International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 11 Issue 11, November-2022

Performance Enhancement of Flywheel Energy Storage System and Micro-Grid using Capacitor Bank

Emmanuel Chukwudi Agbaraji
Dept. of Computer Engineering
Federal Polytechnic Nekede
Owerri, Nigeria

Moses Idowu Owolabi
Dept. of Electrical and Electronics Engineering
Federal Polytechnic Nekede
Owerri, Nigeria

***Abstract*—This study examines the effect of capacitor bank on the Flywheel Energy Storage System (FESS) in order to improve its performance especially when supporting the micro-grid. The FESS is one of the mechanical energy storage systems that stores energy in a rotating mass producing a kinetic energy. The kinetic energy which is stored as rotational energy can be converted back to electrical energy using the generator such a induction machine. The amount of energy stored by the FESS is dependent on the speed of the flywheel. However, when converting the energy to electrical power, the flywheel slows down and this affects its performance. To improve the performance of the FESS, a capacitor bank was proposed in this work to be attached to its output before connecting it to the micro-grid system. The design and simulation were carried out in Simulink. From the results, power recorded at both the generator side and the FESS side when capacitor bank was connected was higher compared to the power recorded without capacitor bank. Connecting the capacitor bank recorded 62% improvement at the generator side and about 87.65% improvement at the FESS side. It was concluded that the capacitor bank is very efficient in providing fast and adequate support and performance improvement to the FESS and the micro-grid when applied.**

***Keywords*—Flywheel Energy Storage System, Converter, Capacitor Bank, Generator, Induction Machine**

I. INTRODUCTION

The use of fossil fuel products in all aspects of our everyday activities has severe environmental impact and it is a serious threat, as it is very obvious from the resulting health problems and extreme climate change (Elsaid et al, 2020; Shehata et al, 2021). To address this issue, there have been numerous number of power supply sources identified and utilized that have little or no environmental consequences which include developing efficient energy conversion systems (Olabi et al, 2021a; Abdelkareem et al, 2021), such as solar and wind energy conversion systems, waste heat recycling (Zhang et al, 2020; Olabi et al, 2020), and, most recently, the carbon dioxide (CO_2) capture (Abdelkareem et al, 2021; Wilberforce et al, 2021). Some of these renewable energy sources such as the solar and wind energy systems have been confirmed very efficient but they are not sufficient all the time. Since they can generate high amount of power when they are very much sufficient therefore, they require storage systems that can store the power and release it when needed. There are different types of energy storage systems and they may be grouped into four categories namely: electrical, electrochemical, thermal, and mechanical (Olabi et al, 2021b). Among these types of the energy storage systems, the mechanical categories are suitable for large-scale capacities with low environmental impacts compared to the other types. In this category of different mechanical energy storage systems, the flywheel energy storage system (FESS) is considered more efficient for commercial applications.

The flywheel energy storage system comprises of a spinning mass made with composite or steel, designed to be secured within a container with very low ambient pressure. This design helps to achieve reduced pressure within the container containing the flywheel which reduces a drag force or resistant force on the spinning mass, thereby maintaining momentum and generating electricity for longer (Olabi et al, 2021b; Mahmoud et al, 2020). The working principle of a flywheel is that it stores energy in a rotating mass producing a kinetic energy, and the kinetic energy which is stored as rotational energy. The concept provides that the amount of kinetic energy stored in the flywheel depends basically on the inertia and speed of the rotating mass. The purpose of placing the flywheel inside a vacuum containment is mainly to eliminate any energy loss due to friction. Consequently, this mechanism results in the flywheel being able to continue spinning without any added power and with very minimal energy loss. The kinetic energy produced is regularly transferred in and out of the flywheel by an electrical machine attached to the rotor. The electrical drive or machine has two modes of operation which determine its functions, namely either a motor or generator. These principle modes of operation are dependent on the term called load angle (Barelli et al, 2019). As a motor mode of operation, electrical energy is provided to the stator winding which produces a rotating magnetic field when energized or electrically powered. This process converts the energy into torque which is then applied to the rotor causing it to spin rapidly and gaining kinetic energy. This occurs when an excess of energy is being produced and connected from an external source, thus the flywheel stores the energy (Kondoh et al, 2018). On the other hand, when the stored energy is required or a load is connected to the FESS system, the electrical machine will quickly function as a generator which converts the energy stored into electrical energy. As a result, the flywheel speed

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

slows down as it releases the stored energy and this affects its performance.

This work proposes the application of a capacitor bank at the output of the flywheel generator instead of batteries, to help improve the performance of the system. This is because, batteries take some time to charge before supplying to support the micro-grid but the capacitor bank does not take time to charge and starts supplying power to support the system. Secondly, the capacitor bank helps to filter the power, improves power factor and compensates the reactive power. The micro-grid comprises of the diesel generator, wind turbine generator and the FESS. However, the FESS is meant to support the grid when the wind turbine generator stops supplying power due to unavailability of sufficient wind.

II. METHODOLOGY

2.1 Flywheel Energy Storage System (FESS)

The FESS, as the name implies, comprises of a flywheel, an induction machine (IM) and a converter (rectifier/inverter), which controls the speed of the flywheel and thus the accepted and supplied power.

2.1.1 The Flywheel Dynamic Model

As the flywheel stores its energy as it rotates, the energy stored in it is dependent on the square of the rotational speed (Hebner and Walls, 2002), for a given inertia and it represented as follows:

$$E_f = \frac{1}{2} J_f v_f^2 \quad (1)$$

Where J_f (Kg.m2) is the inertia moment and v_f (rad/s) is the speed of the flywheel.

To calculate the inertia of the flywheel, power required during time Δt is considered. In order to store the power P_f during the change in time Δt, the change in energy ΔE is an important characteristics of flywheel and it is presented as:

$$\Delta E = P_f \Delta t \quad (2)$$

Combining equations (1) and (2), the necessary value of the wheel inertia is defined as:

$$J_f = \frac{2P_f \Delta t}{\Delta v_f^2} \quad (3)$$

$$\Delta v_f^2 = v_{f\,max}^2 - v_{f\,min}^2 \quad (4)$$

$v_{f\,max}^2$ and $v_{f\,min}^2$ represent the maximal speed limit and the minimal speed limit of the flywheel, respectively. Δt is the storage period. This limit must be considered otherwise there will be risk to deteriorate the flywheel energy storage operation (Suzuki et al, 2005).

2.1.2 Mechanical Shaft Modeling

The speed of the induction machine connected to the flywheel energy storage system can be calculated using the dynamic equation which has been simplified as follows:

$$J_f \frac{dv_f}{dt} = T_m - f v_f \quad (5)$$

Where T_m (N.m) is the electromagnetic torque and f (N.m.s.rad[-1]) is the viscous friction coefficient.

2.2 Flywheel Energy Storage System Control

The control strategy applied in this work is the Proportional Integral (PI) control technique. It was applied because it is easy to implement and its flexibility and efficiency in achieving good compensation in most physical systems. The control strategy applied in the flywheel is based on the current control. The current measured was compared with the reference current to produce an error signal e(t) which was fed to the controller.

This PI controller produces an output, which is the combination of the outputs of proportional and integral terms or controllers. It uses the control terms to control the error generated from the comparison of the actual output current and the reference input or desired output current. The output of the PI controller $u(t)$ is expressed mathematically as follows:

$$u(t) = K_p(t) + K_I \int e(t)dt \quad (6)$$

Where K_p is the proportional term and K_I is the integral term and e(t) is the error term.

Applying Laplace transform on both sides of the equation 3.8 gives the following:

$$U(s) = \left(K_p + \frac{K_I}{s}\right) E(s) \quad (7)$$

$$\frac{U(s)}{E(s)} = \left(K_p + \frac{K_I}{s}\right) \quad (8)$$

Therefore, the PI controller model is expressed as follows:

$$K_p + \frac{K_I}{s} \quad (9)$$

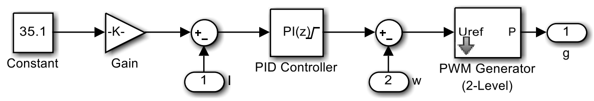

Figure 1: The control model in Simulink

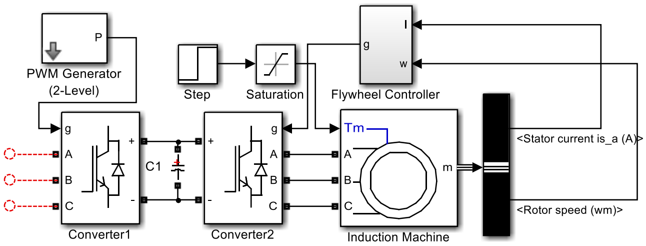

Figure 2: The FESS model in Simulink

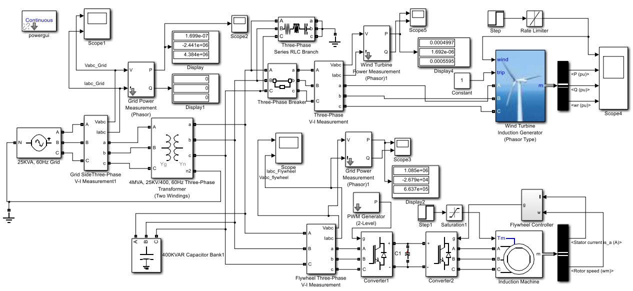

Figure 3: FESS connected to the micro-grid

2.3 Capacitor Bank

A capacitor bank is a physical setup of several capacitors that are of the common specifications that are connected in series or parallel with each other to form a capacitor bank that store electrical energy (Rao, 2022). Like

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

the single capacitor, banks of capacitors are used to store electrical energy and condition the flow of that energy. Hence, increasing the number of capacitors in a bank will increase the capacity of energy that can be stored on a single device (Powers, 2015). The capacitor bank has two connection configurations namely: delta and star configurations.

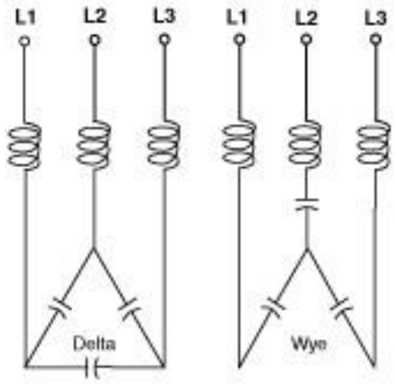

Figure 4: Capacitor bank for delta and star configuration (Source: https://www.elprocus.com/capacitor-bank/)

Capacitor bank has become very useful in electrical power systems and some of its uses are presented as follows (Rao, 2022):

i. In the power system network, the majority of the industrial loads are of inductive nature thus, they require certain proportion of reactive power for them to function properly. This reactive power is provided by the capacitor bank installed parallel to the load.
ii. Capacitor banks act as a source of local reactive power and therefore less reactive power flow through the line.
iii. With the application of a capacitor bank in the power system connection, the power factor can be maintained near to unity. Improving power factor is actually the process of reducing the phase difference between voltage and current in the system.
iv. Fundamentally, capacitor banks reduce the **phase difference** between the voltage and current in the system.
v. On connecting the power bank to the power system, the current leads the voltage, hence the power factor angle is reduced. Achieving reduction in power factor angle indicate causes the improvement of power factor.
vi. The capacitor bank is used for **reactive power compensation** and **power factor correction or improvement** mostly at the electrical substation.

III. RESULTS AND DISCUSSIONS

The results in figures 5 and 6 show the voltage and current behavior at the generator side and FESS side respectively.

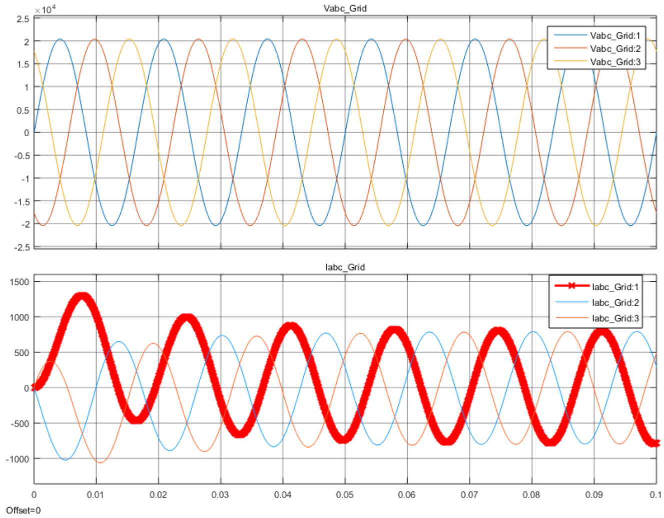

Figure 5: Generator voltage and Current measurement

The results in figure 5 show that the grid generator produced good voltage and current signals.

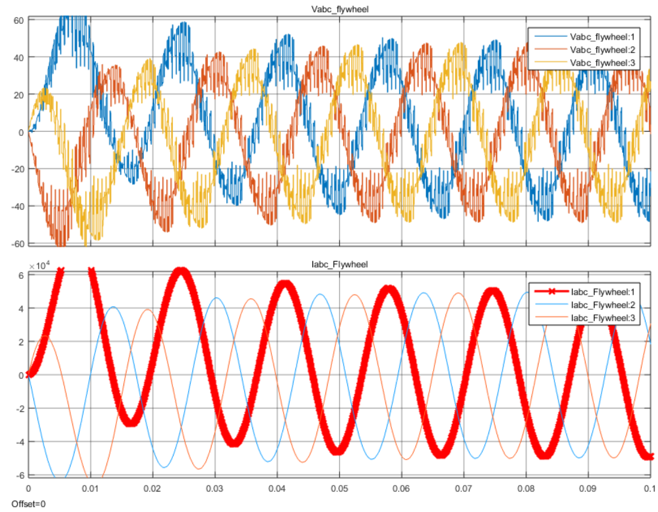

Figure 6: FESS voltage and Current measurement

The results in figure 6 show that the flywheel produced good voltage and current signals. There was a slight change in current signal amplitude at the flywheel it achieved a smooth flow of signal at about 0.05second which shows an adequate compensation from the PI controller.

Table 1: Power measurement for Diesel Generator + flywheel

Generator Power Measurement	Power
Line A	0.1481
Line B	1.789e+06
Line C	3.607e+06
FESS Power Measurement	**Power**
Line A	3.87e+04
Line B	1.065e+05
Line C	2.912e+05

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

Table 2: Power measurement results for Generator + flywheel + Capacitor Bank

Generator Power Measurement	Power
Line A	9.493e+06
Line B	-3.663e+05
Line C	8.895e+05
FESS Power Measurement	**Power**
Line A	2.357e+06
Line B	1.966e+06
Line C	1.867e+04

Comparing results in table 1 and 2, the FESS achieved a significant improvement when a capacitor bank of 4KVAR was connected at its output to the micro-grid system. From the power measurements at the generator side, the system recorded maximum power of 3.607e+06W without the capacitor bank and maximum power of 9.493e+06W with capacitor bank. At the FESS side, the system recorded maximum power of 2.912e+05W without capacitor bank and it recorded maximum power value of 2.357e+06W with the capacitor bank. These mean the power recorded at both the generator side and the FESS side when capacitor bank was connected was higher compared to the power recorded without it. The results show that there was significant improvement in the performance of the FESS and the micro-grid when the capacitor bank was applied.

The computation of the power value in percentage shows that the capacitor bank recorded 62% improvement at the generator side and about 87.65% improvement at the FESS side.

IV. CONCLUSION

The designed in this work micro-grid consists of a generating plant, a wind turbine and an FESS. However, the emphasis is on the examination of the performance of the FESS and the micro-grid with or without a capacitor bank when the wind turbine power reduces or goes off. The FESS has been confirmed to be effective in supporting the renewable energy based micro-grid due to their inconsistencies, however there is need to improve the system performance due to the increasing demand for power through the utilization of the renewable energies. Power measurement was carried out at the generator side and the FESS side for the three lines of the systems. The measurement was recorded when a capacitor bank was connected. Without the capacitor bank, the system recorded maximum power of 3.607e+06W and 2.912e+05W at the generator side and FESS side respectively. When the capacitor bank was connected, the system recorded maximum power of 9.493e+06W and 2.357e+06W at the generator side and FESS side respectively. Thus, power recorded at both the generator side and the FESS side when the capacitor bank was connected was higher than the power recorded without capacitor bank. This means that there was significant improvement in the performance of the FESS and the micro-grid when the capacitor bank was applied.

Computing the power difference in percentage gives 62% improvement at the generator side and about 87.65% improvement at the FESS side. It was concluded that the capacitor bank is very efficient in providing fast and adequate support to the FESS connected to the micro-grid to improve its performance and the general performance of the system.

REFERENCES

[1] Abdelkareem M.A., Elsaid K., Wilberforce T., Kamil M., Sayed E.T., Olabi A., (2021), Environmental aspects of fuel cells: A review. Sci. Total. Environ, pg. 752

[2] Abdelkareem M.A., Lootah M.A., Sayed E.T., Wilberforce T., Alawadhi H., Yousef B.A., Olabi A., (2021), Fuel cells for carbon capture applications. Sci. Total. Environ, pp. 769

[3] Barelli L., Bidini G., Bonucci F., Castellini L., Fratini A., Gallorini F., Zuccari A., (2019), Flywheel hybridization to improve battery life in energy storage systems coupled to RES plants. Energy, Vol. pp. 173, 937–950

[4] Elsaid K., Kamil M., Sayed E.T., Abdelkareem M.A.; Wilberforce T., Olabi, A., (2020), Environmental impact of desalination technologies: A review. Sci. Total. Environ, pg. 748

[5] Hebner R, Walls A. (2002), Flywheel batteries come around again, IEEE Spectr April 2002, Vol.39, pp. 46–51.

[6] Kondoh J., Funamoto T., Nakanishi, T.; Arai, R. Energy characteristics of a fixed-speed flywheel energy storage system with direct grid-connection. Energy 2018, 165, 701–708

[7] Mahmoud M., Ramadan M., Olabi A.G., Pullen K., Naher S., (2020), A Review of Mechanical Energy Storage Systems Combined with Wind and Solar Applications. Energy Convers. Manag., Vol. 210, Iss.112670

[8] Olabi A., Elsaid K., Rabaia M.K.H., Askalany A.A., Abdelkareem M.A., (2020), Waste heat-driven desalination systems: Perspective. Energy, pg. 209

[9] Olabi A., Wilberforce T., Abdelkareem M.A., (2021a), Fuel cell application in the automotive industry and future perspective. Energy, pg. 214

[10] Olabi A.G., Wilberforce T., Abdelkareem M.A. and Ramadan M., (2021b), Critical Review of Flywheel Energy Storage System, Energies, Vol. 14, Iss. 2159, pp. 1-33

[11] Powers N., (2015), Capacitor Banks: Advantages, Uses and How They Work, https://www.arrow.com/en/research-and-events/articles/capacitor-banks-benefit-an-energy-focused-world

[12] Rao R.J.M., (2022), What is a Capacitor Bank? Retrieved from: https://instrumentationtools.com/what-is-a-capacitor-bank/

[13] Shehata N., Sayed E.T., Abdelkareem M.A., (2021), Recent progress in environmentally friendly geopolymers: A review. Sci. Total. Environ, pg. 762

[14] Suzuki Y, Koyanagi A, Kobayashi M, Shimada R., (2005), Novel applications of the flywheel energy storage system, Energy 2005, Vol. 30, No. 21, pp. 28–43.

[15] Wilberforce T., Olabi A., Sayed E.T., Elsaid K., Abdelkareem M.A., (2021), Progress in carbon capture technologies. Sci. Total. Environ, 761

[16] Zhang, Z.; Zhang, Y.; Sui, X.; Li, W.; Xu, D., (2020), Performance of Thermoelectric Power-Generation System for Sufficient Recovery and Reuse of Heat Accumulated at Cold Side of TEG with Water-Cooling Energy Exchange Circuit. Energies, pg. 13

(This work is licensed under a Creative Commons Attribution 4.0 International License.)