Large Induction Motor Reacceleration due to Fast Bus Bar Transfer

P. Marini

***Abstract*--In polypropylene petrochemical plants large power induction motors (e.g. rated 9 to 20 MW) are normally used to drive extruder machines required by this type of industrial process. Sometimes the switchgear supplying the primary side of the transformer being dedicated to feed this type of motors is provided with an automatic bus bar transfer system based on fast non-synchronized voltage measurement on bus bar incoming lines.**

In case of transient phase to phase short circuit events in some points of the plant distribution, the supply network feeding the high voltage primary side of the motor transformer can undergo voltage dips with magnitude such as to enable the fast automatic bus bar transfer and such as not to shed the motor for trip of under-voltage protection relay.

The consequent reacceleration of the complete train (motor plus driven extruder), taking place during the fault event and during the subsequent supply voltage restoring by bus bar transfer, has to be carefully verified to check possible electro-mechanical damage both to motor and to driven equipment.

***Keywords*: induction motor, shedding, under-voltage, reacceleration.**

I. INTRODUCTION

THE use of an induction motor (typical rated power between 9 MW and 20 MW) to drive a high power extruder machine in petrochemical plants, is the most common choice since many years, when there is no particular need for high power factor improvement in the plant, which could make the plant user likely to prefer instead a synchronous motor. The supply of such a large induction motor is always through a dedicated captive transformer [8], in order to guarantee a correct direct-on-line motor starting without causing excessive voltage sags on the high voltage distribution network which feeds the captive transformer.

In most industrial applications, the captive transformer for the extruder motor is fed by a high voltage switchgear installed into a different substation belonging to the national distribution network system operator. Sometimes, this network system operator can decide to equip its high voltage distribution switchgears with a fast automatic bus bar transfer system [4], [5], [6], with the intent of avoiding undue shut-down to the supplied industrial plants, in case of transient voltage dips occurring in the grid being under its responsibility.

As stated in IEC standard for rotating electrical machines [11], any bus bar transfer or fast reclosing of an a.c. machine, as it might occur, for example, due to the voltage ride through requirements of grid codes, can lead to very high peak currents endangering the stator winding overhang and to a very high peak torque of up to 20 times the rated torque endangering the mechanical structure including the coupling and the driven equipment. Bus transfer or fast reclosing [2], [3], is therefore only allowed if specified and accepted by the manufacturers of electric machine and driven equipment.

This work presents the analysis of an accidental short circuit fault occurred inside an industrial plant, which caused the inadvertent activation of the fast automatic transfer system on the upstream 33 kV supply switchgear bus bars, with the consequent trip of several variable speed drive systems in the plant due to voltage dip, and the subsequent reacceleration of the largest 11 kV direct-on-line extruder motor fed by a 33/11.5 kV captive transformer.

II. SYSTEM DATA AND MODELING

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, is shown in Fig. 1.

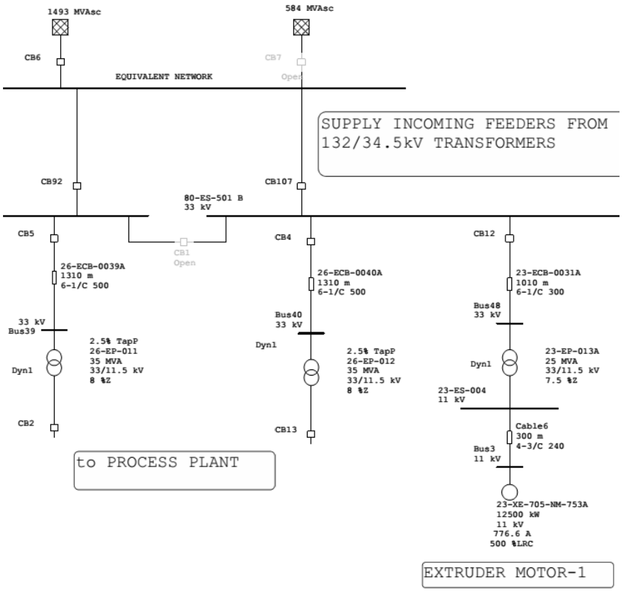

Fig. 1. Single-line diagram of the industrial electrical system

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

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 (IPST2017) in Seoul, Republic of Korea June 26-29, 2017

B. Modeling

For the aim of numerical simulation by ATP (Alternative Transient Program) [10], the electrical network is simplified and modeled as shown in Fig. 2, following the general guidelines presented in [9].

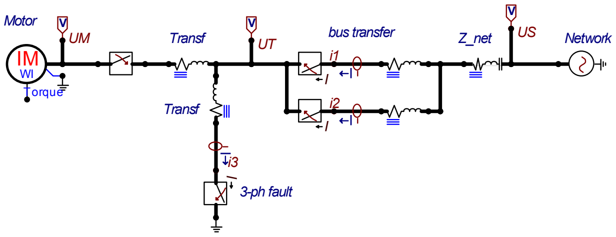

Fig. 2. ATP model of the electrical system

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

Cable and captive transformer are modeled as constant impedances, since they are electrically short lines 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 derived from the corresponding value of available minimum short power at the point of common coupling of the industrial plant to the supply grid.

The motor is modeled by means of ATP universal induction machine model (UMIND) based on d–q reactance Park's theory [1], by entering the input data in the Windows graphical interface of ATP (Windsyn) [10], 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.

Mechanical coupling and driven machine are represented by the equations shown in the Appendix.

The voltage dip is modeled as a 3-phase switch placed downstream of a transformer impedance, for the simulation of a 3-phase bolted short circuit whose effect is a voltage sag of partial magnitude different from zero (e.g. dip of 60% of rated voltage) on the supply distribution being upstream of the transformer. The fast bus bar automatic transfer system is simulated by means of two parallel 3-phase switches which both operate simultaneously: one opens while the other contemporarily closes.

III. PRE-ANALYSIS AND STUDY CASE

A simplified analysis, based on the disturbance recorded data collected by the personnel of the industrial plant, is carried out before ATP numerical simulations, in order to understand the reasons why the fast automatic bus bar transfer took place inadvertently.

A. Description of events

Each one of the two bus bars of the main 33 kV distribution switchgear of the industrial plant is fed by one 132/34.5 kV, 140 MVA transformer, which steps down the voltage from 132 kV level to 33 kV level.

During maintenance, an electrical supervisor closed the incoming earth-switch on live circuit at one 11 kV sub-distribution switchgear dedicated to the supply of one crane package, causing a 3-phase-to-earth short circuit on the 11 kV system, which reached approximately 16 kA peak value. This was an inadvertent action due to lack of knowledge of operating and safety procedures on the 11kV switchgear for the crane. As the 11 kV switchgear design was adequate and the installation / terminations were done properly, fortunately, it did not cause any visible equipment or personnel injury. The crane feeder circuit breaker tripped on phase over-current protection and cleared the short circuit after 170 ms from the fault initiation.

As the fault was one of the most stressful than can be expected on the 11 kV system, this caused a severe under-voltage, which was recorded equal to 50 % of rated voltage by protection voltage relays on the upstream 33 kV distribution system. The fault current at 11 kV was detected also by 33 kV protection over-current relays which recorded a current value equal to 3836 A r.m.s.

A fast transfer operation was registered on main 33 kV switchgear bus bars. The fast transfer system was adjusted to operated when the voltage level drops down more than 20 % of nominal value (33 kV) for more than 8 cycles at 50 Hz (i.e. 160 ms): the 33 kV incomer circuit breaker associated with the faulty power supply was opened within approximately 60 ms while the tie breaker was simultaneously closed within approximately 100 ms. The fast transfer process was completed within 360 ms after the occurrence of the fault on the 11 kV sub-distribution switchgear: 360 ms was given by the summation of 160 ms time delay, plus 100 ms of tripping command from the transfer logics to the breakers, plus finally 100 ms of closing of the bus-tie which lasted longer than the contemporary opening of the incomer.

As a consequence, all motors fed by variable speed drives connected to the 33 kV switchgear bus bar which experienced the voltage dip were stopped by under-voltage, while other direct-on-line motors under the same bus bar were first shed by under-voltage protections and subsequently were subject to the automatic motor restarting procedure, in such a way to continue their operation. The largest extruder motor fed by captive transformer underwent a reacceleration without being stopped by relevant under-voltage protections.

B. Interpretation of accidental events

The main 33 kV switchgear bus bars of the industrial plant were equipped with a fast transfer of the unsupervised type [5], hence the simultaneous commands of opening of the incoming and closing of the bus-tie were implemented without any sync-check device which supervises voltage angle and voltage frequency slip.

This fast bus bar transfer system was anyway necessarily delayed for a minimum time duration (160 ms), in such a way that the bus bar differential protection (ANSI code 87B) installed on 33 kV switchgear could clear a short circuit fault just in the bus bar sections and block the closure of the bus-tie, thus inhibiting the start of the automatic transfer system which would otherwise re-connect the faulted bus to the other healthy incoming supply with the consequent shut down of the entire plant distribution system [7].

Therefore, the fast bus bar transfer activated with success since the bus bar voltage fell under 80% of rated voltage (50% recorded value) for more than 160 ms and there was no bus bar phase fault which could block the transfer within this time frame: the choice of this voltage magnitude and relevant time delay duration were such not to unduly hinder the completion of normal transient events like motor starting and transformer energization within the industrial plant.

The phase-to-phase fault current value of 3836 A recorded at 33 kV side was detected also by the pick-up threshold setting (3000 A) of over-current protection relays installed on 33 kV switchgear incomer circuit breakers, but these protection relays (ANSI code 51 having inverse time vs. current characteristics) were not able to inhibit the fast transfer because their tripping time was necessarily delayed to some tens of seconds, in order to allow for the overcoming of frequent normal transients like extruder motor starting events in the plant [7].

During the fault and the bus bar transfer, and also during the subsequent reacceleration, the induction motor driving the largest extruder machine was not tripped neither by relevant under-voltage protection relay nor by over-current protection relay, having the following settings:

- minimum voltage (ANSI code 27):
  65% rated voltage , trip time = 500 ms

- locked rotor / rotor jam during running (ANSI code 51R)
  200% rated current , trip time = 5 s < locked rotor time (9 s).

Therefore, it is clear that the under-voltage motor protection, although it picked-up correctly during the 50% magnitude voltage dip, had sufficient time (less than 100ms) to drop-off, since the short circuit fault clearing on 11 kV feeder and the simultaneous transfer on 33 kV bus bars completed within 360 ms, and 360 ms plus 100 ms is still lower than the trip time of 500 ms. It is also apparent that during the reacceleration of the largest extruder induction motor, the stator motor current could have exceed two times its rated value during transient state, only for a time duration lasting less than 5 s.

C. Study case

With reference to the electrical distribution system shown in the single-line diagram of Fig. 1, the events summarized in the following table are simulated by means of the ATP circuit of Fig. 2.

TABLE I
SEQUENCE OF SIMULATED EVENTS

Type of event	**Time instants for the occurrence of events**
11kV Extruder motor direct-on-line starting	At time instant t =0.01 s motor circuit breaker is closed
3-phase bolted short circuit on 11 kV sub-distribution feeder dedicated to the supply of a crane package This fault causes a 50 % voltage dip on 33 kV distribution bus bar	At time instant t = 13.995 s short circuit fault initiates At time instant t = 14.165 s short circuit fault is cleared by over-current protection (100 ms relay delay+70 ms of circuit breaker opening)
Fast automatic bus bar transfer on 33 kV switchgear bus bars Sudden reacceleration of 11kV Extruder induction motor fed by 33/11.5kV captive transformer.	At time instant t = 14.255 s (260 ms after fault initiation) Fast bus transfer operates: incomer opens in 60 ms bus-tie closes in 100 ms Dead time for voltage supply recovering on 33kV system is given by 40 ms = 100 ms – 60 ms

IV. RESULTS

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

A. Short circuit fault and fast bus bar transfer events

The effect of the accidental short circuit fault on 11kV feeder and of the subsequent fast transfer on the voltage profile of 33kV switchgear bus bars is shown in the next figures.

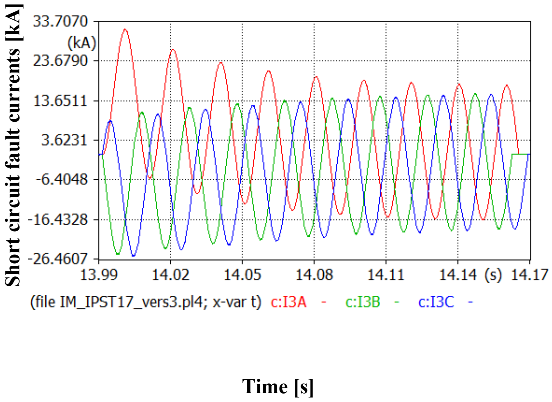

Fig. 3. Three-phase short circuit fault on 11kV feeder as a function of time

As it can be seen, the accidental short circuit fault on 11kV feeder reaches an asymmetrical peak current value equal to approximately 30kA, while the relevant symmetrical peak value attains a value around about 16.9kA.

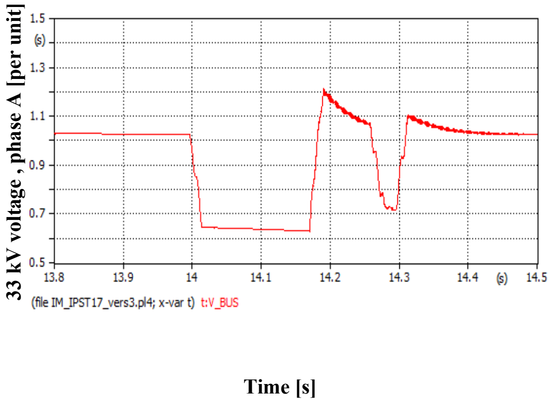

Fig. 4. Main distribution system voltage as a function of time

As it can be seen, the accidental short circuit fault on 11kV bus bars causes a voltage dip on 33kV distribution system, whose supply voltage reaches the calculated value of 0.60 p.u. This simulated value is higher than what was registered (0.50 p.u.) during the real event: this is most likely due to the adoption of a simplified simulation model, in which more attention was focused on the modeling of the largest extruder motor with relevant captive transformer, while neglecting for the sake of simplicity the modeling of all the other motors and distribution transformers fed by the main 33kV bus bars. During the voltage sag and bus transfer, in fact, also these other transformers and motors experience respectively a re-energization and a reacceleration phenomena from the 33kV supply network, which demand more reactive power consumptions than normal condition, causing the 33kV network voltage to further lower from 0.60 p.u. to 0.50 p.u.

In the next figure the motor stator current (r.m.s. value of one phase) is shown.

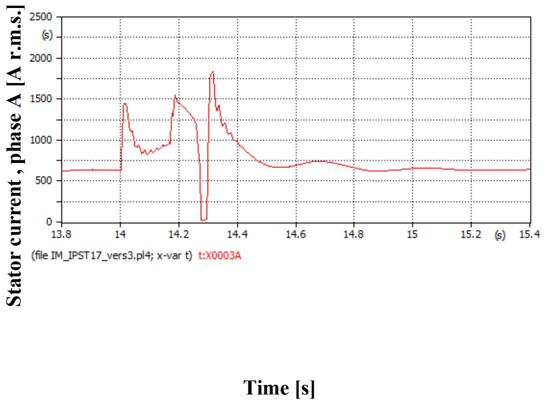

Fig. 5. Motor stator winding current as a function of time

The motor stator current is higher (almost 1820 A, corresponding to 2.43 p.u. of rated current), during the motor reacceleration happening after the bus bar transfer, than during the short circuit fault occurring on other 11kV bus bars (the extruder motor short circuit current contribution amounts to around 1500 A in this case, corresponding to 2.0 p.u. of rated current). The main stator current oscillation during motor reacceleration lasts practically less than 0.2 s.

In the next figure the transient behavior for motor and extruder torques is shown.

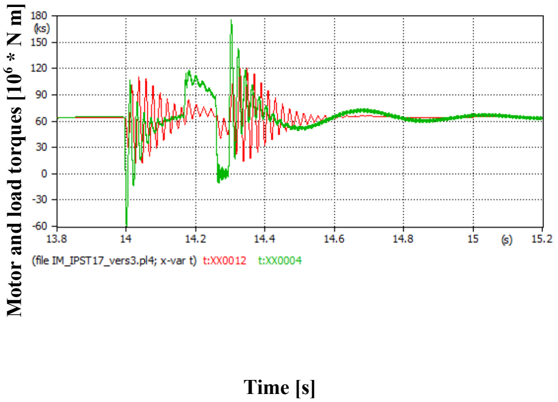

Fig. 6. Electromagnetic and load torques as a function of time

Similarly to the stator currents, also the motor and load torques are more stressed during the motor reacceleration than during the short circuit in the 11kV network. The motor torque reaches a peak value of approximately $180*10^6$ Nm, corresponding to 2.25 p.u. of motor rated torque, while the load torque which is transmitted along the shaft to the extruder machine reaches a smaller value, equal to a peak of $120*10^6$ Nm (corresponding to 1.5 p.u. of motor rated torque). Anyway, the torque stress gives no particular concern because it is quite lower than the design values of maximum air gap torque, given by the motor manufacturer, that the motor and relevant shaft coupling are able to withstand during 3-phase and 2-phase short circuit faults occurring just at motor terminals.

B. Simulations versus on-site measurements

A good correspondence was found between the most significant simulated magnitudes and the relevant measurements on-site, as shown here after:

- Short Circuit fault on 11kV feeder:
  measured 16kA versus calculated 16.9kA
- Transient voltage sag on 33kV distribution bus bars:
  measured 0.50 per unit versus calculated 0.60 per unit.

V. CONCLUSIONS

In this paper a typical industrial distribution system, which supplies an induction motor being used to drive a large extruder for polypropylene process, is analyzed for the aim of studying the reacceleration of motor and driven equipment in case of fast bus bar transfer.

The choice of an induction motor, to drive an extruder machine, gives the proper electrical and mechanical robustness necessary to sustain the reacceleration during sudden under-voltage caused by transient short circuits in the network.

The presence of a captive transformer, being dedicated solely to the supply of the extruder induction motor, gives a sort of impedance decoupling between the 33 kV network where the fast bus bar transfer occurs and the 11 kV motor terminals, and this decoupling helps reducing the transient motor inrush currents and torque peaks arising during the fast un-supervised bus bar transfer operation. Moreover, since the motor inertia is much more higher than the driven extruder inertia, the shaft torque stress is small in comparison to the electromagnetic torque stress that the motor undergoes and more easily withstand during the fast reclosing of the 33 kV supply [3].

On the contrary, the operation of the 33 kV supply switchgear bus bars having a normally open bus-tie and a fast bus bar transfer system is not the best choice, in terms of supply reliability, for the following reasons:

- independently of the type of fast automatic transfer system used, there is always a minimum time delay to be waited for (typically 100 ms to 160 ms), to allow for the inhibition of the transfer logics in case of a bus bar fault properly detected by a 33 kV bus bar differential protection relay, and hence to avoid the reclosing of the supply on fault;
- even in case of successful bus bar transfer on 33 kV system (e.g. within 200 ms), any variable speed drive and synchronous motor inside the plant would be anyway tripped since they are very susceptible to voltage dips (usually, as per relevant manufacturer information, it takes 10 ms to 50 ms of 100 % voltage dip to a variable speed drive to lose its load torque control, or to a synchronous motor to fall out of step);
- any phase-to-phase short circuit fault occurring on sub-distribution levels (11 kV switchgear bus bars), even if is detected by the pick-up of the back-up thresholds of over-current protection relays on 33 kV switchgear incomers, cannot have a magnitude high enough to trip in fast way (that is within the minimum time delay of 100 ms to 160 ms) the incomer circuit breaker, for the aim of blocking the activation of the bus bar transfer process.

The best compromise to solve all the above mentioned problems is to operate the 33 kV supply switchgear bus bars with the bus-tie/bus-coupler as normally closed, without the provision of any fast bus bar transfer system. For the case of the industrial plant being analyzed, the paralleling of two 132/34.5 kV transformer sources is allowed since it does not increase dangerously the actual short circuit fault currents beyond the maximum affordable short circuit withstand rating (40 kA symmetrical value) on 33 kV bus bars, thanks to the still relative high magnitude of this voltage level.

The adoption of a normally closed operated 33 kV bus-tie/coupler is advantageous because there is less impact on voltage dips during sudden load pick-up or motor starting events, there is no more risk of undue fast bus bar transfer activation which causes electrical and mechanical stress to induction machines and, in case of sudden loss of one of the two parallel sources (e.g. fault into one 132/34.5 kV transformer), there is no more inadvertent trip of variable speed drives or undue shedding of synchronous motors for voltage dips.

VI. APPENDIX

A. *Electrical Network Components Data*

TABLE II
SUPPLY NETWORK

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

TABLE III
TRANSFORMERS

Equipment	Parameters
Captive Transformer dedicated to 11kV Extruder Motor supply	25 MVA rated power
	Zt = 7.5% short circuit impedance (referred to rated power)
	33 / 11.5 rated voltage ratio
Distribution Transformer dedicated to the supply of other 11kV loads (Crane Package)	35 MVA rated power
	Zt = 8% short circuit impedance (referred to rated power)
	33 / 11.5 rated voltage ratio

TABLE IV
CABLES

Equipment	Parameters
Cable feeder from 33kV main switchgear to Captive Transformer for Extruder Motor	1035 m length
	500 mm^2 cross section
	1-core copper conductors in tre-foil formation 1 run per phase
	Rc = 0.0497 ohm (90 °C) resistance / phase
	Xc = 0.1035 ohm reactance / phase
Cable feeder from 33kV main switchgear to general Distribution Transformer for plant loads	1310 m length
	500 mm^2 cross section
	1-core copper conductors in tre-foil formation 2 parallel runs per phase
	Rc = 0.0314 ohm (90 °C) resistance / phase
	Xc = 0.0655 ohm reactance / phase

TABLE V
INDUCTION MOTOR DATA

Induction motor used to drive an Extruder machine

All reactance and resistance p.u. (per unit) values are referred to the base power S_b = 14304 kVA (rated base impedance is Z_b = 8.459 ohm)

Manufacturer's Data	**Calculated Model Parameters**
12500 kW rated power	Rs = 0.021444 p.u. (stator resistance)
11000 V rated voltage (r.m.s. line to line)	Xs = 0.108546 p.u. (stator reactance)
750 A full load stator current (FLC)	Xr = 0.108546 p.u. (rotor reactance)
I_{LR} = 450% of FLC locked rotor current	Xm = 0.239496 p.u. (magnetizing reactance)
0.90 rated power factor	R1 = 0.033333 p.u. (rotor cage resistance)
0.971 rated efficiency	R2 = 0.006947 p.u. (deep bar rotor cage resistance)
156.24 rad/s (1492 r.p.m.) rated speed	X2 = 0.067133 p.u. (deep bar rotor cage reactance)
s = 0.53% rated slip	**Equivalent Circuit – Deep Bar Rotor Cage**
U_{min} = 70% of rated voltage min. allowable starting voltage	
t_{start} = 14 s max. allowable starting time	
T_R = 80000 N m full load torque (FLT)	
T_{LR} = 60% of FLT locked rotor motor torque	
T_{MAX} = 195% of FLT breakdown motor torque	
$T_{2\text{-}ph}$ = 731600 N m max. air-gap torque (2ph- fault)	
$T_{3\text{-}ph}$ = 601400 N m max. air-gap torque (3ph- fault)	
t_{LR} = 9 s locked rotor withstand time in hot thermal conditions (at 100% rated voltage)	

```
   Rs    Xs+Xr
-/\/\/\--0000-----------------
                 0       \    \
                 0       /    / R2/s
              Xm 0  R1/s \    0
                 0       /    0 X2
------------------------------
```

B. *Mechanical Equations and Data*

State variable equations for a single-shaft mechanical system are represented here below into matrix formulation [12]:

$$\frac{d}{dt}\left|\begin{matrix} T_K \\ w_M \\ w_L \end{matrix}\right| = \begin{bmatrix} 0 & K & -K \\ -\frac{1}{J_M} & -\frac{G}{J_M} & \frac{G}{J_M} \\ \frac{1}{J_L} & \frac{G}{J_L} & -\frac{G}{J_L} \end{bmatrix} \cdot \left|\begin{matrix} T_K \\ w_M \\ w_L \end{matrix}\right| + \begin{bmatrix} 0 & 0 \\ \frac{1}{J_M} & 0 \\ 0 & -\frac{1}{J_L} \end{bmatrix} \cdot \left|\begin{matrix} T_M \\ T_L \end{matrix}\right| \qquad (1)$$

where:
d/dt = mathematical first derivative with respect to time

Mechanical State variables:
T_K = torque on the shaft coupling [N*m]
w_M = motor angular speed [rad/s]
w_L= load angular speed [rad/s]
Mechanical Input variables:
T_M = motor torque [N*m]
T_L = load torque [N*m]

The mechanical parameters used into (1) are shown in the following table:

TABLE VI
MECHANICAL DATA

Parameter	**Numerical value**
Moment of Inertia of motor J_M	1200 kg m^2
Moment of Inertia of driven Extruder J_L	259 kg m^2
Shaft spring constant K	2 * 10^7 N m / rad
Shaft viscous damping G	8000 N m /(rad/s)
Extruder load torque only during motor start-up	14400 N m (18% of full load torque)

VII. ACKNOWLEDGMENT

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

VIII. REFERENCES

[1] A. E. Fitzgerald, C. Kingsley, S. D. Umans, *Electric Machinery*, McGraw-Hill, 1990.
[2] T. A. Hauck, "Motor Reclosing and Bus Transfer," *IEEE Trans. On Industry and General Applications*, vol. IGA-6, No. 3, May/June 1979.
[3] R. H. Daugherty, "Bus Transfer of AC Induction Motors: A Perspective," *IEEE Trans. On Industry and General Applications*, vol. 26, No. 5, Sept./Oct. 1990.
[4] S. S. Mulukutla, E. M. Gulachenski, "A critical survey of considerations in maintaining process continuity during voltage dips while protecting motors with reclosing and bus-transfer practices," *IEEE Trans. On Power Systems*, vol. 7, No. 3, Aug. 1992.
[5] J. Gardell, D. Fredrickson, "Motor Bus Transfer Applications Issues and Considerations," J9 Working Group Report to the Rotating Machinery Protection Subcommittee of the IEEE-Power System Relay Committee, May 2012.
[6] T. R. Beckwith, W. G. Hartmann, "Motor Bus Transfer: Considerations and Methods," *IEEE Trans. On Industry Applications*, vol. 42, No. 2, March/April 2006.
[7] T. E. Baker, *Electrical Calculations and Guidelines for Generating Stations and Industrial Plants*, CRC Press, 2012.
[8] A. Leiria, P. Nunes, A. Morched and M. T. Correia de Barros, "Induction Motor Response to Voltage Dips," in *Proc. IPST 2003 – International Conference on Power Systems Transients in New Orleans, USA*.
[9] H. W. Dommel, *EMTP Theory Book*, Microtran Power System Analysis Corporation, Vancouver, Canada, 1992.
[10] *Alternative Transient Program (ATP) - Rule Book*, Canadian/American EMTP User Group, 1987-92.
[11] Rotating electrical machines, Part 1: Rating and performance, IEC TC2 Committee Draft Standard 60034-1, June 2015.
[12] W. W. Seto, *Mechanical Vibrations*, McGraw-Hill, 1964.