Modelling the Electrical Drive System for Oil Exploitation

A.C.S. de Lima[†], R.Stephan[†] and J. Mourente*

[†]COPPE/UFRJ
Federal University of Rio de Janeiro
Department of Electrical Engineering
P.O.Box 68504 Rio de Janeiro
21945-970 RJ Brazil

*Cenpes
Petrobras Research & Development Center
Basic Design Division
Rio de Janeiro
21949-900 RJ Brazil

Abstract— **This article deals with the modelling of a drive system used in the Oil Industry. First we present the models used to represent the electrical and mechanical parts of the system. This type of system has very long motor leads, these leads can produce several electromagnetic effects in the motor terminals. In order to have a better assessment of the system behavior a simple model to represent frequency dependent parameters of the electrical cable is proposed. The induction motor used here is different of the known industrial types, its characteristic will also be discussed. A digital model of the system was implemented with EMTP. The model is validated through experimental tests made in an oil platform. To improve the system performance a new configuration is proposed.**

Keywords: Electrical Drive System, Oil Exploitation, Induction Motor, EMTP

1 Introduction

The semiconductor development enabling high frequency switching has improved the performance of pulse-width-modulated (PWM) inverters for driving induction motors, becoming an attactrive option to be used in the oil industry. The Variable Speed Drive System (VSD) can increase oil exploitation by controling the motor speed. So, the VSD is an important tool to give more flexibility in well production, although its use implies the appearance of current and voltage harmonics. In special due to the long length cable, voltage reflection can occur and the motor terminal voltage can be very high.

Some countries have oil prospecting in deep water, this subsea system consists in the use of Electrical Submersible Pumps (ESP) directly in the well. In Brazil, this type of extraction was the main reason that launched the oil production. One very peculiar concern for this type of system is its inaccessibility. After installed we can not access the motor windings or its rotating parts. Further the long cable length demands a special care in the modelling issue, simple cable models with lumped parameters will give answers far from reality. When working with power electronics system, one approach is to analyze the system frequency response. The problem with this approach is that the system must be linearized, and non-linearities, such as motor saturation could not be represented. Instead of that, we chose to study the system by time domain simulation, obtaining directly from the simulation the voltages and currents waveforms. If we had chosen a frequency analysis, to acquire the system non-sinusoidal waveforms would be very time consuming since all (or almost all) harmonics must be taken into account. System digital simulation was done under EMTP. In spite of EMTP was made for power system applications, it has shown good flexibility to represent power electronics systems. Its well-known capability to represent cables and all power parts of the plant makes it an attractive tool to be used in systems with power electronics and industrial power items, turning possible to build detailed models for each system component, from the power semiconductor to the mechanical load. A comparison between platform measurements and simulation results is made in order to build an accurate system model.

The use of power electronics inverter is only beginning in this area and they operate in open loop since we can not use any information about the motor speed. So, it is necessary to improve the knowledge, the efficiency, and to try to develop cheaper system configurations, because the high cost involved whenever a fault happens place a premium on reliability and rating accuracy. Nowadays oil companies world wide are reaching out the know-how to handle this type of exploitation. Among this companies, Petrobras, the Brazilian company, was the first to use submersible centrifugal pumps when the oil well is far from the platform. Suggestion for a new system configuration when the motor is supplied by a static frequency converter located some kilometers apart is given.

2 System Description

In Fig. 1 we have the schematic of the drive system, we can see that this system is very unusual if compared with the conventional industrial ones. Despite the production improvement, the inverter can cause electrical problems, such as harmonic resonance in long feeders and also it can produce mechanical problems due to the interaction between system mechanical parts and the harmonic torques (with complex modes of vibration involving internal movements of motor and pump).

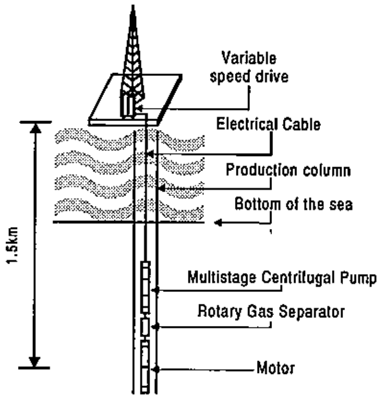

Figure 1: The Drive System

The system consist of an isolated gas turbine group producing 13.8kV at 60Hz. There is a step-down transformer with the ratio of 13.8:0.480kV that connects the generator to the static converter, as usual the static converter has a rectifier and an inverter. The rectifier is an uncontrolled three-phase six-pulse bridge one. The inverter is a VSI-PWM working near its maximum output voltage, so it will behave almost like a Square Wave VSI. There is a step-up transformer with the ratio of 460:1050 V, this transformer is specially built for this application having a very high saturation knee. The cable that connects this transformer to the motor is about 1.5 km long.

3 Induction Motor Model

The ESP motors designed for use in deep oil well applications are, in essence, induction motors with unusual electrical and mechanical parameters. They consist of the association in tandem of small rotors cooled by internal and external oil flows. The motor diameter is about 20cm and its length is about 15m. Some works that have modelled a boosting system like [11] uses the motor as a sinusoidal voltage with fundamental frequency behind an impedance. Although this model is usually found in the literature, it cannot infer anything about the harmonics effects in the torque and in the motor windings. We believe that a detailed model able to represent the motor in wide range is needed. The ESP motor is modelled using the general machine theory. It uses the Park Transformation adopting a d-q-0 rotating frame with angular speed equal to the mechanical one.

The ESP motor was represented by the Universal Machine (U.M.) Module. This module is just for the solution of the equations that describe the electromechanical energy conversion in the machine. So, it needs an interface with EMTP. Currently, there are two types of interface, prediction and compensation. The first method is based upon the prediction of the stator voltages at any time step, once the machine variables are known from previous time steps. In the second method, each subnetwork connected to the U.M. module is replaced with its Thevenin equivalent circuit at the machine terminals.

3.1 Model of the Electrical part

In the case of VSD system the motor works in an environment with harmonic distortion in the voltage as well as in the current. Such type of operation requires special care in modelling for simulation. In order to take skin effect into account, some modifications in the induction motor classical d-q-0 model must be done. In the motor, the vector current density (J) will be a function of the cage deep. Making parallel associations of different conductors with different current distribution, we can approximately represent this situation, as shown in Fig.2. It will lead us to a ladder type equivalent circuit for the rotor as shown in Fig.3.

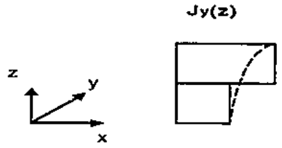

Figure 2: Skin effect in the rotor

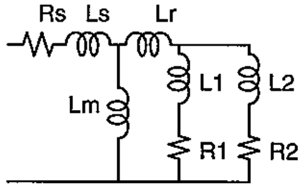

Figure 3: Ladder type circuit for Induction Motor

Rogers and Shirmohammadi developed in [9] a data conversion algorithm that can be used to obtain the induction motor parameters. One of the advantages of this algorithm is that it requires as input available motor data such as rated efficiency, rated power factor, nominal slip. The equivalent circuit of the induction machine that we have used in this paper is slightly different from the one we obtain with the data conversion algorithm. We have put the coupling inductance L_r in the rotor cages, thus the model is similar to a double cage one. We recognize the fact that using the simpler model we do not reproduce the rotor current distribution of the more complex model that includes additional coupling between circuits in the rotors and some minors errors in transient torque calculations are expected.

In several applications magnetic saturation has negligible effects on the motor performance. On the other hand, in the boosting system there are cases in which saturation plays an important role. One of these cases is when a gas bubble comes together with the oil, which makes the load torque lower and tend to saturate the motor. The inductances L_s , L_r, L_m, shown in Fig. 3,can be affected by magnetic saturation. These inductances have different degrees of saturation depending on the magnitude of currents that flow through them. Although the conversion algorithm accounts for saturation effects in the leakage path. In this work, only the saturation in the main magnetic path was modelled, using the two-slopes (piecewise linear) flux versus current curve.

3.2 Model of the Mechanical Part

The submersible pump (ESP) used here is a centrifugal one. In terms of size and length, the pump is very similar to the ESP motor. Due to its long length, an ESP motor and the ESP itself cannot be threat as a single mass system. As a first attempt, we have modelled the mechanical part as a two mass system. The EMTP uses electrical equivalents to represent the mechanical system. In this circuit, the electromagnetic torque will be a current source, the inertia will be a capacitor, the mechanical coupling (spring constant) will be a reciprocal of inductance, and the damping coefficient will be a conductance. Figure 4 shows the equivalent circuit used here.Since the ESP is a crentifugal pump, its torque characteristic can be represented as being proportional to the speed square, except for very low speeds, where it can be considered constant. This is done in EMTP via a voltage controlled current source.

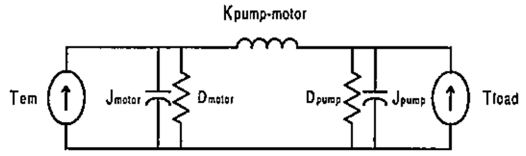

Figure 4: Equivalent circuit for the mechanical network

4 Electrical Cable Model

The subsea cables are specially designed to work in depths up to 1000m to feed ESP motors. These cables are one of the most expensive part in oil boosting system with VSD. Furthermore, long cable length contributes to a damped high frequency ringing at the connection with the motor terminals. This happens due to the distributed nature of the cable leakage and coupling capacitance which cause overvoltages increasing the associated stresses upon the motor. The pulses generated by the PWM-inverter behave like travelling waves on transmission lines. PWM pulses travel from the inverter to the motor, while backward travelling waves move toward the inverter due to voltage reflection. The reflected wave will be identical to the incident one times the voltage reflection coefficient.

The cable length is a crucial point here. In conventional system a long cable would have nothing more than 100m, though in oil pumping system it is normally higher than 1km. That is the reason why a very detailed model is needed. Ideal distributed lines will give conservative results far from reality, and lumped π-circuits could even lead to wrong responses. A simple but frequency dependent model was built. It is strongly based in the idea proposed by Castelhanos and Marti in [3]. All losses are lumped, and it frequency variation is taken into account via a simple series RL circuit. The cable inductance and capacitance are represented by an ideal distributed line, where we neglected the change in inductance due to the variation with the frequency, fig. 5 illustrates the idea. This simplified representation has some drawbacks because it can only represent accurately the cable up to a few kHz. A precisely cable representation would require far more complex models such as idempotent model [3]. The cable data was obtained through a comparison between the manufacturer data and the results of EMTPs subroutine CABLE CONSTANTS. The the cable is 1.8/3kV,#2 AWG.

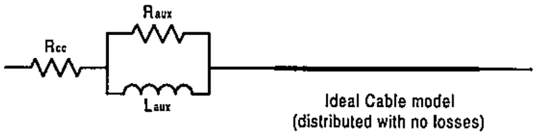

Figure 5: Cable Model

5 Digital Simulation

The power supply (a gas turbine generator and step-down transformer) was represented by a voltage source in series with a reactance. This reactance accounts for the system short circuit level and the transformer series impedance. The inverter was built, in EMTP, in a way that could give a detailed model of the switch. A switch cell was developed to investigate the switches behavior, instead of having EMTP type-13 switch representing the power semiconductor and the anti-parallel diode. This cell is shown in fig. 6, all resistors are linear and are used to represent conduction losses. The user can easily use nonlinear resistors in the place of the linear ones and then represent more accurately the losses.

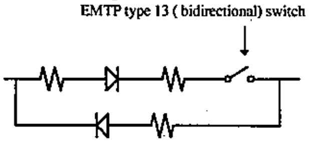

Figure 6: Switch Cell

Figure 7 illustrates the system model built in EMTP. The step-up transformer consists of interconnected single-phase saturable units represented by the standard EMTP transformer model. The motor modelled is a 950V, 100hp, two-poles motor. The inverter is an IGBT one with 460V nominal . The system is working in 66 Hz and the switching frequency is about 198 Hz.

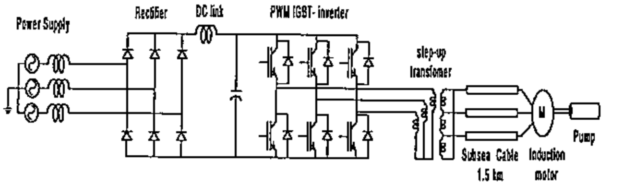

Figure 7: Schematic of the System

Fig. 8 and Fig. 9 show the simulated line-to-line voltage for the step-up transformer in the secondary and in the primary side respectively. In fig. 10 we see the simulated current for secondary side of the second transformer. In fig.11 we see the motor current, it can be noted that this current is far from being sinusoidal, thus the electromagnetic torque will have a considerable ripple. Once the voltage supply is a PWM (or square-wave) inverter a complex waveform for the motor torque is expected. This torque will have ripple in steady state and this is even more important for the ESP motor since its inertia is very low. Thus the ripple in the torque can lead to very unexpected situations as low order resonances in the motor shaft. Fig.12 shows the voltage at the motor terminals. As expected, the motor terminal voltage will have higher oscillations than the voltage at the cable input, this is due, to the voltage reflection at ESPM terminals.

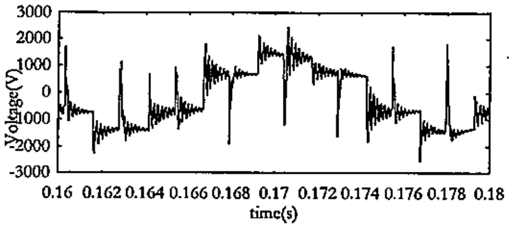

Figure 8: Transformer line voltage at secondary

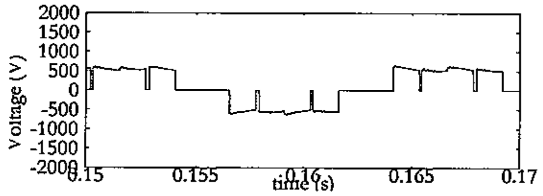

Figure 9: Transformer line voltage at primary

6 Experimental Results

The experimental verification was done in an oil platform belonging to Petrobras. The well is located in the Campos Basin. The voltage and the current in the transformer were measured with a Tektronics 2440, 2 channel oscilloscope. The voltages were measured directly from the step-up transformer terminals, while the current was measured via average current transformers. Fig. 13 and fig. 14 shows the transformer line-to-line voltage in the primary and secondary side, and fig. 15 shows the current in the high side of this transformer.

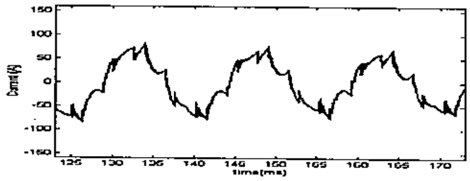

Figure 10: Transformer current at secondary

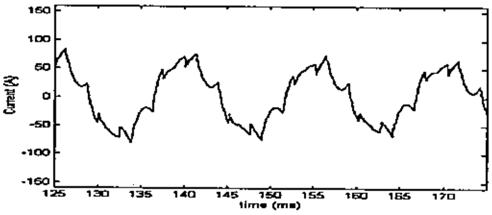

Figure 11: Motor current

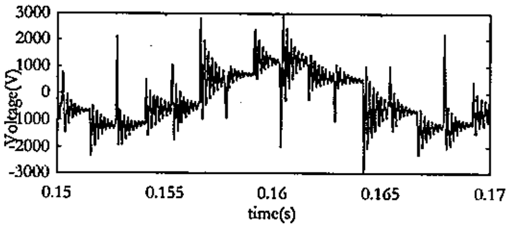

Figure 12: Motor Voltage

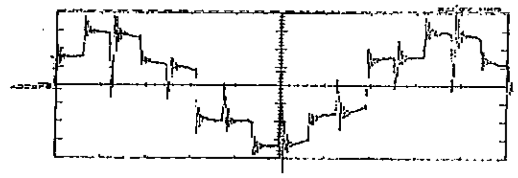

Figure 13: Line voltage at the secondary side
vertical scale: 500V/div
horizontal scale: 2 ms/div

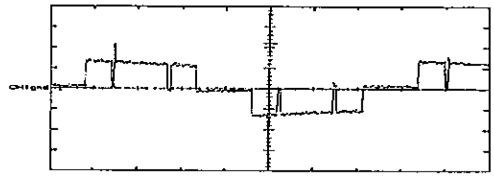

Figure 14: Line voltage at the primary side
vertical scale: 500V/div
horizontal scale: 2ms/div

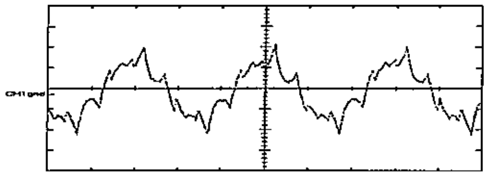

Figure 15: Line current at the secondary side
vertical scale: 40A/div
horizontal scale: 5ms/div

7 New Proposed System Configuration

The new proposed system consists of changing the PWM-VSI for a current regulated (CR-PWM-VSI)one . This type of equipment can produce currents almost sinusoidal and since all power items (cable and motor) are designed to work with sinusoidal variables, it can improve the system performance. In order to make a comparison with the actual configuration, the adaptive PWM was put in the same system as in item 5. The maximum switching frequency of the adaptive PWM was set in 7kHz. Fig. 16 and Fig. 17 show the current and the line voltage in the secondary side of the step-up transformer. Fig. 18 gives the motor current, we can see from that figure that it is almost sinosuoidal. The advantages of the new configuration can be easily seen in the comparison of the electromagnetic torque produced by a VSD with conventional PWM, and one having the adaptive one. In Fig.19 and fig.20 we have the (simulated) electromagnetic torque for the case described in item 5 and the one described here, respectively. As we can see the torque pulsations in conventional system are much higher.

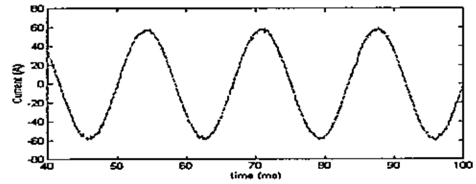

Figure 16: Current in the transformer with CR-PWM-VSI

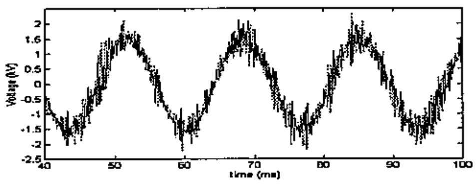

Figure 17: Transformer line voltage with CR-PWM

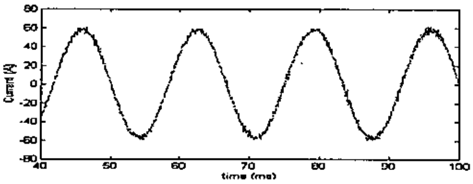

Figure 18: Motor current with CR-PWM

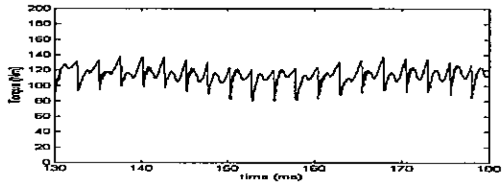

Figure 19: Eletromagnetic Torque for the convenctional system

8 Conclusion

The behavior of an ESP motor supplied by a remote frequency converter has been presented. This system is typical in the offshore oil industries. Simulation results were compared with experimental ones in order to validate a system model. There is a good agreement between simulations and experimental results.

We observed that all simulated waveforms were more conservative than the experimental ones, this is due to the simplifications done in the model. If the cable were represented more accuratelly, it would have a higher impedance and the voltage and the current oscillations (and spikes) would be lower. Other possible cause for the difference is the frequency response of current transducers (CT) used to measure the current.

A new configuration has been proposed and the simulation results seems to indicate that it could be used to improve the system performance. Laboratories propototypes can be constructed in order to validate the model before field mesurements.

A lot of work is yet to be done concearning the modelling of the ESP motor and the subsea cable. Models like the Idempontent Line model seems to be the best solution for the eletrical cable, but for the ESP motor we need some tests to see how accurate is the conversion algorithm for this motor. The algorithm has proven to be realiable when dealing with NEMA class induction motors, but untill today we cannot surely say the same for the case of ESP motors.

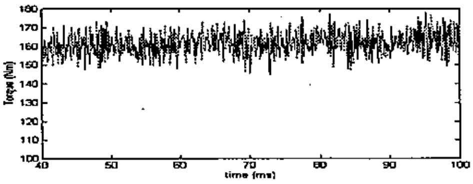

Figure 20: Eletromagnetic Torque for the proposed system

References

[1] A.C.S. Lima et al., "Analysis of a Long Distance Drive for an Induction Motor ", *Proceedings of the IEEE International Symposium in Industrial Electronics* ISIE'96, pp.867-872, Poland, 1996.

[2] H.W. Dommel and R.Hung, "Synchronous Machine Models for Simulation of Induction Motor Transients", *IEEE/PES Summer Meeting,* 1995.

[3] F.Castelhanos, J.R.Marti,"Phase-Domain Multiphase Transmission Line Models", *Proceedings of IPST '95*, pp.17-21, Lisboa, Portugal.

[4] G.A. Capolino and J.A. Martinez, "Teaching Rotating Machine and Electrical Drive Performances Using The EMTP", *Proceedings of EPE95*, Spain

[5] P. Krause, *"Analysis of Eletric Machinery"*, Mc Graw Hill, 1986.

[6] W. Magalhães et al.,*"Relatorio acerca de sobretensão no sistema de BCS com uso de variador de velocidade",* Petrobras Technical Report [in Portuguese], 1994.

[7] M. Kazmierkowski and H. Tunia, *"Automatic Control of Converter Fed Drives",* Elsevier, 1994.

[8] M. Paterson, "On the Efficiency of Electrical Submersible Pumps Equipped with Variable Speed Drives: A Field Study", *Production Operations Symposium,* OK, U.S.A., 1993.

[9] G.J.Rogers and D.Shirmohammadi, "Induction Machine Modelling for Electromagnetic Transients Program", *IEEE Trans. Energy Conversion,* vol.EC-2, pp.622-628, Dec.1987.

[10] J.Oliveira et al., "Electrical Transmission System with Variable Frequency through Long Length Cable", *Proceedings of Offshore Technology Conference (OTC),* Houston, USA. 1996.

[11] R.Rad et al., "Converter Fed Sub Sea Motor Drives", *Procedings of IEEE IAS Anual Meeting,* pp.394-401, vol.1, 1995.

[12] A.C.S.de Lima,"Análise do Sistema de Acionamento para Produção de Petróleo",*M.Sc. Thesis* [In portuguese], COPPE/UFRJ, Fev.1996

[13] A. Jouane et al., "Filtering Techniques to Minimize the Effect of Long Motor Leads on PWM Inverter-Fed AC Motor Drive Systems ", *IEEE Trans. on Industry Applications,* vol.32, no.4, 1996.