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Controlling matrix converter in flywheel energy storage system using AFPM by processor-in-the-loop method

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ABSTRACT

Flywheel energy storage systems are considered as the grid integration of renewable energy sources due to their inherent advantages such as fast response, long cycle life and flexibility in providing auxiliary services to the grid, such as frequency regulation, and voltage support. The article focuses on the design of the controller, then conducts processor-in-the-loop (PIL) simulation of the dynamics part using the axial flux permanent magnet (AFPM) motor with the matrix converter on MATLAB/Simulink combined with the controller on the TMS32F28377S microcontroller card of Texas Instruments to evaluate the efficiency of the energy storage system.

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1. INTRODUCTION

Flywheel energy storage system (FESS) which uses electrical energy input stored as kinetic energy is a clean and efficient method to level supply in consequence demanding in energy grids [1], [2]. When short-term backup power is required because power fluctuates or is lost, inertia allows the rotor to continue rotating and kinetic energy is converted into electricity. Most modern high-speed coil energy storage systems consist of a large rotating cylinder (a rim attached to a shaft) supported on a stator by magnetic prismatic bearings [3]. To maintain performance, the flywheel system is operated in a vacuum to reduce frictional forces. The flywheel is attached to an engine or generator that interacts with the grid through electronics. Flywheels can bridge the gap between short-term power and long-term energy storage with optimum load and circulation characteristics.

FESS systems have high energy density as well as high efficiency [4], [5]. It is capable of charging/discharging at high speed, not affected by temperature or depth of discharge (DoD) like when using batteries [6]. The life of the flywheel is long and is almost independent of the charge and discharge cycles. The flywheel allows efficient energy storage and is very environmentally friendly. The system emits low emissions, does not require periodic maintenance, and the manufacturing materials are not as harmful to the environment as batteries. The disadvantage is that a potential safety risk arises if a flywheel is loaded with more energy than its components can handle. Current systems are only capable of storing energy from a few minutes to a few hours and have only been applied in short-term applications. The cost of FESS is still higher than other types. There are also challenges in minimizing energy loss due to friction [7], classical bearings are not efficient, so the current trend is to use magnetic bearings. However, this is still a trend in the field of energy storage and is receiving a lot of attention from researchers.

FESS is a system that stores energy in a rotating flywheel, with the amount of stored energy depending on the flywheel's mass, type and rotational speed. In charging mode, the flywheel is accelerated to store kinetic energy during its rotation. The kinetic energy is then kept in standby mode. In discharge mode, the flywheel is decelerated to release kinetic energy to the load. When storing energy, the engine takes energy from the source and converts it into kinetic energy to rotate the flywheel. When discharging energy, the flywheel slows down. At this time, the engine acts as a generator to generate energy to the grid. Some common motors used in FESS are induction motors, permanent magnet motor, switched reluctance motor.

The radial flux permanent magnet (RFPM) is the most common choice for FESS employing permanent magnet motors. However, in recent years attention has been drawn to the axial flux permanent magnet (AFPM) as a viable alternative to conventional radial flux machines due to its shape, compact structure and high power density. Due to the structure of axially distributed flux, AFPM motors have higher clearance flux density, power density and torque density compared to RFPM [8]-[10]. This results in a more compact motor structure that uses less core material. AFPM motor belongs to the type of permanently magnet synchronous motor, so the efficiency is higher, the loss on the rotor winding is less than that of the asynchronous motor [11], [12]. In addition, the noise is lower and the vibration during operation is lower compared to RFPM motor. In particular, the disc-shaped structure makes AFPM suitable in FESS applications.

In this paper, we focus on the design of the controller, then conducts processor-in-the-loop (PIL) simulation of the dynamics part using the AFPM motor with the matrix converter on MATLAB/Simulink. PIL's major goal is to bridge the gap between the control design implemented in the simulation software and the actual execution of the control codes in the target. PIL allows us to detect flaws that the compiler might miss, as well as debug and verify controller functions and performance [13]. In addition, the PIL method can offer essential software system measurements such as memory utilization and control algorithm execution time.

2. METHOD

2.1. Mathematical model of AFPM

Any winding's flux linkage is the sum of its own inductances plus mutual inductances induced by other currents. The voltage equations for the AFPM machine can be written as [6], [14]:

$$\begin{cases} u_a = R_s i_a + \frac{d\phi_a}{dt} \\ u_b = R_s i_b + \frac{d\phi_b}{dt} \\ u_c = R_s i_c + \frac{d\phi_c}{dt} \end{cases} \tag{1}$$

where R_s is the stator resistance and i_k, ϕ_k, u_k (k=a,b,c) are respectively the current, flux and reference voltage from the magnet to the stator. Consider that the coordinate axis dq rotates in the rotor direction and the rotor radial coincides with the rotor radial axis. Equation for magnet flux along the dq axis:

$$\begin{cases} \phi_d = L_d i_d + \phi_{PM} \\ \phi_q = L_q i_q \end{cases} \tag{2}$$

where L_d is the direct axis inductance, L_q is the quadrature axis inductance, ϕ_{PM} is the amplitude of the flux and i_d, i_q are the direct and quadrature currents in the d-q reference frame, ϕ_d and ϕ_q are the direct and quadrature-axis linkage fluxs. Voltage equation on the dq axis [6], [15]:

$$\begin{cases} u_d = L_d \frac{di_d}{dt} + R_s i_d - \omega_e L_q i_q \\ u_q = L_q \frac{di_q}{dt} + R_s i_q + \omega_e L_q i_q + \omega_e \phi_{PM} \end{cases} \tag{3}$$

where $\omega_e = p\omega_r$ is the electrical angular velocity, ω_r is the mechanical angular velocity. Instantaneous active power of machine:

$$P = ui = u_a i_a + u_b i_b + u_c i_c \tag{4}$$

Applying the Park transformation as (5)-(7), where Te is the electromagnetic torque, ρ is the mass density of the flywheel.

$$T_e = \rho \frac{P_{ele}}{\omega_e} = \frac{3}{2}\rho(L_d - L_q)I_d I_q + \phi_{PM} I_q \tag{5}$$

$$P = \frac{3}{2}(u_d i_d + u_q i_q) \tag{6}$$

$$P_{ele} = \frac{3}{2}\omega_e(L_d I_d I_q - L_q I_q I_d - \phi_{PM} I_q) = \frac{3}{2}\omega_e(L_d(I_d I_q - I_q I_d) - \phi_{PM} I_q) \tag{7}$$

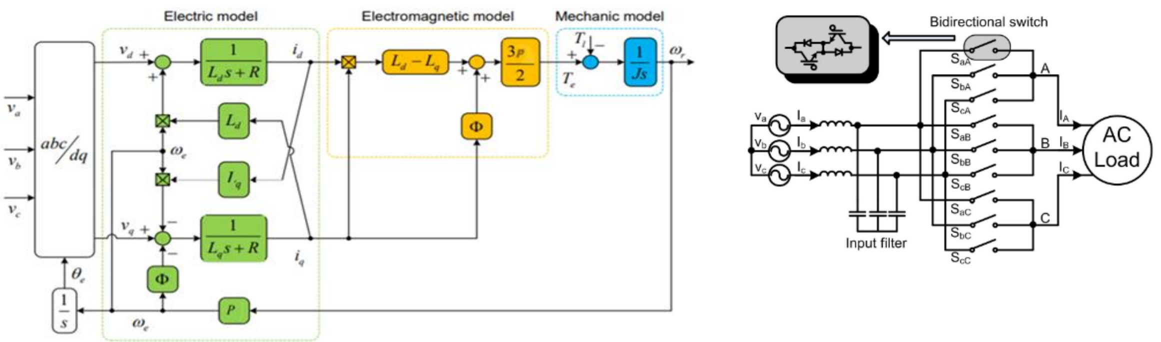
The kinetic as (8), where T_l is load torque, J is the moment of inertia.

$$T_e - T_l - J\frac{d\omega_r}{dt} = 0; \frac{d\omega_r}{dt} = \frac{T_e - T_l}{J}; \omega_r = \frac{1}{Js}(T_e - T_l) \tag{1}$$

Figure 1(a) shows the model structure of the AFPM motor in MATLAB. The model consists of a three-phase electric part to generate three-phase current, an electromechanical part to generate electromagnetic torque and a mechanical part to produce the motor speed.

2.2. Matrix converter

The converters help transform voltage when changing motor speed and convert energy while the motor returns power to the grid. The matrix converter provides two-way energy exchange in FESS. With the use of two-way semiconductor valves combined with control algorithms, it is highly efficient. The direct converter is an AC-AC converter in Figure 1(b), with a valve diagram that directly connects the alternating load to the phases of the input AC voltage, thereby reducing power loss on the valves. Each phase of the direct converter is composed of a rectifier with reversing, so it is possible to exchange power with the grid in both directions.



(a) (b)

Figure 1. The structure illustration for (a) modeling AFPM and (b) diagram of direct matrix converter

Matrix converter is a direct converter but uses two-way semiconductor valves. Appropriate modulation rules produce an output voltage close to the sine whose higher harmonic component is the frequency or multiple of the carrier, attenuating itself on inductive loads. Regarding the matrix converter structure, there is absolutely no need to use LC passive elements, no need for RC circuits to support switching for valves, so it can be fabricated only on a silicon semiconductor crystal (also known as “all silicon” method), capable of integrating with the motor to form a single drive mechanism [16], [17]. Matrix converter is not limited in power range, can be built from a few hundred watts to thousands of kW.

2.3. Controller structure

The matrix converter is suitable for two-way energy exchange in the FESS, with control algorithms that make the two-way energy exchange highly efficient. The purpose of the modulation method is to create a sinusoidal three-phase output voltage system, and the input dissipation current is also sinusoidal with an adjustable phase angle to the input voltage. The amount set for the modulation scheme is the output voltage and the phase angle of the input current [18]. The configuration of the investigated system with

MATLAB/Simulink is presented in Figure 2 and the modulation rule for matrix converter includes the following steps.

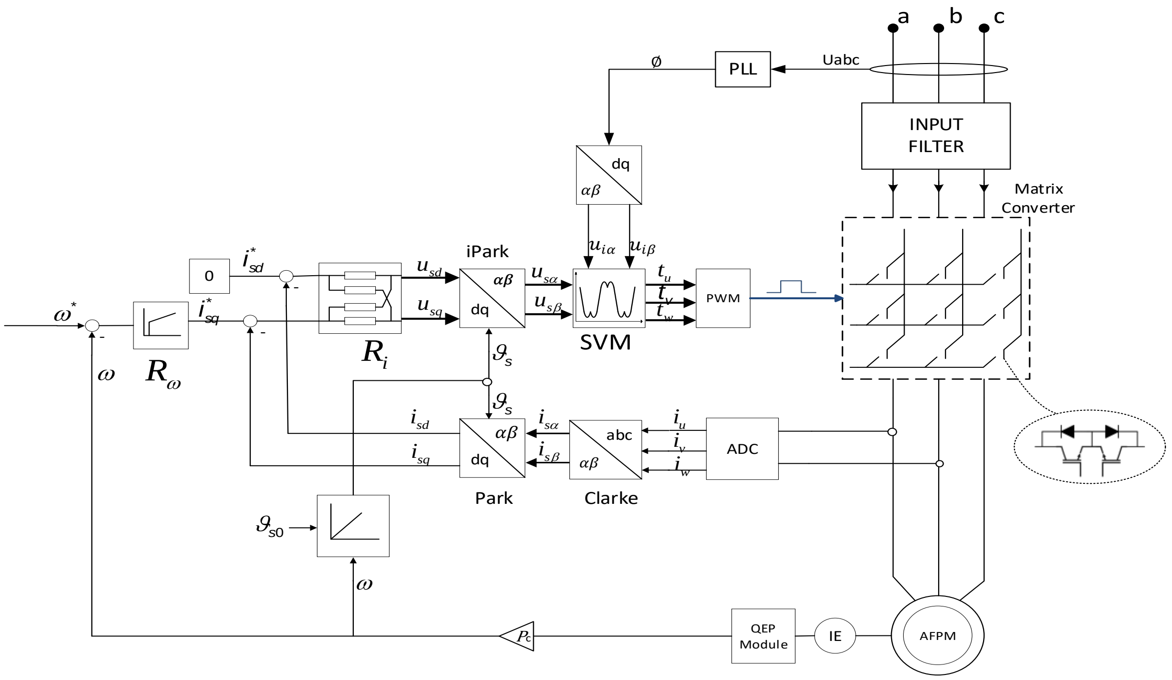


Figure 2. Structure of MC in FESS

Step 1: Determine the position of the desired output voltage vector and input current vector on the coordinate plane in the hexagons.
Step 2: Calculate the relative energizing time of the vectors used d_1, d_2, d_3, d_4, d_0, according to the formula [19], [20]:

$$\begin{cases} d_1 = m \sin \Delta_0 \sin(\frac{\pi}{3} - \Delta_i) \\ d_2 = m \sin \Delta_0 \sin \Delta_i \\ d_3 = m \sin(\frac{\pi}{3} - \Delta_0) \sin(\frac{\pi}{3} - \Delta_i) \\ d_4 = m \sin(\frac{\pi}{3} - \Delta_0) \sin \Delta_i \end{cases} \quad (9)$$

$$d_0 = 1 - (d_1 + d_2 + d_3 + d_4) \quad (10)$$

where m is the modulation index ($0<m<1$). Δ_o is the angle formed by the vector of desired output voltage and the bisector of the sector in which it's located, Δ_i is the angle formed by the vector of desired input current and the bisector of the sector in which it's located.
Step 3: Select the valve combinations and the execution order of the standard vectors used in a logical sequence [21].
Step 4: Output the control signals to the external circuit.

Internal current loop circuit includes two independent PI controllers, controlling two DC current components i_{sd} and i_{sq}, responsible for calculating voltage components u_{sd} and u_{sq} as output quantities of the two sets. PI [22]. To ensure no interaction between the d-axis and q-axis components, we have the structure of the current controller as follows in Figure 3(a). The external speed loop controls the motor speed according to the set speed value using the PI controller as in Figure 3(b). P_c: the number of pole pairs, ψ_p: rotor flux.

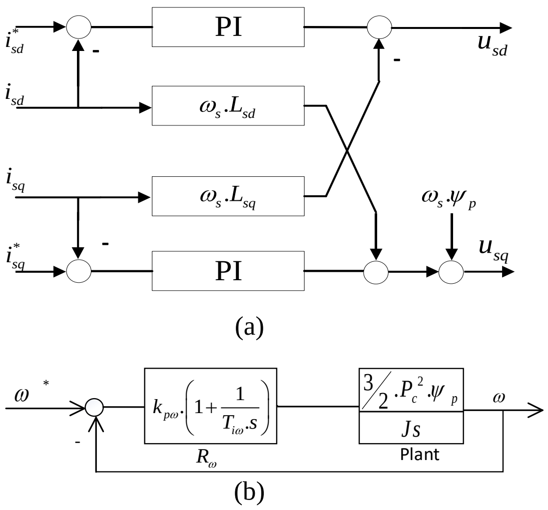


Figure 3. The control structure of the (a) current controller and (b) the rotational speed controller

3. RESULTS AND DISCUSSION
3.1. PIL method

PIL is a testing technique that allows designers to analyze a controller, running in a specialized processor; verify the correctness of the control structure when running the same system on the microcontroller without having to connect to the hardware circuit. This is particularly useful in detecting control problems before they are implemented on expensive or high-powered hardware, and this testing significantly reduces development time [23]. The prototyping environment also enables testing for boundary conditions that would damage hardware or cause crashes and unstable operations that lead to costly repairs. PIL provides valuable information about hardware controls because it can take advantage of the simulation environment to pre-check results in situations. PIL simulation is a great premise as an addition good for HIL simulation in design cycle [24]. The block diagram of the control PIL test configurations is shown in Figure 4.

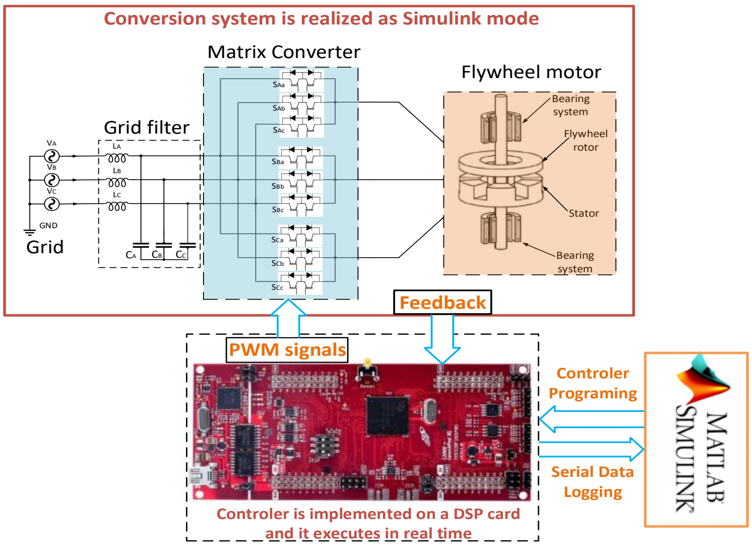


Figure 4. PIL simulation structure

The hardware here is simulated by the model on MATLAB/Simulink including matrix converter and AFPM motor, in which the feedback loop is sent to the microcontroller, which will execute the algorithm and give a signal. control the switching of semiconductor valves of the matrix converter. The C code for the microcontroller is generated by the code generation platform (or embedded coder) of MATLAB/Simulink. DSP microprocessors are known as a special type of microcontroller with the ability to perform problems requiring large amounts of computation, with very high accuracy and speed. Developed for signal processing related fields. The DSP processor family is a line that supports floating point and static floating-point calculations, so the calculation on this line is very fast. In addition, to support transmission control problems, Texas Intruments also "C28x DMC Library" library with Park, Clarke coordinate transfer blocks, proportional–integral–derivative (PID) control block, SVGenDQ spatial vector modulation block. With the above control structure, in this paper, we use Texas Instrument's TMS320F28377s DSP processor.

3.2. Results of experiment

Change the engine speed according to different working modes of FESS. Measure the power received from the grid and the power that the system pushes to the grid after the storage process. Then evaluate the quality of the voltage pushed to the grid, the ability to mobilize capacity and the efficiency of the storage system. Simulation scenario as in Figure 5. Table 1 shows AFPM datasheet. The scenario for changing the engine speed profile is as shown in Table 2. The period from 2.5-4 s corresponds to the next operating cycle of the energy storage system with the same operating modes as the previous cycle.

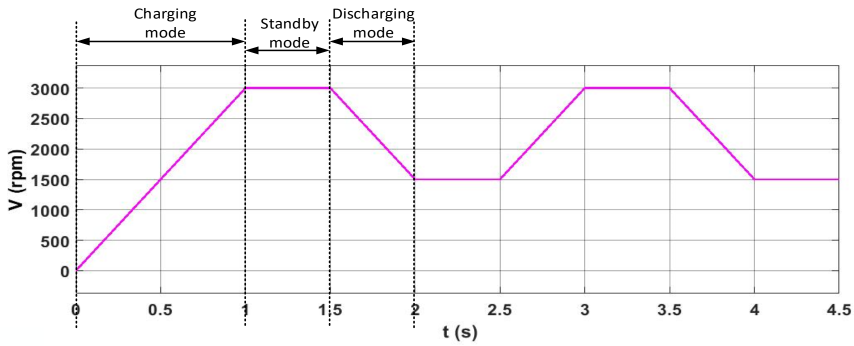


Figure 5. Diagram of motor speed setting

Table 1. AFPM datasheet

Motor parameters	Value
Stator resistance	Rs=5Ω
Armature inductance	L_{sd}=L_{sq}=0.0039H
The number of pole pairs	Pc=2
Magnetic flux	Flux=0.05048T
Moment of inertia	J=0.0185 kg.m^2

Table 2. Profile of motor speed

Time	0-1(s)	1-1.5(s)	1.5-2(s)
Motor speed(rpm)	0 ⇨3000	3000	3000 ⇨1500
Operation mode	Charging	Standby	Discharging

3.2.1. Speed response

The simulation results of matrix converter are shown in Figure 6. In this case, when using the matrix converter, the motor speed line follows the set speed. There is almost no adjustment effect in the operating modes of the system when simulating by PIL method.

3.2.2. Motor torque response

The simulation results of matrix converter are shown in Figure 7. When starting the standby mode at 1s, the matrix converter has a very fast steady-state torque. But the resulting torque response of matrix converter still show a large pulse.

3.2.3. Power response

Observe the grid capacity graph in the period of 1.5-2s the system is in the power discharge mode to push the power to the grid as in Figure 8. When starting the discharge mode at 1.5s, it can be seen that the matrix converter responds to power immediately. When using matrix converter, the ability to feedback power to the grid is fast.

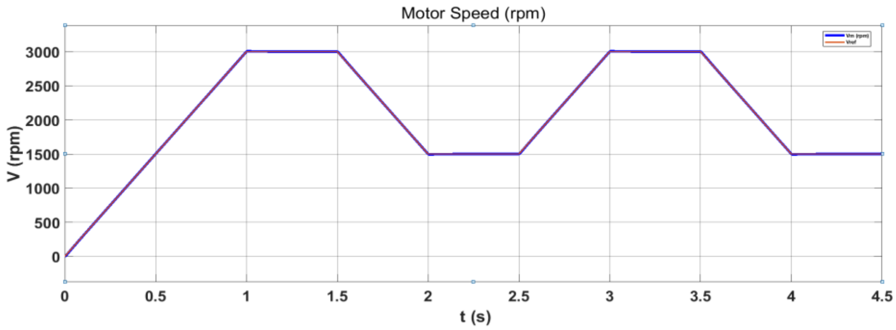


Figure 6. Graph of speed response using PIL

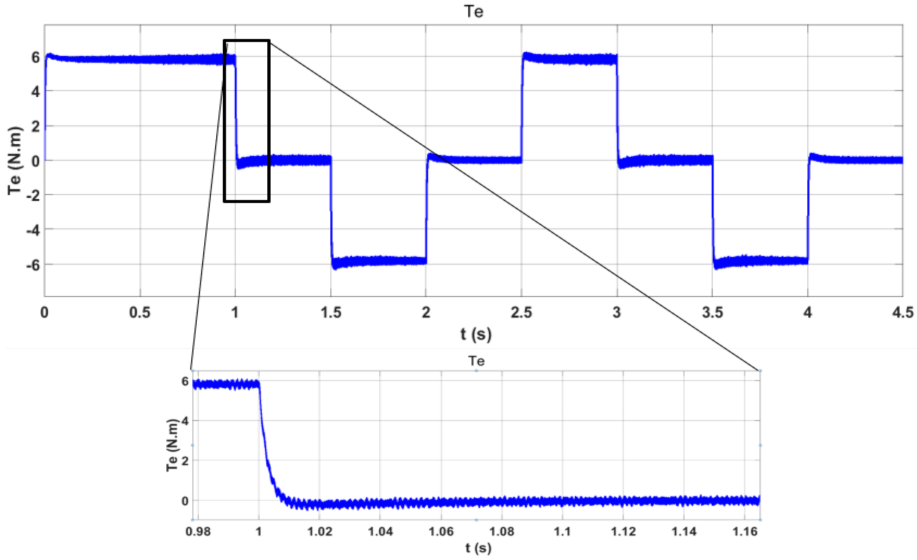


Figure 7. Graph of torque response using PIL

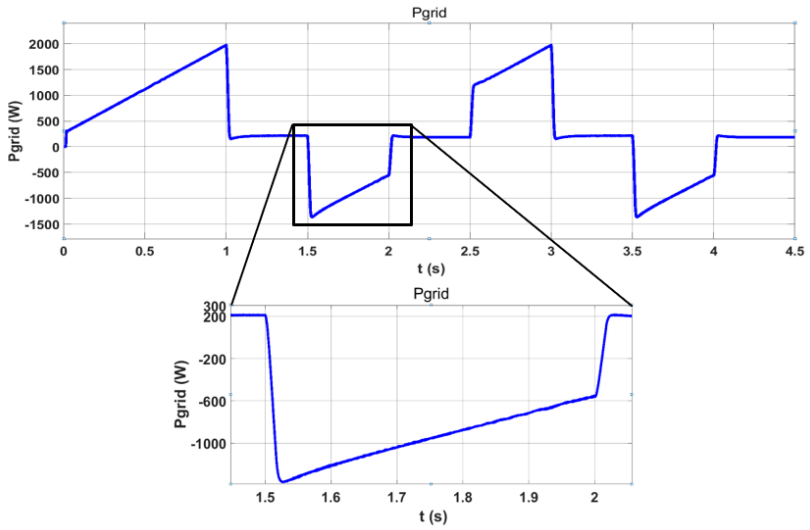


Figure 8. Graph of power response using PIL

3.2.4. Evaluate system performance

The 2-way energy exchange between the grid and the flywheel is done through converters and AFPM, resulting in losses. These losses reduce the energy conversion efficiency. The energy storage efficiency of the system is:

$$H_{\text{FESS}} = \frac{P_{grid\_discharge}}{P_{grid\_charge}} 100\% \quad (11)$$

From the simulation results, the performance of the system using the matrix converter is quite good. Evaluation of responsiveness pushing power to the grid as shown in Figure 8. When the system is in standby mode, standby power losses are loss components that steadily deplete stored energy. The flywheel design determines standby power losses, which are typically caused by friction, aerodynamic drag, and open-circuit engine/generator losses, which slow down the rotor. To reduce standby power losses, vacuum confinement and magnetic bearings are widely utilized [4], [25]. Standby losses are intended to be very low, typically less than 25 W/kWh of stored energy and within 1-2 percent of power output.

3.2.5. Energy response

In charging mode, simulation results in Figure 9 show that matrix converter has fast charge-to-steady-state time. In power charging mode, the system draws power from the grid, engine speed increases to 3000 rpm and E also increases to 900(J). In standby mode, engine speed unchanged at 3000 rpm, the system no longer mobilizes much power from the grid and mainly to maintain engine speed and E remains 900(J). In energy discharge mode, engine speed is reduced, the system starts to push power to the grid for a period of 0.5(s) and the energy stored in the system also decreases gradually.

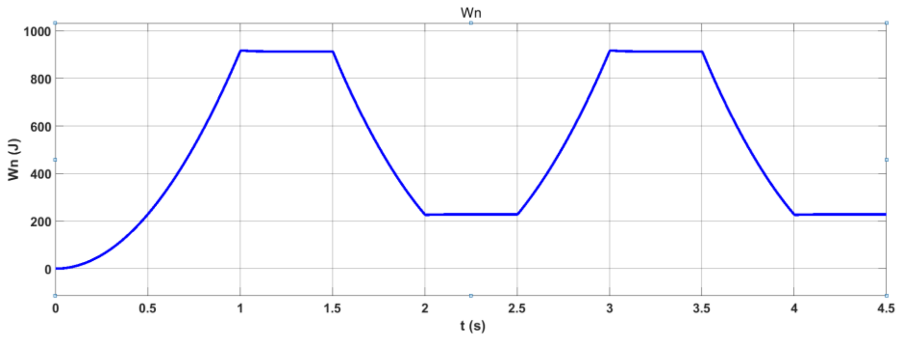


Figure 9. Graph of energy response

4. CONCLUSION

High speed AFPMs are rated for specific power/density strength, efficiency and open-circuit power loss at high rotational speeds, demonstrating their practically in FESS with high power density/ private energy opens a possibility for AFPMs in grid integration of renewable energy. The matrix converter meets the desired speed range of the motor, responds to fast power feedback to the grid, and achieves good performance suitable for the system. Simulation results show that this model can be used to study different converter models and control methods to improve energy storage efficiency. Quality improvement issues when using the FESS model can be considered in further studies. The use of PIL method in this report gives correct results to meet the proposed simulation scenario, making a great contribution to checking the suitability of the controller when running on a microcontroller environment. PIL offers a secure debugging environment, as well as improved quality control and fault analysis. It helps to verify the control system through a simple microcontroller kit. Control algorithms can be defined on high-speed microcontrollers, eliminating hardware flaws in the development phase. Thus, it allows to eliminate the risk of damaging any real or expensive hardware. It also aids in detecting any platform-specific issues or bugs, allowing control algorithms to be tested in isolation from the source. This model can then be researched and implemented on HIL simulation and deployed on experimental equipment to test and evaluate the results.

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