On Studying Ship Electric Propulsion Motor Driving Schemes

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Abstract – In this paper, an effort is made to identify the problems encountered during studying and modeling ship electric propulsion schemes. It is shown that where no existing models are available in programs like ATP/EMTP, new ones can be developed, with the new ones being able to co-operate with the rest of the computer package. In this way, several phenomena can be studied like those related to power quality on shipboard.

Keywords: ship propulsion, electric motors, converters, motor drives, power quality, EMTP

I. INTRODUCTION

Electric propulsion has been applied to ships via DC motors for more than a century offering effective maneuverability, precise and smooth speed control, reduced space machinery, low noise and low pollution rates [1-11].

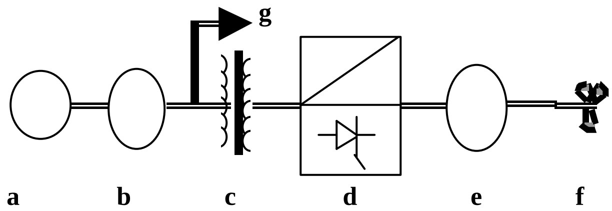
The advent of the great evolution in the power electronics domain offered the means for efficient AC machines control even in the case of the large scale ones implemented in ship propulsion. The current practice has already integrated synchronous and inductive motors of up to 25 MVA rated power in almost every type of ship [1-11]

Meanwhile the integrated ship electrification is identified in the current trends where the All Electric Ship (AES) - esp. referring to warships – are under construction [1-4,7-8]. In brief, in such a ship every energy demand is met by electric energy conversion.

In this paper, an overview of the techniques applied to the AC electric propulsion field is done, while the interest is focused on ways of modeling all related components in order to perform analysis of power quality problems emerging from the application of power electronic schemes. The prospective application of EMTP-like computer programs [12-14], for the simulation and study of the related phenomena is investigated and discussed. Furthermore, the quality of the power supplied both to the propulsion motor and the rest of the electric network is examined. Representative study cases of actual 5kV/10 MVA propulsion schemes are considered.

II. SHIP ELECTRIC PROPULSION SCHEMES

A typical arrangement of the electric network of a ship with electric propulsion motor is shown in Figure 1.



- **a.** prime mover (Diesel engine or Natural Gas/COGEN)
- **b.** synchronous generator
- **c.** power transformer
- **d.** motor drive (frequency converter)
- **e.** motor (synchronous/inductive)
- **f.** propeller
- ***g*.** other load demands (pumps, winches, lighting etc)

Figure 1 Typical electric propulsion scheme

In the following, the components presented in Figure 1, are further explained.

A. Power Generation

Power generation is accomplished via 2-4 synchronous generators each one of which is capable of covering more than 50% of the installed load (this multiple redundancy is common to all ships for increased power availability and robustness purposes). The prime movers of these generators are most frequently diesel-engines or sometimes COGEN gas turbines [3,9] with the exception of submarines, where fuel cells or nuclear power can be used instead [6].

B. Propulsion Motors

Most frequently, there are one or two main propulsion motors depending on the type and size of the ship. In the past, DC motors have been used to quite a significant extent. However, as it is widely known, DC motors are the least advantageous propulsion machines due to their increased size, weight, cost and maintenance requirements. Anyhow, DC motors are still exploited especially in submarine applications where they match better with the Air Independent Propulsion (AIP) schemes in conjunction with batteries and fuel cells [6].

In order to suppress further the DC-requirements, decreasing also the needs for brush-gear maintenance, two different trends have been evolved:

Exploitation of Induction (asynchronous) machines, which in turn means improvement in the speed control domain of the converter [5, 15-18]

Permanent magnet synchronous motors (PMSM), which implies besides ameliorated efficiency of the motor drives, non-expensive magnet materials. Rare earth magnets NdFeB (Neodymium Iron Boron) alloy seems to be the key-magnetic material dominating these applications. [7,8,19]

C. Motor drives - Converters

AC-motor drives comprise one of the following converters [1-11,15-16,20-21]:

Sinusoidal Pulse Width Modulators (SPWM): the widely-known converter consisting of an uncontrolled rectifier in series to an SPWM-driven inverter [15-16,20], see Figure 2. They are used in high speed propulsion applications (often in combination with a reduction gear) and in particular in low rated power motor cases (below 5 MW).

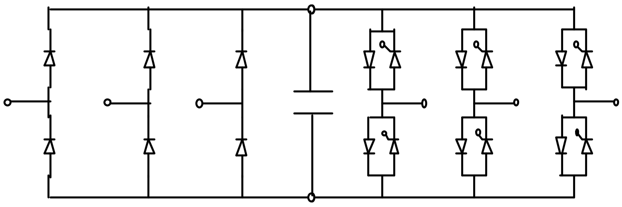


Figure 2. Typical 3-phase SPWM converter comprising a rectifier and an inverter (the capacitor in the middle ensures the good quality of DC voltage)

Cyclo-converters: the most complicated and recently-developed converter. They are used in cases where both slow speed and high power are needed [15-16]. A typical 12-pulse scheme comprising three 12-switch bridges, one for each phase, is shown in Figure 3. In ship propulsion cases, output frequency is a small portion of input frequency and directly proportional to the propeller speed.

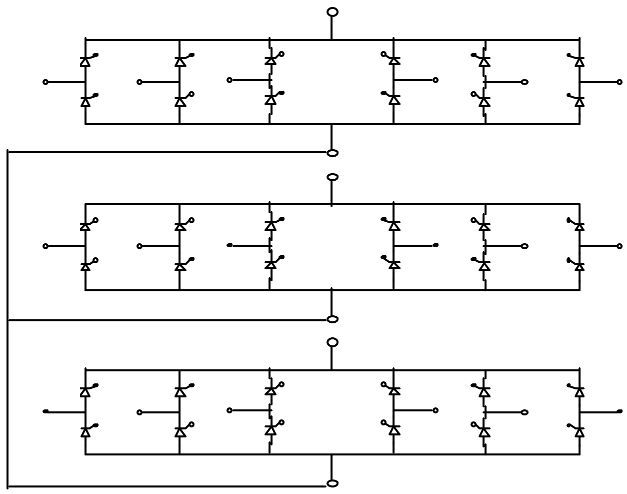


Figure 3. Typical 3-phase 12-pulse cyclo-converter

Synchro-converters: the simplest and less used driving scheme comprising load commutated converters. They are applied only to synchronous machines and are in general used where slow propeller speed is required.

Referring to control systems of the converters described above, there have been three main approaches followed [15-16]:

i) Pulse Width Modulation Control
ii) Flux Vector Control
iii) Direct Torque Control (DTC)
with the latter being the most recently developed and most promising technique

III. MODELING PROBLEMS IN EMTP PROGRAMS

In an attempt to study network applications similar to that of Figure 1, an investigation of the modeling capabilities of electric ship propulsion components in ATP environment [12-13] is made, resulting in the following:

A major problem referring to machine models is the limitation to three-phase ones. Increased number of phases seems to be advantageous in many ways, [1-3] while extensions of conventional models based on Park's transforms have started being developed [22] but not yet incorporated.

Permanent magnet synchronous machines (PMSM) have no readily available model, although already existing ones can be modified and incorporate the PM feature as an equivalent current source supplying the excitation winding, [14,16]. However, further complicated but most promising machine designs like the transverse flux motors [3,16,19], can not be accurately modeled in EMTP.

Converters comprise quite often transformers with non-conventional winding connections like the polygon ones [21]in the attempt to reduce harmonic distortion. However, besides conventional star and delta connections no other type can be easily modeled.

Furthermore, converters comprise switches in parallel the operation of which could cause numerical noise under certain circumstances[12-13]. In most cases, these problems can be resolved resorting to small integration steps of the simulations. However considering that most of machine related phenomena have long duration, the resulting computer simulation times could be significantly long.

IV. SOLUTIONS PROPOSED

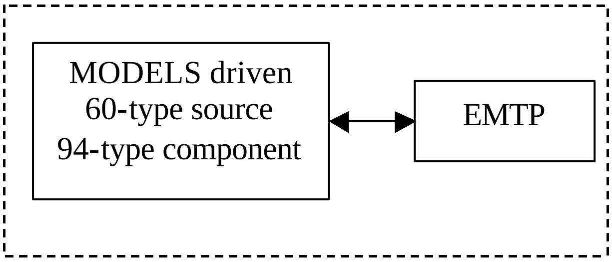
Considering the aforementioned modeling difficulties, several solutions have been sought in the ATP/EMTP environment. The finalized approaches followed are summarized in the following:

MODELS interface of EMTP provide the option of model-based integration step which can even be dynamically set [12-13,23].

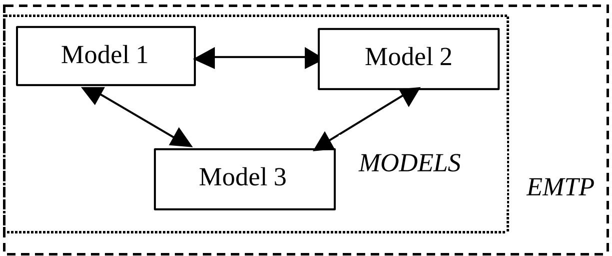
Should the non-ideal behavior of the converter switching devices is not of interest, ideal converter output can be produced directly by 60-type sources (MODELS/TACS controlled sources) [13].

Moreover, even machine models can be developed in MODELS environment [17] superseding any modeling obstacles raised by the UNIVERSAL MACHINE Module. Finally, the control system of the machine drives can easily be incorporated in MODELS [13,17,23]

In this way, an alternative approach, being currently under development, is the construction of a MODEL for each "problematic" type of equipment and incorporate it with the rest of the network modeled via ordinary EMTP Models, see Figure 4. 60-type sources and 94-type elements are the principal means towards this direction [13,23], Figure 4a. Furthermore, even the entire application can be built via MODELS, Figure 4b.



(a)



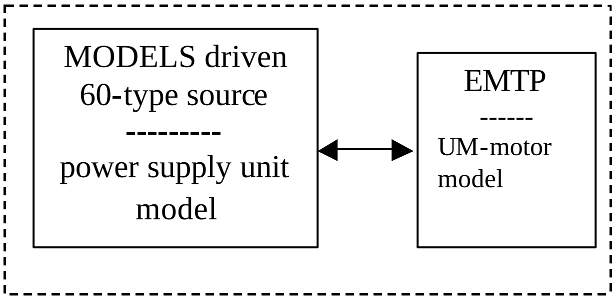
(b)

Figure 4. Alternative approach of EMTP simulations
- **(a)** Some components are modeled via MODELS
- **(b)** All components are modeled via MODELS

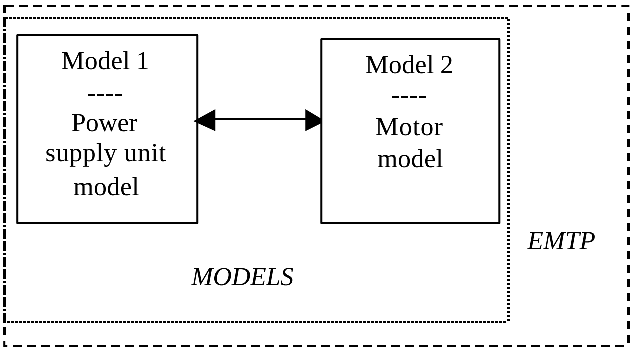
Concentrating on the components involved in ship electric propulsion schemes, the electric network upstream the propulsion motor, see Figure 1, comprising a voltage source, a power transformer and a power electronic converter can be modeled as a compact MODEL driving a 60-type source. The output of this MODELS-driven multi-phase source equals the converted power supplying the propulsion motor, see Figure 5a.

On the other hand, propulsion motor model can be created in two ways. Either by using the ordinary EMTP Universal Machine (UM) module configured as synchronous or induction machine, see Figure 5a, or by programming the relevant set of differential and algebraic equations into MODELS environment which is the only alternative, should the machine model is not supported by UM-module. In this latter case, the power supply unit does not drive any EMTP-source but provides its output directly to the motor model, see Figure 5b.

The application of the method shown in Figure 4 to the ship electric propulsion scheme is figuratively presented in Figure 5.



(a)



(b)

Figure 5. Alternative approach of modeling propulsion schemes in EMTP
- **(a)** Some components are modeled via MODELS
- **(b)** All components are modeled via MODELS

Furthermore, in this way of modeling via MODELS, both demands on the timesteps size are met: small timestep can be assigned to power converter MODEL whereas a fairly bigger timestep can be assigned to the motor MODEL.

IV. STUDY CASES

The problems discussed above have been encountered during the effort to represent actual ship propulsion schemes, comprising:

i) an SPWM-driven induction motor
ii) a cyclo-converter driven induction motor
iii) a cyclo-converter driven synchronous motor

Interest has been focused primarily on the correct modeling of both machine and converter and secondarily on the power quality (voltage and current harmonic distortion) downstream the converter.

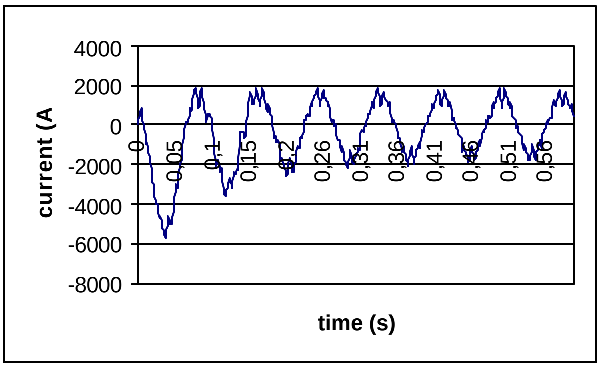
A. SPWM-driven induction motor

The technical features of the machine and its SPWM-converter are summarized in Table I.

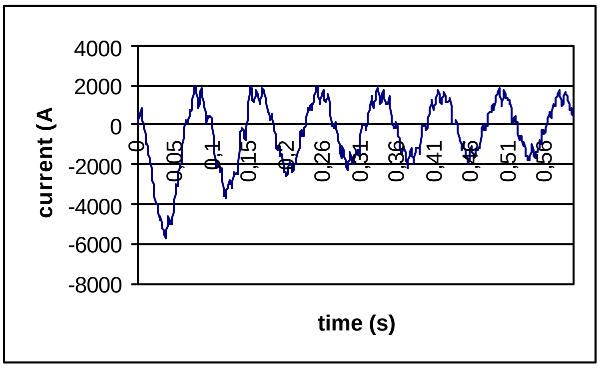
Table I. Technical data of 1st study case

Induction motor
3-phase, 12 Hz, 5kV/ 10 MVA Y, 4 poles
SPWM converter
Input Frequency, Output Frequency: 12 Hz
Amplitude factor:0.9, Carrier Frequency: 108 Hz
Scheme: see Figure 2

The induction motor is modeled via UNIVERSAL MACHINE MODULE and MODELS. In an attempt to show that new machine models can be developed and co-operate successfully with EMTP, the armature currents during starting-up of that motor, modeled in both ways, are compared in Figure 6a and 6b. The waveforms are almost identical.



(a)



(b)

Figure 6. Start-up current of SPWM-driven inductive propulsion motor (see Table I).
(a) induction motor modeled by Universal Machine model
(b) induction motor modeled by MODELS

Furthermore, considering the steady state operation of the system, the converter output voltage is shown in Figure 7, while the converter output (motor armature) current is shown in Figure 8. The current and voltage THDs are summarized in Table II.

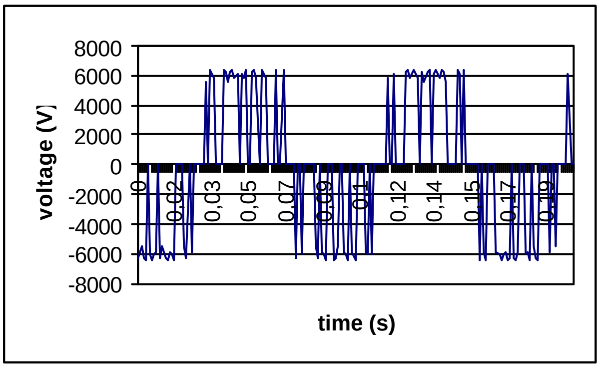


Figure 7. SPWM-converter output voltage (motor line-to-line input voltage) at steady-state operation of inductive propulsion motor (see Table I).

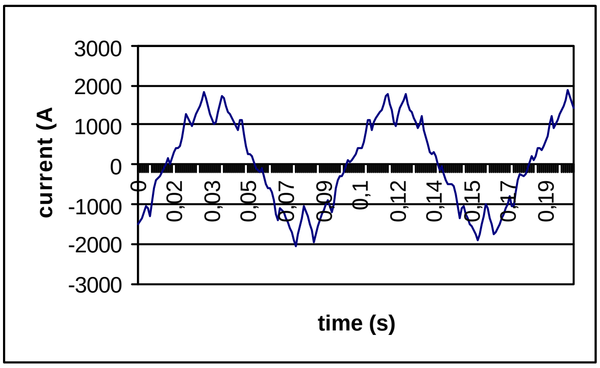


Figure 8. SPWM-converter output current (motor armature current) at steady-state operation of inductive propulsion motor (see Table I).

Table II. Harmonic distortion of 1st study case

Voltage THD	66%
Current THD	22%

B. Cyclo-converter-driven induction motor

The same inductive motor, see Table I, is studied using a 12-pulse cyclo-converter the characteristics of which are shown in Table III. The converter output voltage is shown in Figure 9, while the corresponding current (motor armature current) is shown in Figure 10. The voltage and current harmonic distortion are summarized in Table IV.

Table III. Technical Characteristics of cyclo-converter of 2nd study-case

12-pulse cyclo-converter (12 IGBTs per phase)
Input Frequency: 50 Hz
Output Frequency: 12 Hz
Scheme: see Figure 3

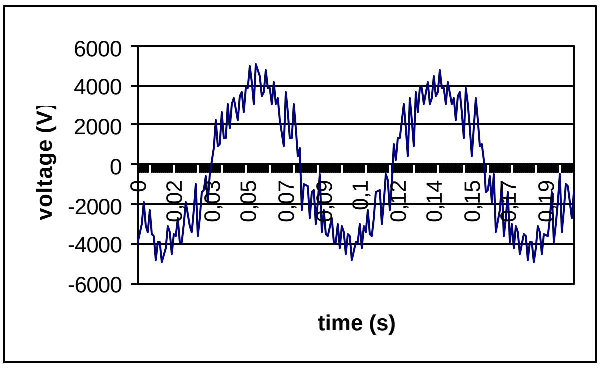


Figure 9. Cyclo-converter output voltage (motor line-to-line input voltage) at steady-state operation of inductive propulsion motor (see Table III).

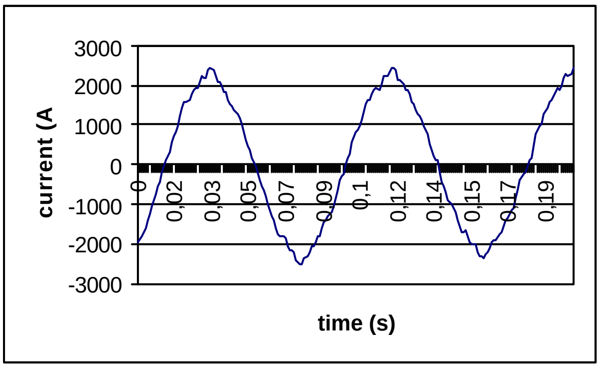


Figure 10. Cyclo-converter output current (motor armature current) at steady-state operation of inductive propulsion motor (see Table III).

Table IV. Harmonic distortion of 2nd study case

Voltage THD	24%
Current THD	13%

C. Cyclo-converter-driven synchronous motor

This study case comprises a synchronous motor driven by a 12-pulse cyclo-converter, see Table V. The converter output voltage is shown in Figure 11, while the converter output (motor armature) current is shown in Figure 12. The voltage and current harmonic distortion are summarized in Table VI.

Table V. Technical data of 3rd study case

Synchronous motor
3-phase, 5 Hz, 5kV/ 10 MVA Y, 4 poles
Cyclo-converter
12-pulse cyclo-converter (12 IGBTs per phase)
Input Frequency:50 Hz, Output Frequency: 5 Hz
Scheme: see Figure 3

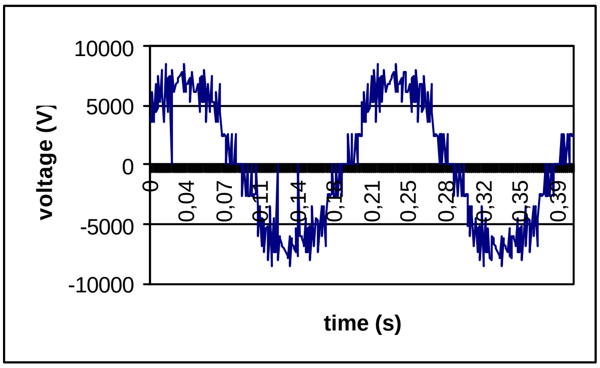


Figure 11. Cyclo-converter output voltage (motor line-to-line input voltage) at steady-state operation of synchronous propulsion motor (see Table V).

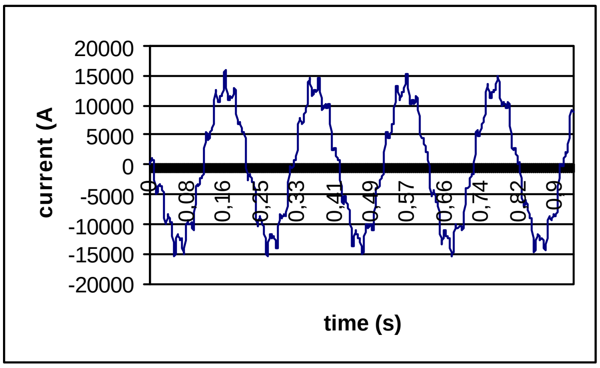


Figure 12. Cyclo-converter output current (motor armature current) at steady-state operation of synchronous propulsion motor (see Table V).

Table VI. Harmonic distortion of 3rd study case

Voltage THD	14%
Current THD	19%

Finally, in Table VII, the harmonic distortion of all three study cases is summarized for comparison purposes.

Table VII. Harmonic distortion of all study cases

Study case	**Voltage THD**	**Current THD**
1. SPWM+induction motor	66%	22%
2. cyclo-converter + induction motor	24%	13%
3. cyclo-converter + synchronous motor	14%	19%

VI. DISCUSSION

Considering the results presented above, the following conclusions are drawn:

- Machine models developed via MODELS can co-operate quite successfully with the conventional EMTP models. This conclusion is very useful for the development of complicated machine models in an individual manner and independent to the expansion of EMTP. The development of a multi-phase Permanent Magnet Transverse Flux Synchronous Motor model is one of the primary goals after this conclusion.
- As expected, SPWM produces greater distortion than the 12-pulse cyclo-converters [20,22]. On the other hand, the latter is more expensive and is used only when required.
- In general, considering that the voltage drop and power quality standards applied to ship electrical installations are less strict than those on the continental grids [11], the distortion levels of both voltage and current are relatively low, due to the efficient operation of both types of converters studied. This remark is more evident in all cyclo-converter applications.

VII. CONCLUSIONS

In this paper, an effort is made to identify the problems encountered during studying and modeling ship electric propulsion schemes. It is shown that even where no existing models are available in programs like ATP/EMTP, new ones can be developed and co-operate with the rest of the computer package. In this way, several phenomena can be studied like the ones related to power quality on shipboard. The introduction of power electronic devices in the propulsion motor driving systems generates voltage and harmonic distortion to the ship electric network, however, the application of sophisticated driving schemes like SPWM and in particular cyclo-converters reduces the problem considerably.

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