the stator voltage disturbances. Hence it is assumed that no voltage dynamic regulation can happen during the abnormal transient phenomena being studied: this is on the conservative side for the transient stability, since the forcing of excitation is really unlikely to take place during few hundreds of milliseconds and its effect would be also greatly reduced when appreciable reactance is introduced between the supply and the user [1]. Moreover, the mechanical load torque is assumed as constant during the voltage transients, due to the fast phenomenon happening on the machine armature side.

The voltage dips are modeled as a 3-phase switch, for the simulation of a 3-phase bolted short circuit which gives a complete supply interruption, or as an additional 3-phase voltage generator whose negative amplitude superimposes on the steady state supply network 3-phase voltage generator, to simulate a voltage dip of partial magnitude different from zero (e.g. dip of 60% of rated voltage).

III. PRE-ANALYSIS AND STUDY CASES

A simplified analysis, based on methods and procedures for transient stability studies explained in [1], [2], [3], is carried out before simulations, to estimate the stability condition against a 3-phase bolted fault in some point of the supply network.

Machine pole saliency is also neglected (only direct axis reactances being considered) because in transient state the d-axis and q-axis reactances have practically the same value. Instead the difference between d-axis and q-axis steady state values gives rise to an actual stable static angle less than π/2 rad (90 deg) being typical of a round-rotor machine. However, for the majority of problems, the round-rotor method is satisfactory since it gives a more conservative stability limit evaluation and is preferable due to the simplicity of its calculations [1].

A. Approximate analysis of transient stability

The main electro-mechanical equation being used as description of transient behavior, also known as swing equation, is:

$$\frac{H}{\pi f_o}\frac{d^2\delta}{dt}+D\omega=P_e-P_m \qquad (1)$$

where
H is the inertia time constant (s)
f_o is the system frequency (Hz)
D is the damping factor (p.u./rad/s)
ω is the angular speed (rad/s)
δ is the rotor angle (rad)
P_m is the driven mechanical power output (p.u.)
P_e is the electrical absorbed power (p.u.)
π is the pi-grec number.

In case of a voltage dip which causes a complete supply interruption, the electrical power P_e becomes null and the time duration t the rotor takes to make an angular swing, relative to the initial motor rotor angle, can be computed from "(1)", by neglecting conservatively the damping factor D, as follows:

$$t=\sqrt{\frac{2H}{\pi f_o}\frac{P_n}{P_o}}\sqrt{\delta-\delta_o} \qquad (2)$$

where
H is the inertia time constant (s)
f_o is the system frequency (Hz)
δ is the generic rotor angle (rad)
δ_o is the initial rotor angle (rad)
P_n is the nominal electrical power (MVA)
P_o is the initial electrical absorbed power (MW)

π is the pi-grec number
t is the maximum rotor swing duration (s).

To obtain the transient stability rotor angle δ_1, i.e. the largest value of transient rotor angle being necessary to prevent the machine instability, the "Equal Area Criterion" [5] can be applied, which states that the decelerating energy lost by the rotor during the transient fault condition must be counterbalanced by the accelerating energy gained by the rotor during supply voltage recovery once the fault condition is cleared. The following relationship results:

$$\frac{P_o}{P_n}(\pi - 2\delta_o) = -\frac{E'_m E_r}{X_r + X_t + X'_d}\left[\cos(\pi - \delta_o) - \cos(\delta_1)\right] \quad (3)$$

where
P_o is the initial electrical absorbed power (MW)
P_n is the nominal electrical power (MVA)
E'_m is the transient internal motor voltage (p.u.)
E_r is the supply network voltage (p.u.)
X_r is the supply network reactance (p.u. of nominal motor power in kVA)
X_t is the unit transformer reactance (p.u. of nominal motor power in kVA)
X'_d is the motor transient direct axis reactance (p.u. of nominal motor power in kVA)
δ_o is the initial rotor angle (rad)
δ_1 is the transient stability rotor angle (rad)
π is the pi-grec number.

Hence, also the maximum time duration within which the abnormal transient fault condition must be eliminated can be calculated through "2", by assigning to the generic rotor angle δ the value δ_1 calculated from "3".

The following approximate results are obtained:

X'_d = 0.36 p.u.
X_r = 0.0091 p.u.
X_t = 0.02 p.u.
H = 1.13 s
E_r = 1.0 p.u.
E'_m = 0.95 p.u.
(P_o / P_n) = 0.86 p.u.
δ_o = 0.36 rad (21 deg)
δ_1 = 1.64 rad (94 deg)
t = 0.146 s.

Due to the simplifications being adopted, the estimated maximum clearing time value t for the 3-phase short circuit event could be a bit higher than the actual one which can be withstood by the synchronous motor and which will be verified through numerical simulations.

B. Study Cases

Three types of voltage dips are simulated in the ATP circuit of Fig. 2 and their significance, with reference to the electrical distribution system shown in the Single-line diagram of Fig. 1, is summarized here below.

TABLE I
VOLTAGE DIP SCENARIOS

Dip Magnitude	Dip Duration
100 % of system rated voltage 3-phase bolted short circuit on 33 kV or 11 kV distribution feeders being close to the compressor motor supply feeder	140 ms = 80 ms + 60 ms 80 ms maximum opening time of circuit breaker 60 ms maximum operating time of main protection relays (over-current type)
100 % of system rated voltage 3-phase bolted short circuit on 33 kV or 11 kV distribution feeders being close to the compressor motor supply feeder	100 ms = 80 ms + 20 ms 80 ms maximum opening time of circuit breaker 20 ms maximum operating time of main protection relays (zone-differential type)
60 % of system rated voltage Sudden re-energization of motor loads on 11 kV busbars or 3-phase faults on 11 kV distribution feeders being far from the compressor motor supply feeder	200 ms

IV. RESULTS

The results of numerical simulations are shown graphically in the following figures. Stator winding currents, speed and electromagnetic torque are selected as the most significant magnitudes to evaluate the performance of the motor during the transient disturbances.

A. Network 3-phase fault for 140 ms

In the next figures, the case of voltage dip of 100% of rated voltage for 140 ms is analyzed.

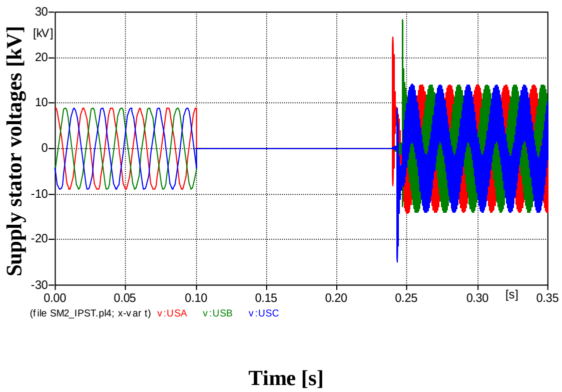

Fig. 3. Stator winding voltages as a function of time (100% dip - 140 ms)

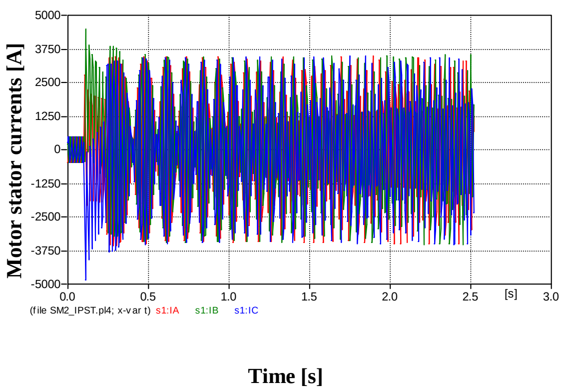

Fig. 4. Stator winding currents as a function of time

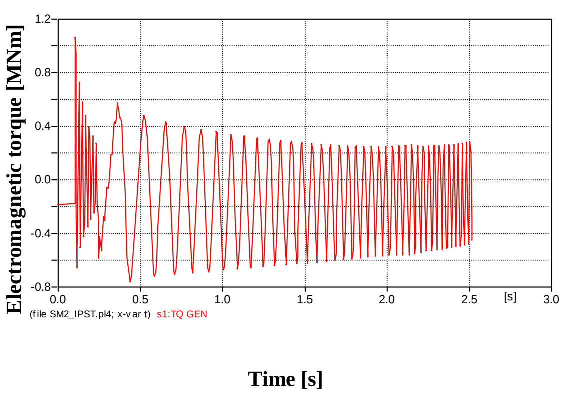

Fig. 5. Electromagnetic torque as a function of time

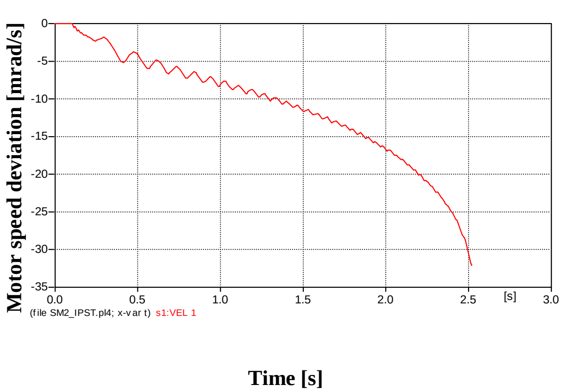

Fig. 6. Angular speed deviation as a function of time

As it can be seen, after the voltage dip application, the system is not capable to revert to the previous working conditions and the motor goes out of step: this is quite visible from the oscillating behavior of stator winding currents and electromagnetic torque. A prolonged out of step operation should be avoided to minimize both mechanical damage (e.g. to shaft and coupling) and stator winding damage: for this reason, only few pole slipping cycles can be tolerated.

B. Network 3-phase fault for100 ms

An upper bound for the time application of 100% voltage dip is found equal to 100 ms, and results are visible in the next figures.

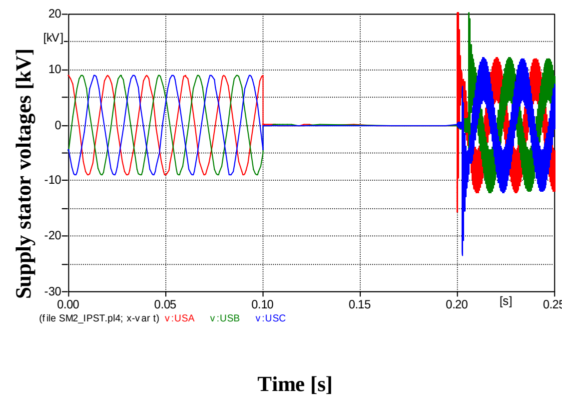

Fig. 7. Stator winding voltages as a function of time (100% dip - 100 ms)

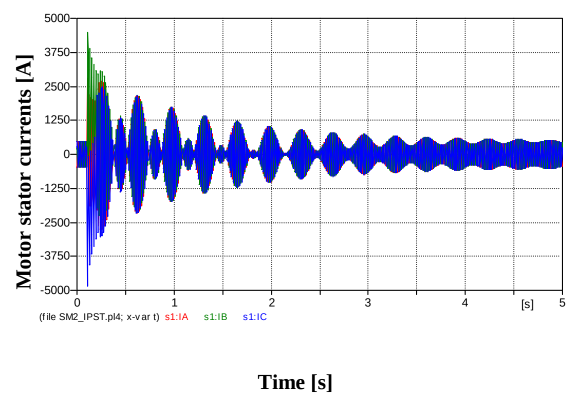

Fig. 8. Stator winding currents as a function of time

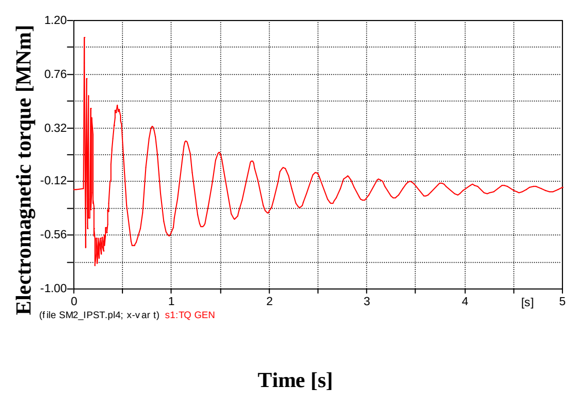

Fig. 9. Electromagnetic torque as a function of time

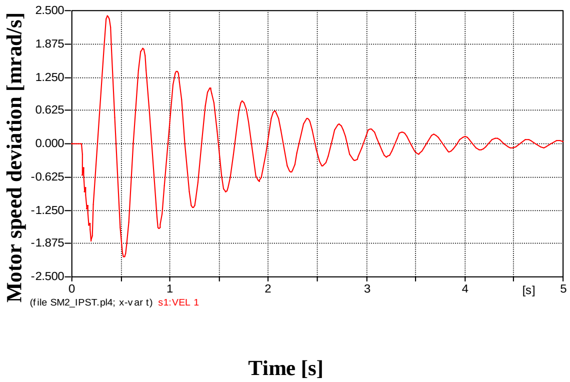

Fig. 10. Angular speed deviation as a function of time

As it can be seen, the motor manages to keep the synchronism, and the transient electromechanical magnitudes take about 5 s to recover their steady state value.

C. Network voltage dip (60% of rated voltage - 200ms)

In the next figures the case of voltage dip with partial magnitude (60% of rated voltage) for a duration longer than that of short circuit events (200 ms) is analyzed.

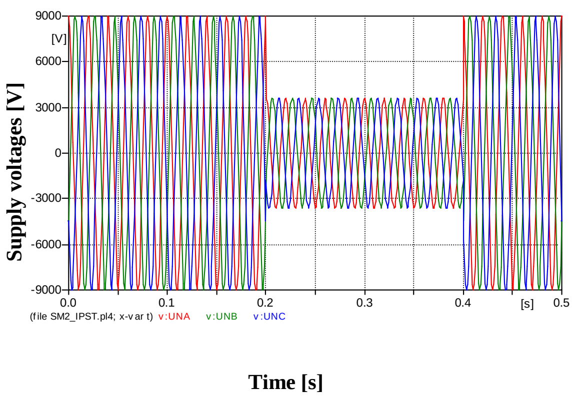

Fig. 11. Voltage dip on network supply voltages as a function of time (60% dip - 200 ms)

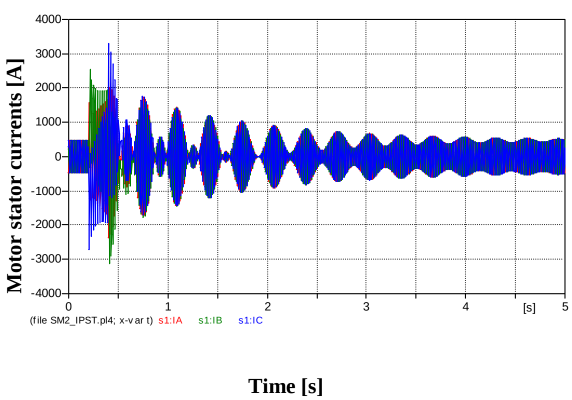

Fig. 12. Stator winding currents as a function of time

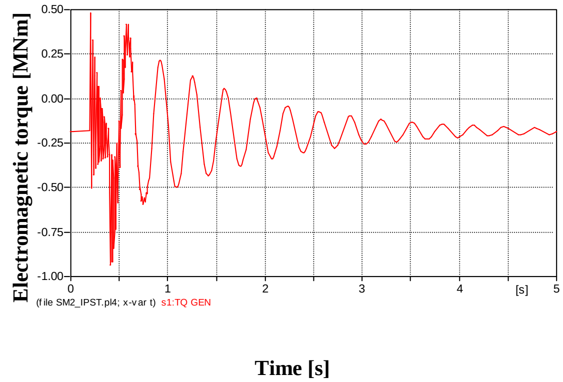

Fig. 13. Electromagnetic torque as a function of time

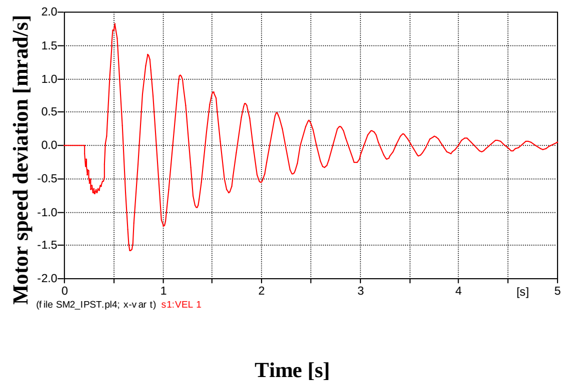

Fig. 14. Angular speed deviation as a function of time

As it can be seen, the transient behavior is quite similar to the case of 100% dip for 100 ms: as would be intuitively expected, the motor can withstand a longer voltage dip (200 ms instead of 100 ms) for a partial voltage failure (dip of 60% of rated voltage instead of 100% of rated voltage).

D. Manufacturer data for immunity to voltage dips

Data about immunity to voltage dips were provided also by motor Manufacturer and are summarized here below:

0% of 11 kV (100% dip)	for 0.100 s
40% of 11 kV (60% dip)	for 0.230 s
75% of 11 kV (25% dip)	for 60 s.

The above values (in particular the 100% dip case) are quite in accordance with what has been simulated and what was expected by the approximate simplified analysis carried out in section III.

V. Conclusions

In this paper a typical industrial distribution system, which supplies a synchronous motor being used to drive a large compressor, is analyzed for the aim of motor transient stability.

In case of serious short circuit events (e.g. of three-phase bolted type) occurring in points of the supply network close to the supplied load, the motor can lose easily its synchronizing condition. When the fault lasts for 140 ms or more, the motor undergoes abnormal electromechanical oscillations so high to fall out of step and stops: this is well shown by excessive oscillations of rotor angle, which does not reach a steady state value within the stable static value of $\pi/2$ rad (90 deg), and by the magnitudes of absorbed stator currents, which tend to assume values much higher than nominal values for prolonged time.

Reducing the fault clearing time (e.g. less than 100 ms) can be beneficial to keep the machine stability: at this aim it is recommended to employ differential protections (being practically instantaneous) on adjacent feeders of the industrial distribution system, in addition to simple over-current protections, whose differential zones overlap among supply switchgear busbars, cables and transformers.

The case of network voltage failure consisting in a voltage dip of partial magnitude (e.g. 60% of rated voltage) is less severe with respect to a three-phase bolted short circuit event and gives the synchronous motor a longer withstand duration (e.g. 200 ms) against the out of step condition.

It is advisable that information about immunity to voltage dips for a synchronous motor (e.g. given as several combinations of % of terminal voltage for corresponding withstand time duration) be always provided by the relevant Manufacturer and clearly stated in the machine data sheet due to its influence on the motor electromechanical design.

VI. Appendix

TABLE II
SUPPLY NETWORK DATA

Equipment	Parameters
Equivalent Network at the point of common coupling for the industrial plant	33 kV rated voltage
	50 Hz rated frequency
	600 MVA min. 3-phase short circuit power
	10.5 kA min. 3-phase sub-transient short circuit current at rated voltage
	X/R = 10 reactance to resistance ratio

TABLE III
UNIT TRANSFORMER DATA

Equipment	Parameters
Unit Transformer dedicated to Compressor Motor supply	50 MVA rated power
	Zt = 12% short circuit impedance (referred to rated power)
	33 / 11.5 rated voltage ratio

TABLE IV
CABLE DATA

Equipment	Parameters
Cable feeder from Unit Transformer to Motor	300 m length
	300 mm^2 cross section
	3-core copper conductors 2 parallel runs
	Rc = 0.012 ohm resistance / phase
	Xc = 0.015 ohm reactance / phase

TABLE V
SYNCHRONOUS MOTOR DATA

Equipment	Parameters
Synchronous motor to drive a Compressor	8000 kW rated power
	11000 V rated voltage (r.m.s. line to line) 8980 V rated voltage (peak line to neutral)
	484 A rated stator winding current
	34.9 rad/s rated angular speed
	18 number of poles
	300 A rated rotor field winding current
	Ra = 0.00568 p.u. armature resistance
	Xd = 1.2 p.u. d–axis synchronous reactance
	Xq = 0.78 p.u. q–axis synchronous reactance
	X'd = 0.36 p.u. d–axis transient reactance
All reactance and resistance p.u. (per unit) values are referred to the base power Sb = 9280 kVA	X'q = 0.36 p.u. q–axis transient reactance
	X"d = 0.23 p.u. d–axis sub-transient reactance
	X"q = 0.255 p.u. q–axis sub-transient reactance
	T'do = 5.2 s Transient d-axis open circuit time constant
	T"do = 0.0156 s Sub-transient d-axis open circuit time constant
	J = 15832 kg m^2 Moment of Inertia of motor + driven load
	H = 1.13 s Inertia time constant
	T_L = 229185 Nm full load torque

VII. ACKNOWLEDGMENT

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