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CONCEPT AND DESIGN OF KINETIC ENERGY RECUPERATION SYSTEM

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Abstract: *Power sensitive devices such as computers, data centers and several manufacturing systems relay on UPS (Uninterruptible Power Supply). Typically these auxiliary power systems use a battery to be able to maintain the devices running for a short period of time until the main or a second power source is resumed. This study is focused on defining and developing a conceptual model of a UPS device that uses a rotational mass (flywheel) instead of a battery to store backup energy. The developing of this design contains a series of steps that allow inertial characteristics of the flywheel to be calculated for a specific power requirements. Development approach is demonstrated with an example for reserve energy generator maintaining 18.5 kW for 25 seconds. The primary advantage of this design is the ability to obtain a cost-effective solution at early stage of the product development process. This is achieved by several computational models prepared to evaluate structural rigidity and efficiency of the system. Virtual prototyping application combines overall product performance optimization, time and expenses reduction and detailed diagnosis of ongoing physical phenomena.*

Key words: *UPS, KERS, engineering analysis, virtual prototyping, flywheel.*

1. INTRODUCTION

In recent years uninterruptible power supply depends much on the battery packs as to be able to maintain the stable power output until the main electric source can be recovered.

There are a variety of technologies that can be used to store energy on the utility power system, including: lead-acid, nickel-electrode, and sodium-sulfur modular batteries; zinc-bromine, vanadium redox, and polysulfide-bromide flow batteries; superconducting magnetic energy storage (SMES); flywheels; electrochemical capacitors (ultracaps); compressed air energy storage (CAES); pumped hydro; and production and storage of gases such as hydrogen (to run fuel cells or hydrogen IC engines). Of these technologies, batteries and flywheels are commonly integrated at the distribution system level and are commercially available [3]. The low side of the battery powered UPS technology lies in the limitation of the lead acid batteries mainly used for storing energy. The cost of the battery driven UPS system is substantially higher compared to a system with rotational flywheel design, especially when the power output exceeds several kilowatts.

The key element, when it comes to energy storage efficiency, is the amount of energy required to keep the energy storage equipment charged. In the case of a flywheel, for example, energy is required to keep the flywheel spinning (this is called standby loss). In the case of batteries, energy is required to provide the batteries with a float charge (this is called trickle charge loss). In both cases, the energy that constantly feeds these devices to keep them in a state of readiness is lost forever. [4]

This study examines in detail an uninterruptible power supply (UPS) with kinetic energy storage device (KERS) of mechanical type (flywheel) system that has several benefits in comparison to the traditional UPS systems. The system have substantially bigger cost effectiveness compared to the other devices because of the low static losses and the absence of frequent maintenance, that can give up to 20 years of life. The other benefit is it is cheaper to maintain one KERS system than running several conventional UPS device when there is a bigger power demand. The only downside of flywheel UPS systems is the static power losses that are needed to accelerate the mass and overcome the friction and air resistance in the system. Two types of flywheels are mainly used for energy storage, first concept utilize an idea with low inertial characteristics, but to compensate for this, the rotational speeds are often exceeding 50 000 rpm. Because of that the flywheel is often made of lightweight composite material like carbon fiber. Second concept is a heavyweight type of flywheel that has a low rotational speed but have a massive inertial moment Current research focuses on heavy flywheels because of their relatively low cost.

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2. NEW CONCEPT DEVELOPMENT

2.1. State of the art

Developed UPS module consists of KERS of mechanical type (flywheel) that is working in combination with a generator driven by the internal combustion engine. It is characterized in comparison with similar systems with very simple design. This concept has significantly increased reliability and lower cost due to the use of only one reversible asynchronous electric rotor and the removal of complex control electronics. Its greater durability (due to the elimination of chemical batteries with a limited life expectancy, reduced time to accumulate energy in the flywheel) allows operation at frequent breaks power and low total cost of maintenance for the lifetime of the module.

UPS devices with KERS of mechanical type (flywheel) have emerged as an alternative to electrochemical batteries that can prevent electricity outages on important applications from medium to high loads. Electrochemical batteries used in these applications are often of lead-acid type and in general this is disadvantage. Life cycle of the batteries is usually between 1 to 7 years depending on the application and use. They require periodic maintenance and inspection, emit heat that can also compromise their performance. Generally they are environmentally harmful, but the lead storage batteries are relatively inexpensive and widely available.

UPS devices with kinetic energy of mechanical type (flywheel) have the potential to increase their applicability due to the possibility of reaching over twenty years of operation with minimal or no maintenance. This type has temperature insensitivity and their unattainable for other types of battery reliability is additional outcome to their environmental friendliness.

There are already widely used systems for UPS with KERS of mechanical type (flywheel) [1, 2, 7] using a high-speed synchronous electric reversible motor - electric motor / generator connected to the flywheel shaft. This module replaces chemical batteries, providing the energy required for short-term energy supply, until starting separate diesel generator. After starting the diesel-generator group, it can provide a sustained uninterruptible power supply.

The disadvantage of these solutions is complex [7] and costly [6] structure because of the high-speed electric motor – synchronous electric motor / generator mounted on a common axis with kinetic energy storage (flywheel). The flywheel and the rotor are housed in a vacuum chamber, a stator is insulated by a membrane and is outside the vacuum chamber. The use of synchronous generator requires a special construction of the flywheel to provide sustainable frequency power output when the main power supply is interrupted. High speed mechanics require special bearing solutions, depending on heat and power availability to maintain their function, vibration control and special protections to prevent the breaking of the flywheel, reducing reliability and increased operating costs.

2.2. Concept general scheme

Figure 1 represents a scheme of the above described concept model.

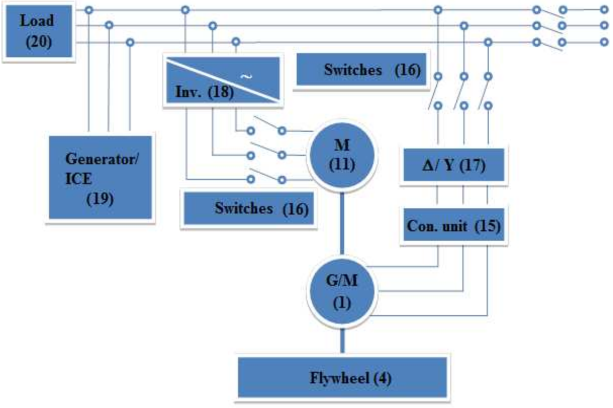


Fig. 1. Operational scheme of UPS with KERS.

The proposed solution eliminates the high-speed electric motor, using a reversible asynchronous motor equipped with an additional section with a rotor directly coupled by shaft to the flywheel. This significantly simplifies and reduces the cost of the modules by increasing its reliability due to reduced (up to 3300 rev/min with bipolar motor) speeds. In fact, this solution uses a modified standard asynchronous motor working in reverse mode. Asynchronous motor is brushless, which also increases reliability and operating time without maintenance. To make it more efficient, special bearings with reduced friction are used, directly attached to the shaft and flywheel. The concept uses also reduced gap between the rotor/stator. Complete system is working in closed housings as to be able to work in vacuum. This leads to a substantial reduction in the overall mechanical, electromagnetic and aerodynamic drag and significantly reduce noise, which reduces losses when operating the unit in idle mode. Power network, increases its overall performance and result increases significantly the overall energy efficiency of the module. All these gains reduce the cost of ownership.

2.3. Functionality

Normal mode. In normal mode (idle mode for the system), the reversible asynchronous three-phase electric motor operates as an electric motor (for example, bipolar, with synchronous frequency exemplary n_s = 3000 rev/min). Thus, it rotates with higher than its synchronous frequency mode – n_{id} (e.g. 3300 rev/min) as the desired speed is maintained by periodically switching on/off via a frequency inverter. A separate, specially prepared section of the stator, is used to drive the electric motor. This allows to keep minimal energy consumption. Consumed energy is used mainly to compensate power losses from mechanical friction in the bearings of the reversible three-phase asynchronous electric engine and electric losses in the motor (about 2.5% of the nominal power of reversible three-phase asynchronous electric motor).

Power breakdown mode. In case of power breakdown, the reversible asynchronous three-phase electric motor automatically (in less than a half period of current) begins to operate as generator with frequency starting from idle frequency ω_k (e.g. bipolar with 3300 rpm) and generates electricity with a frequency f_n and voltage U_H as rotated with decreasing frequency, taking the kinetic energy of the flywheel and maintaining requested power level to the consumers. The generator is automatically switched on, in parallel, powered by an internal combustion engine (ICE), which in the absence of power is automatically turned in. It is needed not more than 15 seconds for asynchronous three-phase electric motor to be switched from motor to generator mode. Thus, it is possible to accelerate the reversible asynchronous three-phase electric motor from the reached current rate (e.g. for bipolar with 2700 rev/min) to that which it rotates continuously at idle n_{id} (e.g. bipolar with 3300 rev/min). The entire transition process of switching to UPS mode takes less than 20 seconds. The required energy is provided by a suitably sized for the purpose kinetic energy storage (flywheel).

2.4. Specific technical requirements

It is necessary to use a block of three capacitors in order to operate the reversible three-phase asynchronous electric motor in generator mode and in motor mode. These components would enable long term runtimes.

Transition processes (as when the reversible three-phase asynchronous electric generator switches to motor) require a special electronic unit to manage automatically the timing of the switch to the network. This unit provides generator phase synchronization to the network. In opposite, this unit also controls the entire system when the power supply is restored and the internal combustion engine is switched off.

Another component is the frequency regulator of three-phase power supply. It provides necessary frequency f (e.g. 55 Hz) to the reversible asynchronous three-phase electric motor when it is operated in normal mode at flywheel speed n_{id} (e.g. 3300 rev/min).

The advantages of the proposed solution is that it uses a single reversible asynchronous motor. This simplifies and decreases the cost of each used module and significantly increases reliability. This concept requires usage of one long shaft as rotor for two separate electric motors used in series. This reduces the overall mechanical resistance, which reduces losses when operating the unit in standby normal mode. Generally, it increases overall efficiency of system.

The reversible three-phase asynchronous electric motor is equipped with special bearings. These bearings guarantee low power dissipation due to internal friction, at requested load rating and rotational velocity. The motor itself is designed to have reduced air gap (clearance) between its rotor and stator. This dramatically reduces electromagnetic power loss. The motor is brushless, leading to increased reliability.

All these features significantly extend the operating time without maintenance. In distinction from the battery uninterruptible systems, the proposed solution provides long term runtime. In fact, it only depends on filling regularly the fuel tank of used ICE (internal combustion engine).

3. MECHANICAL DESIGN DEVELOPMENT

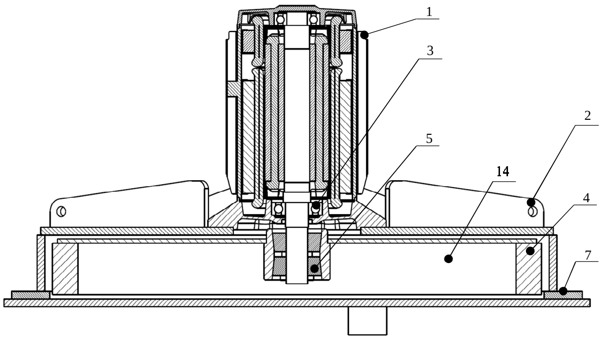


Fig. 2. Section view of design model.

Developed design of mechanical part of so proposed UPS with KERS is shown in general on Fig. 2 and contains next major components:

- reversible three-phase asynchronous electric motor (1);
- kinetic energy storage (flywheel) (4);
- hermetic housing (2);
- base plate block (7);
- collet chuck system (5).

The flywheel (4) is directly mounted on rotor shaft (9) of electrical motor (1). The whole system is presented on the Fig. 2 by a section view through a symmetry plane.

Three-phase asynchronous electric motor (1) is reversible as from side to its shaft is connected to the kinetic energy storage (flywheel) (4). The flywheel is placed in a sealed housing (2) closed by base plate block (7) and connected to the three-phase asynchronous electric motor (1) by a front flange (8). Used three-phase asynchronous electric motor (1) is assembled of two separate sections - the main section (10) and an additional section (11). These sections are mounted and arranged in the housing (12). The rotor (9) of the electric motor (1) is supported by two bearings (3). These bearings have low frictional resistance and are designed to work in vacuum environment. Exploded view of the three-phase asynchronous electric motor is presented on Fig. 3.

Reversible asynchronous electric motor (1) is connected to the electrical grid by before mentioned control unit that consists of three capacitors (15), power frequency inverter (18) and switches (16).

If the main power supply is uninterrupted the three-phase asynchronous electric motor (1) works as a bipolar motor and rotates with frequency which is higher than synchronous. This is maintained by periodically switching on/off the additional section of the motor. This additional section is dimensioned to minimize electromagnetic losses. Normal functionality mode is provided by the

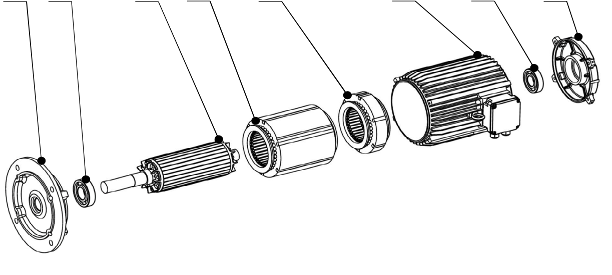


Fig. 3. Exploded view of used for developed concept three-phase asynchronous motor.

frequency controller (18). The entire rotating part of the module – KERS (flywheel) (4) and the rotor of the electric motor (9) are supported by above mentioned two bearings (3). Important feature is that there is no opening for rotor shaft (deaf cover) in the back cover (13). This chamber (14), which consists of sealed housing and the interior of the electrical motor (1), forms a vacuum chamber (not more than 100 Pa). It reduces aerodynamic losses of the rotating elements to a minimum. The absence of movable seals ensures a static vacuum and does not require the use of continuously running vacuum pump. These features:

- operation of the entire system in a vacuum, leading to low aerodynamic power losses;
- low loss by mechanical friction in the bearings;
- low electromagnetic losses due to specially sized section for continuous rotation;
- reduced air gap (clearance) between the rotor (9) and the additional section of the stator (11);
- ensure minimal energy consumption of reverse-phase asynchronous electric motor (1) and the kinetic energy storage (flywheel) (4) during its continuous rotation.

The reversible asynchronous three-phase electric motor (1) has a short time of active work as a generator and it produces heat that does not require the use of continuously cooling fan. A separate fan (not shown) is provided for withdrawing the heat if frequent switching in generator mode presents, as well as initial acceleration to asynchronous frequency n_{nom} (e.g. 2900 rev/min). This fan unit has no mechanical connection with the reversible asynchronous three-phase electric motor (1). It is placed at rear of the motor casing and it is driven by temperature sensor located on the outer casing (12) of reverse-phase asynchronous electric motor (1). Figure 4 represents an exploded view of the built 3d concept variant of the described working principle.

The main advantage of the proposed solution is the use of only one reversible asynchronous motor (1), following which achieves lower cost and higher reliability due to the elimination of long shaft used in the decisions of two series-connected electric motors. Another advantage is significantly reduced aerodynamic losses and noise emission from rotation of flywheel and electric rotor and bearings achieved through the use of static vacuum chamber (no moving seals). The third major advantage is the reduction of mechanical losses in the bearings by using special ones with reduced friction and the elimination of built-in cooling fan. An additional advantage is the use of special additional stator section (11) to drive the flywheel until n_{ph} (e.g. 3300 rev/min) and in supporting normal mode with minimal electromagnetic losses due to optimized design and a minimum air gap (clearance) of 0.25 mm between the rotor (9) and the additional section (11).

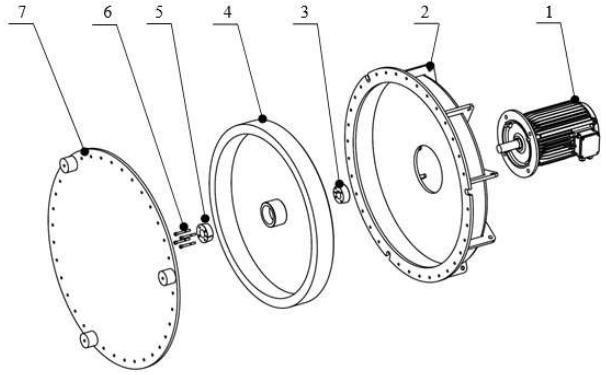


Fig. 4. Exploded view of the system.

This design has a reduction of the total integrated electro-mechanical power loss to less than 3% of the useful power of the reversible asynchronous motor (1) in the generator mode. The total efficiency of the module is increased to more than 97%. An additional advantage is the increase of reliability and increase of operating time without maintenance due to use of standard brushless asynchronous motor in reverse mode. General result is that long term runtimes are ensured, limited only by the available supply of fuel to the combustion engine generator powered by internal combustion engine (19). This results in more efficient solution compared to design solutions that are using chemical batteries (accumulators).

3. DESIGN SIMULATIONS

Examined concept variants are also evaluated by using a modern CAE instruments. Several analysis have been performed to be able to obtain a good vision about the operational parameters and also the force deflection behavior of the whole concept system. This led to the research and development of the innovative three-phase asynchronous motor/generator with separate sections as described in the previous chapter.

3.1. Evaluation of aerodynamic behavior

The whole concept of the hermetic vacuum chamber that is built around the flywheel and the motor/generator is designed and evaluated by using the modern CFD tools. A graphic is presented below (Fig. 5) that represents the power losses over the operational pressure inside the vacuum chamber. These results are obtained by several numerical analyses of examined fluid area of the chamber. Increasing of pressure inside chamber leads to exponential increase of power losses.

Requested approximate max value for power losses due to air resistance is 100 W. This value requires max-

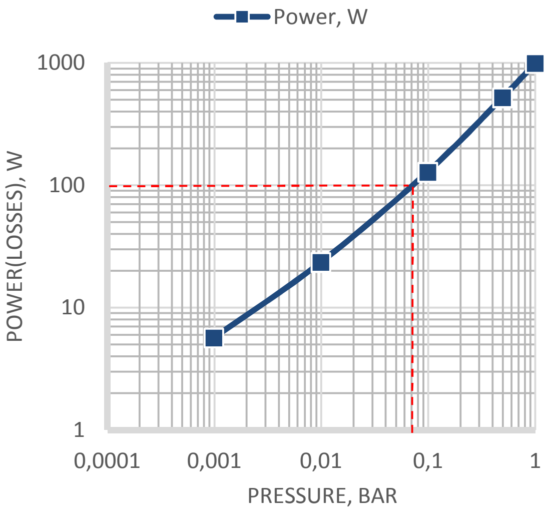


Fig. 5. Pressure over power losses diagram.

mal pressure value inside vacuum chamber of 0.06 bar (60 hPa). This value is possible for most of supplied vacuum pumps (usual values are of about 2 hPa) and will be guaranteed by proper sealing of entire assembly. Pressure will be set once – when the system is manufactured – and will be inspected at periodically as significant leakage is not expected.

3.2. Overall structural behavior

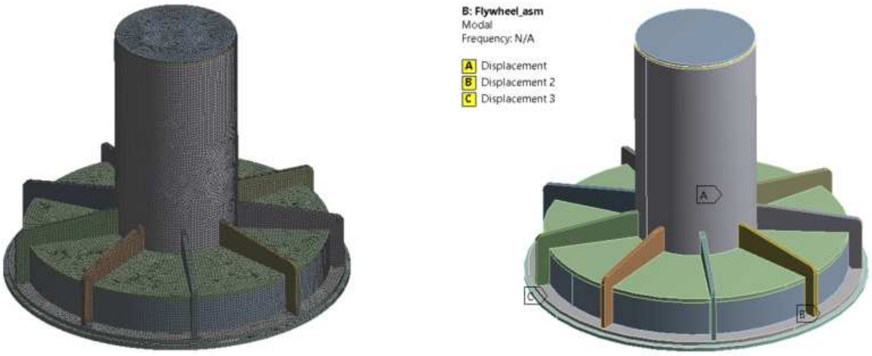
Mechanical parameters of developed design are evaluated in general by performing dynamic analysis to determine natural frequencies. Separate simulation model is built as it is shown on Fig. 6 (mesh density and applied boundary conditions).

Applied boundary conditions correspond to system fixation to ground. All bearing supports are presented as spring-mass system that connects rotor subassembly (electric rotor and attached flywheel) to the casing. Used values for bearings rigidity is based on supplied by manufacturer ones. Electric motor components are modeled in general, mainly to introduce its components' masses in this dynamic model.

This simulation model also presents a design variant with additional casing for the motor and is a result of continuous design development process.

Analysis results are shown as deformations by natural modes on Fig. 7.

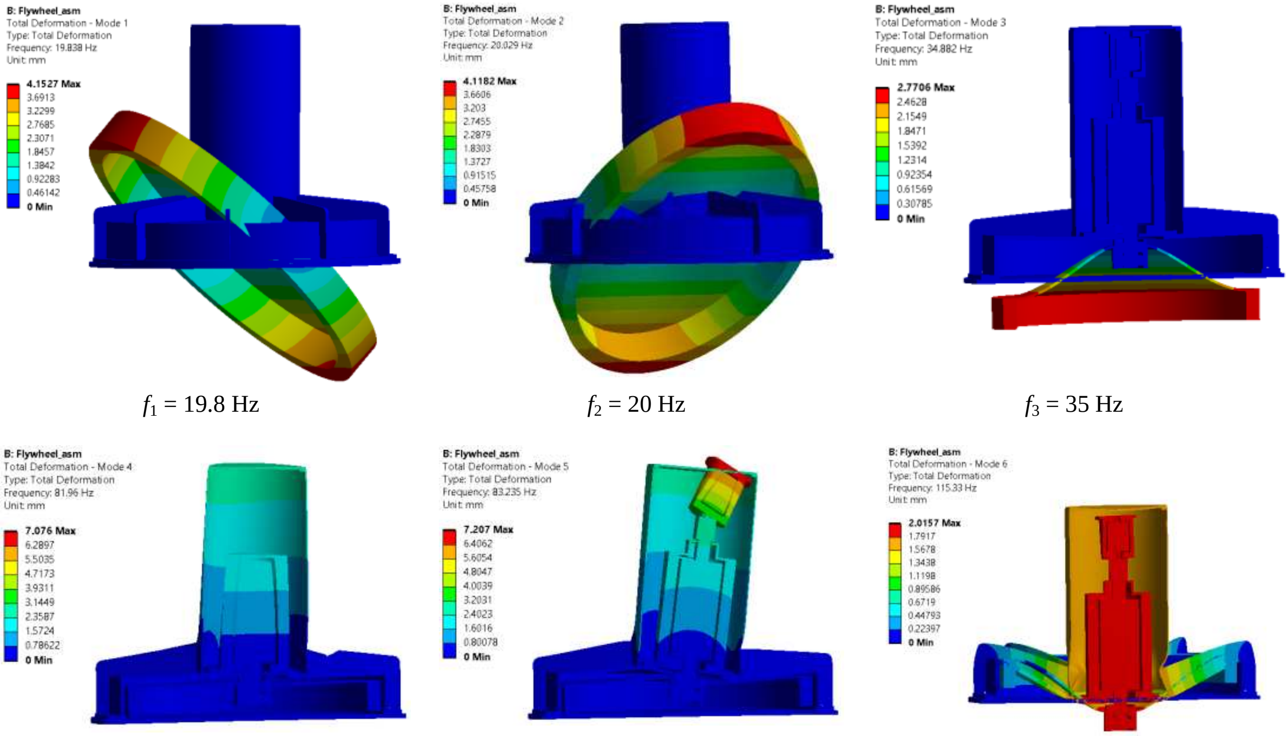
First two frequencies are close and are in fact a single one, about two perpendicular axes. These shapes present rigidity of the flywheel disk in rotation about planar axes (in rotation plane). Third frequency is also of the flywheel – in axial direction – along rotational axis of electric motor.



a

b

Fig. 6. Structural simulation model: *a* – mesh model; *b* – applied boundary conditions.



f_1 = 19.8 Hz

f_2 = 20 Hz

f_3 = 35 Hz

f_4 = 82 Hz

f_5 = 83 Hz

f_6 = 115 Hz

Fig. 7. Total deformation distribution fields by natural frequencies.

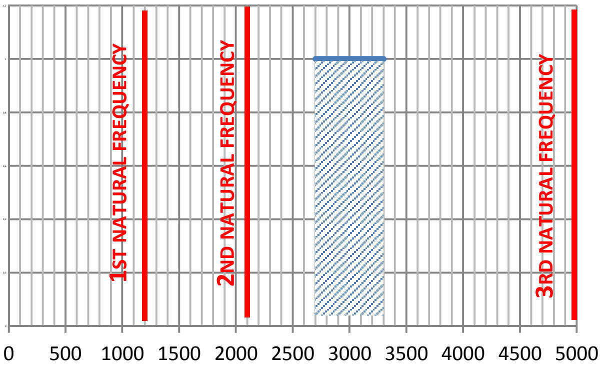


Fig. 8. Work range and natural frequencies.

The system rigidity is dominated by the flywheel as it is the most "flexible" body. Certain increase of flywheel rigidity could be achieved by adding radial internal ribs, but this design will also has an increased aerodynamic resistance (torque) and will increase power losses.

All other natural frequencies are pre-defined by electric motor design characteristics. Fourth and fifth frequencies are very close and are of rear bearing support. Their character will be changed in real situation where no additional cover will be used.

Sixth natural frequency is defined by housing rigidity and is axial. It is too high (corresponds to 6900 rpm) and is out of work range.

First natural frequencies, in fact, correspond to 1200 rpm and 2100 rpm and are placed just before system entering its work range. Next natural frequency is of electrical motor supports – about 5000 rpm/min. This is visualized on Fig. 8, where work range of the system is marked too (rectangular form) together with natural frequencies over a revolutions per minute horizontal axis.

This diagram shows that there is no danger for normal work mode of the system for resonance. Important notice is concerning flywheel acceleration up to its work range when the system is started initially. Certain rotation control will allow to pass resonance without significant influence over the system performance. This mode will be rarely in use and it is not expected to be dangerous.

4. CONCLUSIONS

This study presents a new concept for an uninterruptible power supply system using flywheel. The presented system works in cooperation with a three-phase asynchronous motor/generator and a diesel ICE generator for medium to high power applications.

It could successfully replace UPS systems that are using batteries, providing practically no interruption independently of duration of power supply break out. This is also an affordable solution that gives a cost effective alternative to existing UPS with KERS on the market as it uses simple, low speed kinetic energy storage. Another advantage is its simplified control management system.

The concept is successfully demonstrated through an example of a possible design of a system that utilizes energy from a rotational mass (flywheel). All initial engineering analyses that are performed over built virtual prototype shows positive results and further detailed design development will take place.

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