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Advanced exercise bike with an E-core transverse flux-machine

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Abstract**—***This paper presents a new motor design well suited for an advanced exercise bike. The advanced exercise bike setup high demands for performance and physical dimensions, which is high torque, wide speed range and a diameter/length ratio around 5. These requirements makes the new motor design called an E-core Transverse Flux Machine (ETFM) very interesting because the segmented design of the stator and rotor poles enables high diameter without increasing the flux-path and since the ETFM is similar to the switched reluctance motor, high torque and wide speed range is possible. The design of the ETFM can be performed using a developed design program, which is also introduced in the paper. A prototype of the exercise bike with the ETFM and a classical H-bridge converter with analog current control is constructed for verification of the concept.*

Keywords-component; Exercise bike, Transverse flux machine, switched Relcutance Manchine, Design program, torque control.

1. Introduction

Today there is a huge number of exercise/motion machines that exist in the fitness industry, where their primary purpose is to provide a method for the user to burn calories. The motion machines are typically used in the winter season, when the weather outside is not conducive for outside and "real" motion activities. A good example of a motion-machine is the exercise bike, where the idea is to imitate the riding of a bike. The success for that in real commercial motion machines is reasonable, if riding a bike just is to rotate some pedals under friction. The friction on commercial exercise bikes, which in the real world is controlled by the terrain and weather, like wind, is normally controlled manually with a handle. Depending on the commercial bike a friction band is tightened up or a row of permanent magnets is moved closer to a steel plate, which gives higher iron-losses in the steel plate. In the most advanced exercise bikes the permanent magnets are replaced with an electro-magnet, which makes electronic control of the eddy-current/hysteresis brake possible. Common for all available motion bikes is that only friction can be applied, where for example the experience of downhill acceleration can't be emulated.

In commercial exercise bikes is it quickly observed that they are constructed with a flywheel (inertia) with the purpose of filtering the pulsating torque from the rider to a smooth speed as it is in the real world. To get an idea of the requirement for such a flywheel, the stored energy from the translation of movement of the bike set equal to a rotational movement, i.e

$$E = \frac{1}{2}mv^2 = \frac{1}{2}m(R\omega)^2 = \frac{1}{2}J\omega^2 . \qquad (1)$$

Where m is the total mass of the rider and bike, v is the translation speed, $\omega = v/R$ is the angular velocity of the wheels with radius R and $J = mR^2$ is the inertia seen from wheel-hub. If it is assumed that the mass of the rider and bike is 100 kg, the radius on the back-wheel is 0.337 m and the inertia and mass from the wheels is ignored an inertia of 11.4 kgm^2 is required. This corresponds to a solid cylinder with a length of 0.3 m, a diameter of 0.47 m and a total mass of 411 kg. By using this example is it quite clear that gearing to the flywheel is preferable and also that a compromise needs to be done such that the light rider does not meet the same inertia as the heavy rider. On the other hand, if the inertia is too low, the heavy rider will feel it is unrealistic under acceleration, which actually is the case with the majority of commercial exercise bikes.

A third aspect of commercial exercise bikes is that they seldom are constructed with the same principle functionality as a normal bike. The basic construction is made simple, cheap and handy. Also the possibility to change gearing is non existent.

From the short review of classical exercise bikes is it quite clear that many properties are missing in order to give the rider the virtual experience of riding a bike, which is the goal in this paper.

The following paper is divided into five sections, where the first section deals with a discussion about the preferable load unit, which is primary in the exercise bike. Next, the chosen load unit in the form of the new E-core transverse flux machine is described. The third section gives a short description of how the E-core transverse flux machine is installed on a new exercise bike. After this, a short discussion about the controller and converter implementation is done and finally a conclusion is given.

2. Power electronic controlled electrical machine as load unit

For the new exercise bike technology it is obvious to consider a power electronic controlled electrical machine, which can operate both in generator and motor mode which is required to replicate riding down-hill.
With help of the machine and controller is it also possible to emulate inertia such that both the light and heavy rider will experience accelerations as typical in the real world.

Since the goal is to construct an exercise bike with similar functionalities as a real bike the idea is to take a normal bicycle and replace the rear wheel with the new load unit. By doing so, the same bike can by used for both indoor exercise training and real outside training, where for instance changing gears is similar in both cases.

In order to identify the most suitable machine (load unit) for the exercise bike application the torque-speed characteristics for well-trained rider is inspected, see Fig 1.

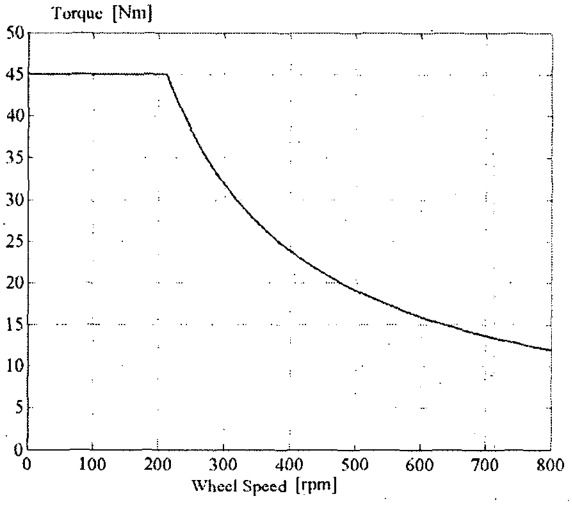

Fig. 1. Continuous torque-speed characteristics of well-trained rider.

In intermittent operation is it possible that the rider is developing more torque, which typically is used for acceleration. This is also something that the load unit has to emulate if the mechanical inertia doesn't match the rider. Accelerations done by the rider is typically short in time and therefore is it expected that load unit can catch these by overloading.

The torque-speed characteristic in Fig. 1 is what the load unit has to fulfil in generator operation but in motor operation is the requirement much lower. Only the internal friction has to be over-wound such that the speed can be maintained or accelerated a little during emulation of downhill operation.

The torque speed curve for the rider is characterized with the fact that in low speed operation a large maximum torque component is developed and after a certain nominal speed constant power is developed and maintained up to four times nominal speed. With this required torque speed curve it is obvious to consider machine types where it is possible to make field reduction. This leads to machine types like the induction machine, the DC machine with wound armature and field and the Switched reluctance machine. Permanent magnet machines, which is characterized with high efficiency and a high torque per volume density, has a fixed magnetization which means the ratings for the power-electronics components in the converter has to be oversized to fulfil the torque speed characteristics. Furthermore, the machine will be more expensive due to the permanent magnets.

The DC-machine with wound armature and field is still interesting due to the simple transfer function. But due the fact that the machine both needs to operate as a motor and generator and that the field has to be controlled the complexity of the converter topology is almost similar to the converters for the induction- and Switched Reluctance machines. The life of the brushes can also be a problem if the load unit is used frequently.

By considering the available space for the load unit (exchange of the back-wheel) is it realized that a machine with diameter/length (D/L) ratio of typically 5 is required, where standard machines typically have a D/L ratio of 1-2. This means a new machine technology can be considered, where the invented E-core transverse flux machine (ETFM) [1] may be an excellent choice. The ETFM is a combination of the transverse flux machine [2] and a switched reluctance machine, which is simply constructed using standard transformer laminations.

3. The E-core transverse flux machine

The physical layout of the EFTM can be seen in Fig 2., where a cross-section and an axial view of the machine is presented, with 6 stator- and 4 rotor-poles. Each stator pole is simply made of an E-core with a bobbin winding, where the rotor poles only consist of I-segments from the transformer lamination. This means that the lamination is axial for both stator and rotor, where for instance the typical synchronous reluctance motor only has an axial laminated rotor [3]. As it can be noticed from Fig. 2 is flux flowing both axial and radial direction, where conventional machines only has flux radial.

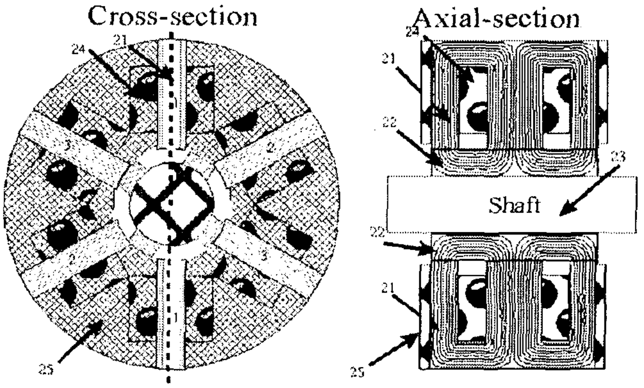

Fig. 2. Cross- and axial-section of the E-core transverse flux machine. 21 – E-core section, 22 – Yoke section, 23 – Shaft, 24 – coil, 25 – End shield.

The operational principle of the ETFM is similar to Switched Reluctance Machine, where the stator-poles attract the rotor-poles. By excitation of the stator poles with a correct excitation sequence it is possible to make the rotor rotate. The machines generator operation is also similar to the Switched Reluctance Machine.

The ETFM is characterized by the segmented/modular construction, where each pole has it own closed magnetic system. The core losses seem small in the construction due to the closed magnetic systems without common yokes and also the usage of grain oriented transformer laminations seem to give a plus. However there may be a chance that some flux will cross the lamination plane with slightly overlapping poles, which may give higher eddy current losses.

With the new modular construction is it also possible to make untraditional pole configurations, like 9 stator and 6 rotor poles. Worth to notice when compared to classical TFM's is the possibility to make more phases in the same stack, where the TFM requires one stack per phase. Due to the closed magnetic systems for each pole the coupling between phases is very small, which makes the machine attractive in systems with a high fault-tolerance requirement.

In order to design the ETFM a design and simulation program is developed based on the SRDaS package [4]. In Fig. 3 a screen shot of the design part is shown.

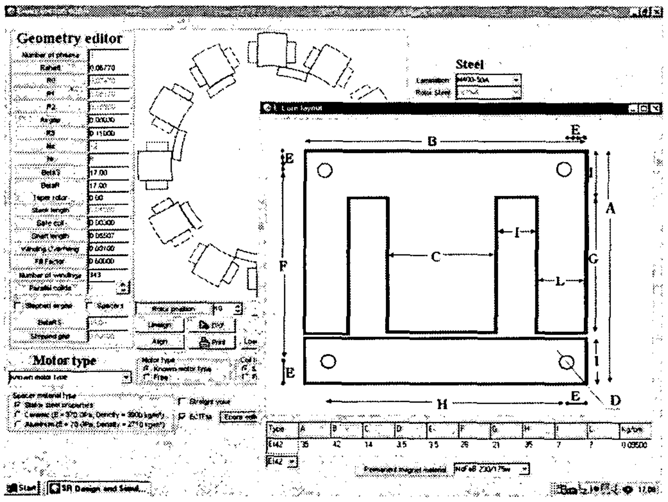

Fig. 3. Design and simulation package for the ETFM.

In the design and simulation program the dimensions are parameterised in the form of outer radius, number of turns, number of poles etc. The EI core used in the design can be selected from a list of standardized EI-cores. The output from the program is simulated currents, flux-linkage, torque, power-factor efficiency etc. With the help of the developed design program, the load unit for the exercise bike is designed.

4. Construciton of the exercise Bike

The essential part of the exercise bike is the requirement of providing the feeling that you are riding a real bike. This, as previously mentioned, requires a very large and unacceptable flywheel to be installed in the motion bike. An alternative to this is to emulate the whole inertia by the ETFM, which as a drawback requires a large torque demand from the ETFM. With a constant tread (speed) from the rider is it in principal required that the ETFM has to give a load torque identical to the pulsating torque generated by the rider. The compromise is to use a flywheel with only part of the required inertia such that the speed is relatively constant with a smooth tread from the rider and constant load torque from the ETFM. Sometimes the rider is accelerating and when this happens is it important that inertia is emulated, such that the rider doesn't accelerate very fast (example from 10 km/h to 40 km/h) in a few seconds, which often is the case for classical exercise bikes.

In order to reduce the torque requirement for the ETFM and the mass of the flywheel, a gearbox with a gearing ratio G between the back-wheel and the rotor of the ETFM is introduced. With the introduced gearbox the torque requirement for the ETFM is thus proportional with G^{-1} and the required inertia for the flywheel is proportional with G^{-2}. By these proportionality factors is it obvious that flywheel size and torque and thus size of the ETFM can be reduced significantly. A drawback of the added gearbox is an increased rotor velocity and thus increased mechanical noise.

The first prototype of the ETFM with integrated gearbox and flywheel is shown Fig. 4. The ETFM is fixed to a special flexible rack, which makes it possible for the user to oscillate the bike.

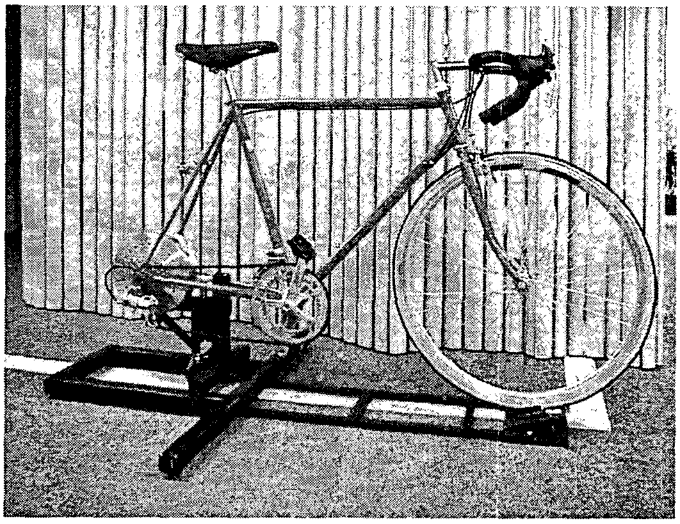

Fig. 4. The load unit mounted on a bike-cycle.

The integrated flywheel, shown in Fig. 5, is made of massive brass weighing approx. 5.5 Kg. This corresponds to an equivalent mass of the rider and bike of 6.2 kg. The missing portion between the 6.2 kg and the users weight needs to be emulated by the ETFM at acceleration. When the user has a constant tread there is no emulation of the missing inertia, which gives a slightly larger speed ripple, but not large enough to be annoying.

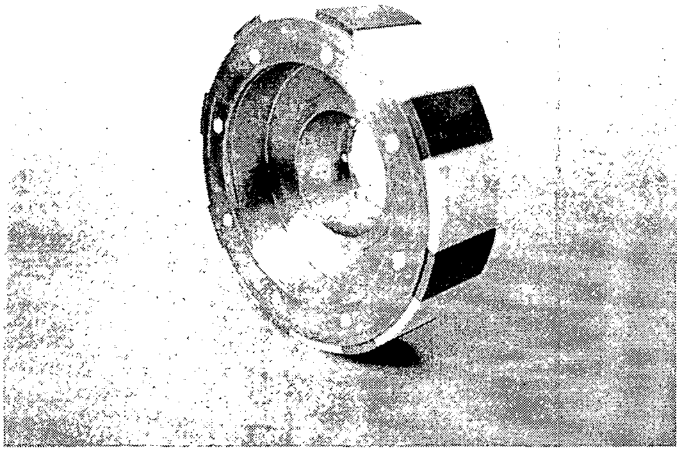

Fig. 5. Rotor I-segments and the integrated flywheel in form of a brass.

The inertia is emulated in the form of a load torque in phase with the acceleration, which is arrived by re-writing Newtons law 2.

$$\sum F = m\frac{dv}{dt} \Leftrightarrow \sum T = J\frac{d\omega}{dt}. \qquad (2)$$

where $\sum F$ and $\sum T$ is the force and torque available for the mass and inertia respectively. As it may be noticed from the equation (2) the knowledge of the acceleration is important when the inertia has to be emulated.

5. ConverteR and Control

In order to operate the ETFM a classical asymmetric H-bridge converter is used for each phase and a 16bit µC (C167) from Infinion is used as main controller. Commutation (position) signals, speed and acceleration are obtained with help of three hall-effect switches. The load torque can basically be controlled by either Average Torque Control (ATC) or Instantaneous Torque Control (ITC) [5]. ITC is the most advanced and is typically used for applications requiring a high torque quality (servo drives). The idea in ITC is to control the phase current after a complicated current profile giving the machine a low torque ripple.

The simple ATC is fast realized with analog hysteresis current controllers whereby a simple microprocessor can be applied. The idea with ATC is to control the current with a simple squared current reference, which as a drawback gives some torque ripple. In the specific application the torque ripple from the load unit is not a problem caused by a high frequency due to the many poles in the ETFM and the gearbox. The natural torque ripple frequency from the rider is much lower which means the inertia will dampen the load unit ripple torque much better than the component from the rider.

The first test model of the converter is designed with ATC, where the current reference and commutation strategy is controlled by the micro-controller with help of a model of the rider and tables of commutation angles giving minimum losses. The model of the rider is based on following major equation.

$$T_{ref} = T_{frik} + T_{hill} + T_{vind} + J_{tot}\frac{d\omega}{dt}. \qquad (3)$$

where T_{ref} is the required torque on the rear-wheel when riding a bike. T_{frik} is a torque component from a friction model, T_{hill} is the torque component from up-hill (positive) or down-hill (negative) operation. T_{vind} is the component from wind, which either can be positive or negative and finally J_{tot} is the total equivalent inertia of the rider and bike. Each of the torque components contains a row of parameters like friction-coefficients, effective front area of rider etc. which has to be determined by experiments. For this purpose professionals from TEAM DANMARK and TEAM CSC are playing an important role.

6. Conclusion

A traditional application in form of an exercise bike and a new technology in form of an electrical machine made with classical transformer laminations are meld together in a new elegant product. The new product may set new standards for fitness products in general and make it significantly more fun to exercise. The new electrical machine technology is a candidate for many other interesting applications, where standard machines are far from the most suitable choice.

Acknowledgment

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