MODULAR TRANSVERSAL FLUX TUBULAR MACHINE – PRESENTATION AND PROGRESS ACHIEVEMENTS

Vasile-Ioan GLIGA, Dan-Cristian POPA, Vasile IANCU,

Technical University of Cluj-Napoca, 400114 Cluj-Napoca, 28 Memorandumului str., Romania
Email: gliga_vasile@hotmail.com, Dan.Cristian.Popa@mae.utcluj.ro, Vasile.Iancu@mae.utcluj.ro

***Abstract* – This paper proposes an interesting new type of tubular machine that can work like a tubular motor or a tubular generator. The machine's topologies for both operating regimes are presented here. In the paper a prototype of a tubular machine working as a motor, built from laminated sheet in stator and from soft magnetic composite material in core mover is presented. After a short analysis of the possibilities to control and drive a modular transversal flux tubular machines having active and non active mover, a driver and a control strategy are proposed. Different types of driver diagrams are presented, followed by the optimum solution adopted for experimental work. A system circuits consists of a power supply module, a converter module with current sensor, a programmable logic controller PLC and an equipped tubular motor, represent the experimental prototyping set-up. The implementation of the control strategy on a constructed laboratory model, allows validation of the results obtained via analytic and numeric field computations. The force values as function of mover position at various energizing currents were measured, and its profile was plotted. The innovative construction has very good performances and major advantages of the unique properties of the new soft magnetic composite material, Somaloy 700 HR, particularly the 3D magnetic isotropy. Some conclusions concerning the technical potential of the proposed machine are also presented.**

Keywords: *tubular machine, SMC core, unipolar driver, sensorless control.*

1. INTRODUCTION

Modular Transverse Flux Tubular Machine (MTFTM) is a novel transverse flux machine in modular construction [1], working using linear switched reluctance machine principle. Magnetic field lines, generated by stator coils, have transversal path regarding mover movements [2]. That explains the name of transversal flux machine.
Due to their behaviors, such tubular machines seem to be good solutions for precise industrial linear positioning systems, membrane pumps, healthcare [3], short track transfer system drives against other linear motors, tubular linear PM Ocean Wave Energy Generator [4,5], aerospace actuators, launching Systems in military or sports applications, electromagnetic valve actuators [6], transportation, vibrators or active shock absorbers [7], automotive actuator [8], etc. This paper presents the topology of MTFTM and a tubular motor.

2. MTFTM TOPOLOGIES

As function of topology, MTFTM can work like either motor or generator. In the first case, the machine can be with passive mover or with active mover, using NdFeB magnets. In the second case, when machine has generator function, an active mover must be used to produce energy [4,5].
The machine has a fixed armature or stator with coil on each tooth and a mobile armature or mover connected to a load. Mobile armature due translated movement left and right in successive step as a function of stator coil excitation.
Fixed armature, Figure 1, can have a number of phases, built from ferromagnetic core, having a number of radial teeth on which there are wound coils, separated with nonmagnetic ring spacer. Spacer's width is equal to mover pitch step to phase number rate.

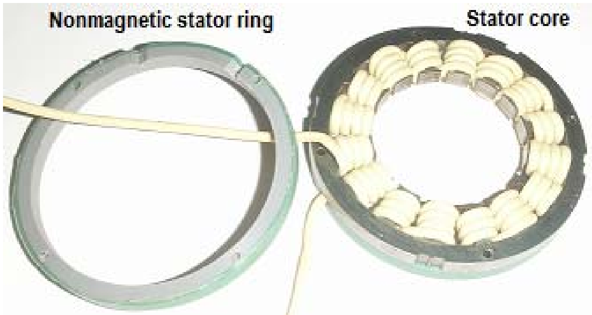

Figure 1: Nonmagnetic stator ring and stator core with coil

The number of phases is limited only by practical reason and driver sophisticated construction. 3 or 4 phases represent feasible solutions to build and drive the tubular machine.
Mobile armature, Figure 2, was built from a number of ferromagnetic rings having same width as stator core separated by nonmagnetic spacers. The rings must be assembled on a nonmagnetic shaft. The number of successive rings gives mobile armature length.
This mobile armature arrangement forces the field lines to close from a mover's transversal direction,

generating truth force between mover's ferromagnetic rings and stator cores.
Mobile armature have two degree of freedom, one is axial direction left and right, and second is verticity or pivoting motion. In this paper pivoting motion was neglected, but it is possible to design machine topologies and drivers having simultaneous translation and rotation movement, only by appropriate energizing of coils.

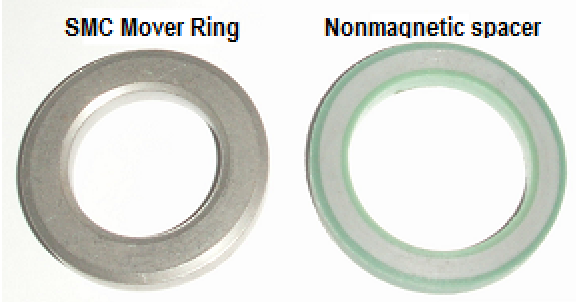

Figure 2: SMC Mover ring and nonmagnetic spacer

The stator and mover ferromagnetic parts can be made of laminations or soft magnetic composites (SMC).
To obtain a controlled continuous movement, the minimum number of phases required is three [1]. Each phase can be built from a number of modules, connected series or parallel. In order the machine to work properly, the stator's phases have to be shifted one from neighbored one by $k\tau + s_m + \tau/N, \quad k \in \aleph$. The necessary shifting between the modules is assured by corresponding non-magnetic spacers.
A three phase module of MTFTM with active mover is presented in figure 3.

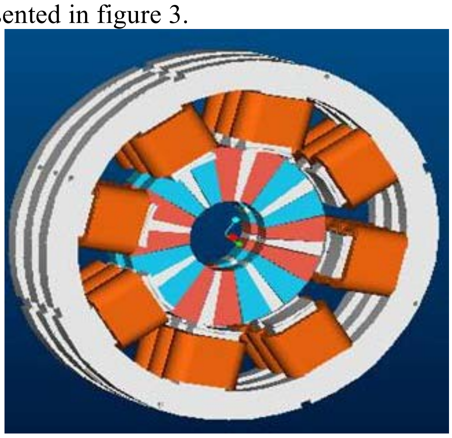

Figure 3: One 3- phase module of MTFTM with active mover

The normal force is about ten times bigger than the tangential one, but in the case of the tubular machines the attraction forces acting round all the circumference of the air-gap are totally balanced due to the machine's radial symmetry [6].
Therefore, the existence of only the traction force is one of the most important advantages of the tubular variant. The force is given, like in the case of the linear structure, by a single phase in case of non-active machines.
The 90 deg. section from MTFTM optimized narrow structure with two modules per phase, is given in Figure 4.

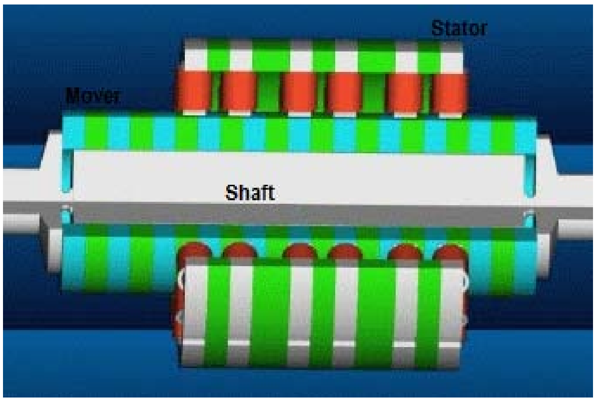

Figure 4: 90 Deg section from MTFTM

Using powder technology and major advantages of the unique properties of the new soft magnetic composite material, with 3D magnetic isotropy, particularly Somaloy 700 HR, price competitive tubular machines can be achieved.
In experimental work, two type of ferromagnetic powder were used: ANCORBOND 45P, mixed with 0,5 % in weight, KENOLUBE P11 Lot No: 3700000731 STD. L-434, supplied from HOEGANAES Corp. Germany, and Somaloy 700 HR process 1P supplied from Höganäs AB Suedia.
Different ring was compacted from both powders, at different compacting pressure, sintered at different conditions and tested to find the optimum producing parameters. For ANCORBOND 45P, the measured parameter' values, is presented in Table 1. The core losses, measured at 1000 Hz were considerable high.
Metallographic structure was realized as well.

Parameter	Sample 1	Sample 2	Sample 3
Pressure [bar]	170	190	210
Temperature [gr.C]	1120	1125	1130
HRB Hardness	32	46	61

Table 1: Parameters and theirs values

After Somaloy 700 HR sintering, graces to an accurate process, better values of measured parameters were obtained. The permeability's values of 6000 and fluxes of 2.1 T at 100 kA/m can be

achieved. The increased resistivity of ferromagnetic core reduces the core losses.
The advantages offered by this construction are the lower weight and cost, and the unsophisticated machines building technology.
Must be mentioned that, a large number of phases, respective a small width of each module give us a high precision movement.
A machine working as motor, constructed from two modules per phase, having 3-phase was presented disassembled, in figure 5.

Figure 5: Two modules 3- phase MTFTM disassembled

3. MTFTM DRIVERS AND CONTROL

MTFTM working as motor can have passive mover or active mover, using NdFeB magnets. The control and driver are different for each one. In the generator case, the polyphases must be bond to a rectifier, and then to a 3 phase inverter before to connect to the mains.
Because it is about a SRM machine, obviously it is need a driver, a position sensor and a controller of the mover parts [9]. Basically, a system controller contains three control loops: currents, position and force loop. Researches done to develop such a driver and controller [10], show that it is strongly need to control current flowing through the driver and compute the perfect moments to open and close it's switches, all, as function of mover displacement. It is quite clear that accurate position information of the mover is very important [11] for the control of the tubular motor, because, the right commutation sequences are decided based on accurate mover position, and that affects the performances of the machine. Two directions were developed. Firstly, use mover position transducers [9], like Hall sensors, optical encoder, etc. Because of precision advantages, most of the control diagrams have this kind of transducer. Secondly, use a sensorless driving method to compute mover position. Many such position sensorless control techniques were developed based on phase's currents and voltages or determined inductances parameters by injection of sinusoidal high frequency signals. An improved sensorless driving method for a SRM, using a phase-shift circuit technique is described in [12], and a sensorless closed loop position control, based on a FEM assisted estimator that use two extra coils near to the main coils are presented in [13]. Some sensorless techniques were patented [14].

3.1. Control diagrams for active mover

Different currents and speed control strategies [15] such as voltage control, PI control and hysteresis control can be applied to achieve the optimum movement, efficiency and precise positioning control.

To abrupt increase machine performances, power and his weight to power ratio, it must use the machine topologies with active mover, by using high power NdFeB magnets arranged as shown in Figure 3. All movers' magnets must be radial polarized. Mover can be built also, from magnetic rings with radial magnetic fluxes [16], segregate with non magnetic spacers. The magnetic rings must have the same number of pair of poles like stator.

The control can implement a very sophisticated complex strategy of IGBT firing. That helps us use both field directions to thrust and to pull the mover, increasing the motor's power and his efficiency.
In this case, the driver topology is designed to supply bipolar motor coil. The most appropriate electronic switch, for one phase of such application, is outlined in figure 6, and represents the so called H-Bridge.

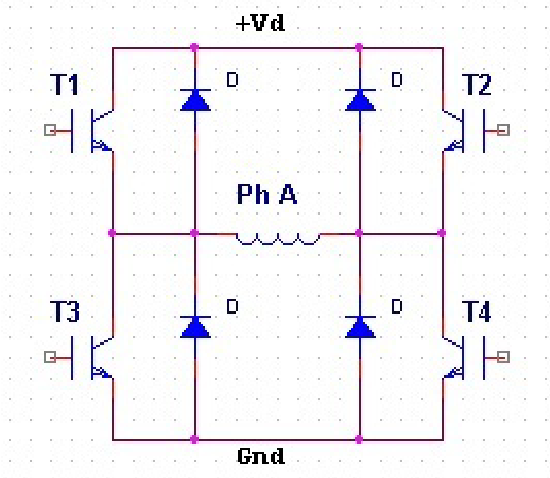

Figure 6: One phase of full H-Bridge converter

The switches used in the H-bridge must be protected from the voltage spikes, caused by turning off the power in a motor winding, by connecting high speed diode, in parallel with each of the switches.
Only active mover or active stator machine works like generator. The outputs of generator must be connected to the input of a polyphased rectifier, in accordance with his phase number, followed by 3-phases inverter. The system can have output

connected to a consumer's main or to national electrical distribution.

3.2. Control diagrams for SMC non-active mover

The machines with no active parts are simple, price competitive, and need unsophisticated assembly technologies. For this kind of motor, was used an unipolar driver.

To realize a controlled potential, for energizing the phase coils, we can use also, a converter driver (figure 7), with a buck converter in the front end [16,17,18]. This is a simple, practical, an economical power converter, derived from the classic converter and it holds similar characteristics to it, but with only one high-side switching device T_buck and one low-side synchronous low-side rectifier device Ts.

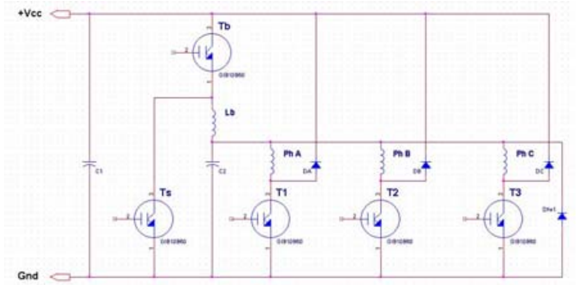

Figure 7: Converter topology with a synchronous buck converter on the front end

The optimum driver and control device were presented, in accordance with the building material and topology used for this kind of machines. In figure 8, was presented a two quadrant chopping converter topology [12], supplied from a tree phase AC network source.

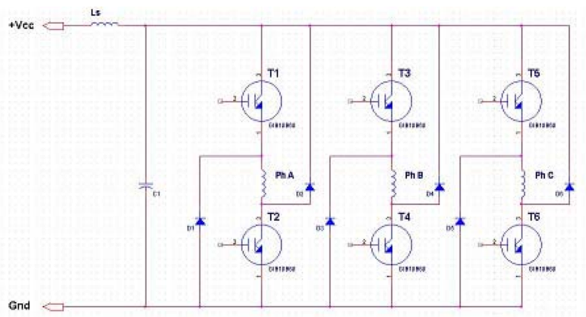

Figure 8: Two Quadrant synchronous chopping converter topology

4. EXPERIMENTAL PROTOTYPE SYSTEM

The system circuit consists of the following modules (figure 9):

a. 24 V dc power supply module;
b. converter module with current sensor and PWM;
c. programmable logic controller PLC;
d. equipped tubular motor.

The first module has two independent 24 V dc and 24 V dc regulated power supplies, used for the motor, PLC and driver supply.

Figure 9: Experimental prototype work

The schematic diagram used in our experimental prototyping work, is an improved unipolar driver shown in figure 10. It starts from a classical converter, and using a ground resistor Rs1, can control the currents flowing in each phases.

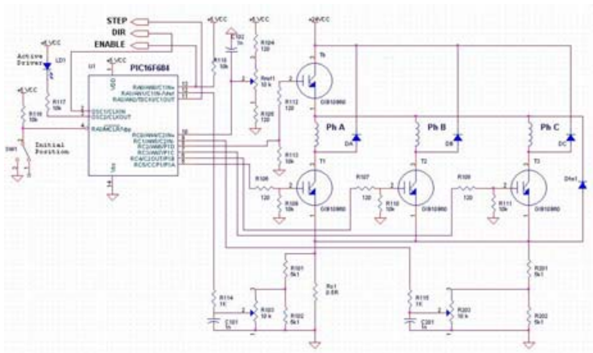

Figure 10: Schematic diagram used in experimental work

The phase coils were energized sequentially by switching appropriate IGBT transistors. The PCB board is a multifunction board that was equipped with 4 modules. Each module has two, three or four phases, ready to be used in experimental work.

The currents measured with a Fluke scopemeter is graphically presented in figure 11.

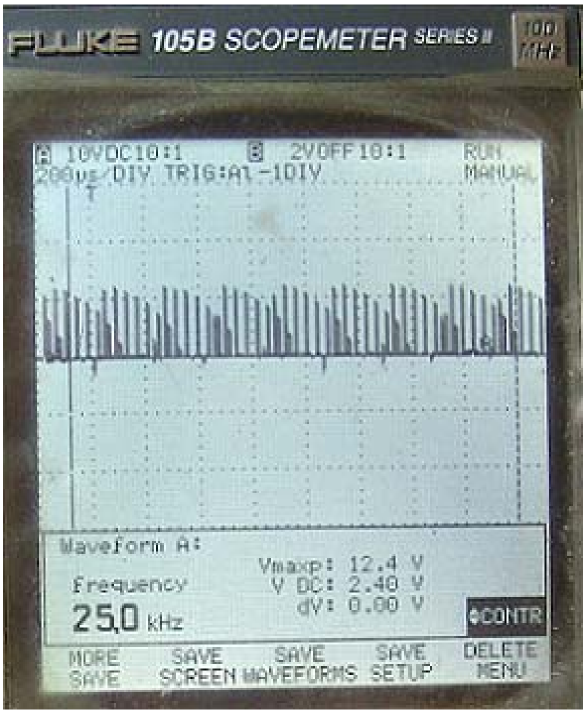

Figure 11: Graphical currents displayed on Fluke Scopemeter

The mover' movement is torque sensitive, with torque value trimmed by a potentiometer. Torque control algorithm with PWM function, kept constant trusth force in stationary regime. Also, the module implements a maximal current limiter, and a function named stationary current. This functions, limits the maximal currents flowing from motor and keeps the mover in an unmoved position, to avoid uncontrolled displacements (free wheeling).

The block diagram implemented in 16F684 PIC firmware is shown in figure 12.

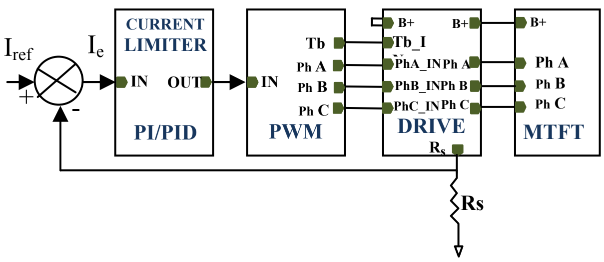

Figure 12: Block diagram of PWM current regulator

The PWM block is a 10-bit PWM, working at 20 kHz frequency. The firing pulses delivered, open and close the IGBTs from converter module, in such a way to obtain needed mover torque.

The PLC was connected to a laptop computer, and controls the speed stage and number of steps to move left or right. Approach speed to target position is settled with a separate potentiometer and starts with a number of steps, before the stop position, computed as a function of weight and load. The two-module 3-phase MTFTM, working as motor, was equipped with two inductive sensors, two mechanical springs and a load cell. The position sensors precisely detect the mover position by sensing the SMC mover rings. Improved accuracy was made by interpolate sensors. The force values as a function of mover position (figure 13) at various energizing currents were measured, and its profile is shown below.

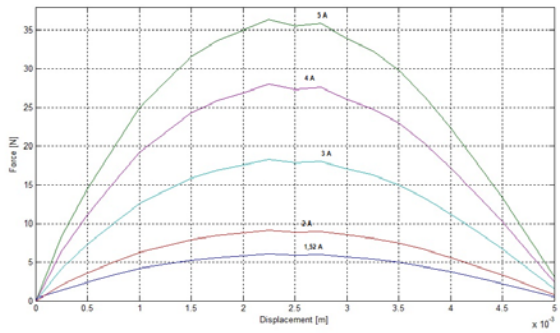

Figure 13: Force profile for proposed tubular motor at various energizing phase currents and positions

A mechanical spring was mounted at both mover ends, needed to discharge dynamic energy [17,18], and to avoid unexpected mover behaviors. As an option, we can use a separate magnetic springs [18]. Adequate firing angle of IGBTs, is capable to realize needed dynamic braking to precisely positioning of the mover. The dynamic braking mode coincides with the negative slope of the inductance profile.

Because we test an experimental work, a differential fuse and an Emergency Stop was implemented, for protection requirements.

5. CONCLUSIONS

The paper presents a new interesting type of tubular linear machine. The innovative construction, has very good performances and major advantages of the unique properties of the new soft magnetic composite material, Somaloy 700 HR, particularly the 3D magnetic isotropy [12,13].

The truth of the established design algorithm was proven both by analytic computation and by FEM analysis. The results were in good accordance with the initial estimations.

Due to their force / mass ratio such tubular machines has captured attention from specialists to be a new potential solutions for precise industrial applications.

Results of each test performed on the above mentioned condition, with experimental prototype looking like figure 6, are good. The firmware implemented in microprocessor has normally working and the currents flowing from each phases were trimmed by potentiometer, from 0.65 A to 5.2 A.

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