A Flywheel Energy Storage System in a Microgrid for Powering Small Villages in Remote Islands in the South Pacific

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Abstract—In most Pacific Island Countries (PICs), the populations reside in isolated communities where electricity generation is hard to access and therefore these communities are heavily dependent on fossil fuel based generation plants. One way to reduce the dependence on these fuels is to use the abundant, albeit intermittent, Renewable Energy Sources (RES). At present most RES based microgrids (MGs) use lead acid battery batteries as the only way to store energy, which can be detrimental for the environment. This paper proposes to minimize the ecological impact support them by using Flywheel Energy Storage Systems (FESS) so as to reduce the size of battery strings required or increase the storage performance of the MG. A case study on data for a small village in Taveuni (Fiji) is presented and the advantages of using a FESS as a back-up storage system are highlighted and discussed.

I. INTRODUCTION

A third of the earth's surface is encompassed by the Pacific Islands Region, and the vast majority of its population is scattered over hundreds of small islands. Actually, Pacific Island Countries (PICs) are mostly composed of rural communities because of their isolated locations and dispersion over large areas across many islands or archipelagos. The distances between islands can be daunting, and consequently the provision of services like health care, education, clean water, electrical power and communications to people often incurs substantial expenses due to the uncertain and inadequate transport networks as well as limited infrastructures and difficult energy supply. Electricity access in particular is essential for facilitating any economic activity and the delivery of key public services. The issues relating to the energy sector cannot be separated from the wider development challenges of PICs and they are majorly impacted by the high import prices of petroleum products [1]–[3].

The current electrification structure in PICs is mostly reliant on electrical grids provided by either the government or privately owned electrical power generation stations. PICs such as Samoa and Fiji have greater dependency on hydro-power generation and the vast majority of non-electrified households in PICs reside in rural areas separated from urban areas by the Pacific Ocean. The potential of grid extension is therefore limited, increasing the importance of off-grid electrification [2].

In most isolated small islands in the region, the electricity power generation is still highly dependent on fossil fuel based grids, but the obvious trend is to develop microgrids (MG) powered by a combination of hydropower, photovoltaic and sometimes wind turbines. However, because of the intermittent supply of Renewable Energy Sources (RES), households usually rely on using wet cell batteries for energy storage (like lead acid batteries) so they can have stable electricity supply. However, the lack of access to recycling facilities in isolated locations results in destructive local recycling or dumping which have adverse environmental effects especially because collection and transportation of these batteries may be a logistical challenge in scarcely populated areas [4]–[7].

Most households and businesses located on Fiji's largest islands (Viti Levu and Vanua Levu) are provided with electrical energy by the Energy Fiji Limited (EFL). Rural communities in Fiji on Vanua Levu and other smaller islands are provided with electrification solutions by the government either through grid electricity extensions, where technically and economically feasible, or by diesel generators, sometimes connected to RES, like hydro-power or biomass. Other options are available through government programs such as the Fiji Solar Home System program, to power a few villages in Vanua Levu with solar panels [8], [9].

In [10], [11], energy profiles for PICs are described along with plans to expand the power production towards RES. Most of the countries in the reports compiled by the International Renewable Energy Agency (IRENA) show PICs moving towards expansions in hydropower generation ,wind and solar farms. In New Caledonia, 16.45 MW wind farms have been built in its southern district to reduce the country's heavy dependency on fossil fuels to generate electricity. About 97% of New Caledonia's electric generation relied previously on fossil fuels. In Samoa, similar wind farm projects have been constructed to meet 2% of annual electricity demand.

Despite the utilization of RES in PICs there are still quite a few challenges in their fast adoption, [12], like for example, the intermittent RES characteristic in the provision of good services in weak grids, giving rise to voltage and frequency instabilities. One possible solution is the use of energy storage systems in MGs to achieve a better reliability, which results in the drawback of their recycling, as hinted above. Another option is to support batteries by using other forms of energy storage systems, among which Flywheel Energy Storage Systems (FESS). Given the remoteness of most islands and their low energy demand, it was identified in [13] that a low speed FESS is feasible especially for its longer life-cycle, lower pollution and the possibility to be developed by utilizing locally available resources. Moreover, the backup of battery based system with a FESS has further benefits in terms of reduction

of the cycles of the battery with resulting increase of the life span, as well as being independent of the temperature of use, which is an issue for batteries in tropical countries. Finally, FESS require less space than strings of batteries, reducing the occupied space of as much as 80%. [13].

In this paper, the authors propose the development of a FESS for a MG suitable for a small Fijian village and compare in simulation the system performance with a traditional lead acid battery energy storage. The paper describes the design, development and implementation of a proof of concept prototype FESS for a PICs small community. Finally, the paper highlights the effective reduction of batteries used in PICs MG with the introduction of FESS which results in an environmentally friendlier power storage solution..

II. PROPOSED MICROGRID WITH FESS

Fig.1 shows a schematic of an isolated microgrid in a small island of the PICs with the proposed FESS. It is composed of a DC-link which supplies the FESS by an AC/DC IGBT inverter connected to the loads of the village, a battery and a Photovoltaic (PV) array, each connected to the DC link via their respective converter. Fig.2 shows the same scheme detailing the FESS made up of an AC/DC bidirectional IGBT converter supplying an induction motor: the drive is controlled in torque by a Field Oriented Control (FOC) technique with a speed sensor. The DC link is controlled by a Proportional-Integral (PI) controller that outputs the required power to keep the DC voltage constant.

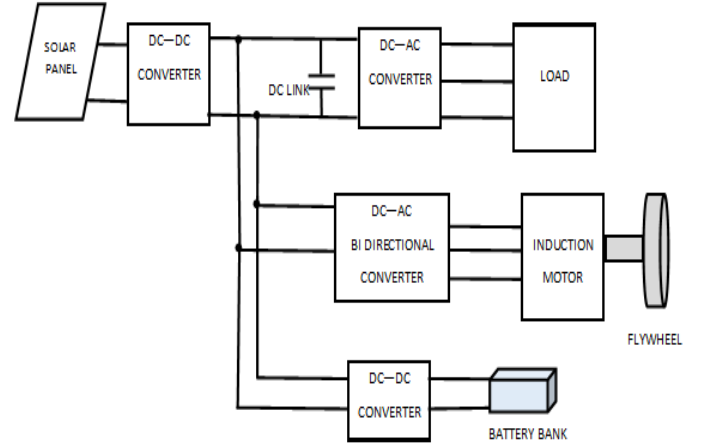In the following each of the components are described.

Fig.1. Schematic of the proposed MG with FESS

A. FESS Modelling

The FESS is made up of a flywheel (FW) connected with an electrical drive with an induction motor with FOC. The system is controlled in torque in such a way that the DC link is controlled to a constant value.

As known, the energy storage equation for a flywheel (FW) is defined in (1) below:

$$E = \frac{1}{2} J \omega^2 \quad [J] \qquad (1)$$

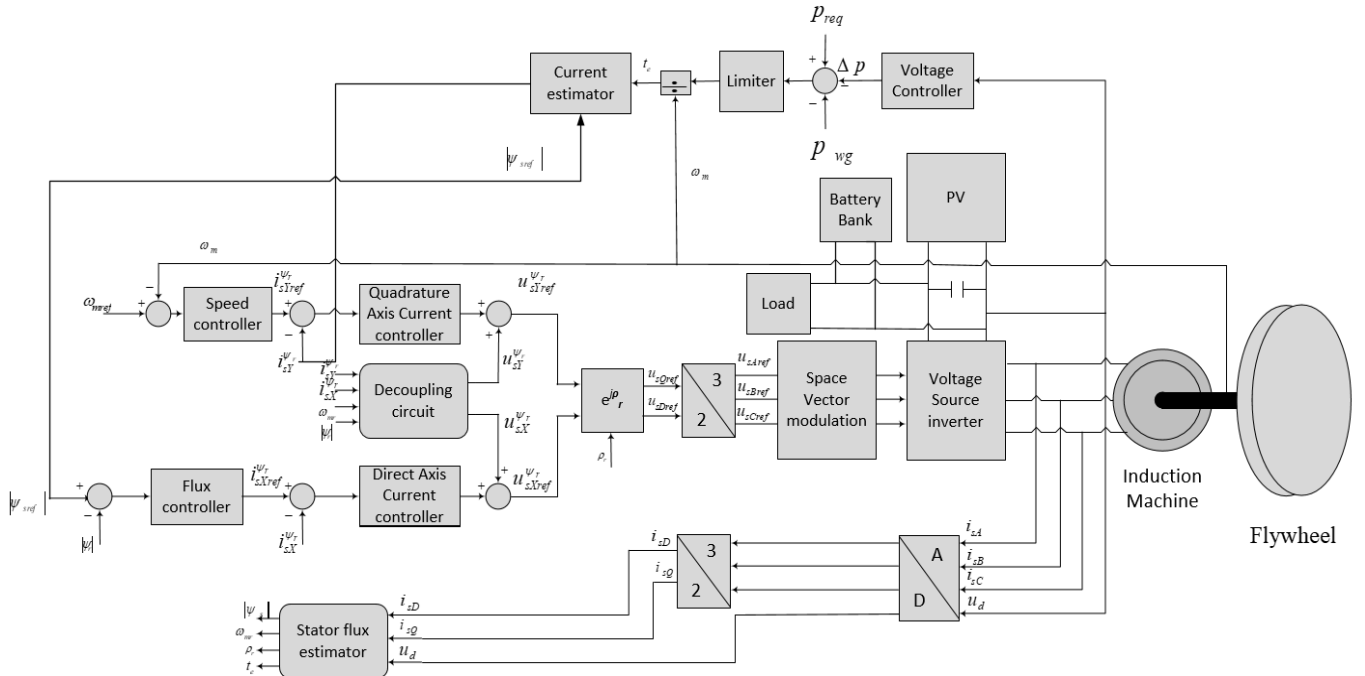where J is the inertia of the flywheel (kgm^2) and ω is the rotational speed (rad/s).

Fig.2. Microgrid DC Link control using FOC with a FESS

The FW scaled prototype has been designed and realized in Fiji, USP [13][14] and its values are shown in Table I. In considering the flywheel rotor sizing, local materials have been prioritized to ensure availability and manufacturability with locally available machinery and labour skills

Table I. Flywheel Rotor Material Selection and Design Dimensions

Energy Need	1.32 MJ
Rotation Speed, ω	10000 rpm
Material Selection	Mild Steel
Working Stress	486 MPa
Mild Steel Density, ρ	7830 kg/m3
Poisson's Ratio, v:	0.29
Rotor Shape Selection:	Solid Cylinder
Rotor Disc Radius, r:	0.25 m
Rotor Disc Width, h:	0.05 m

The torque balance equation of the FESS considered is as follows [13]:

$$J \frac{d\omega}{dt} = T_{em} - M_B - T_{air} \qquad (2)$$

where T_{em} is the electromagnetic torque of the electrical machine driving the FW (Nm), M_B is the FW mechanical bearing torque (Nm) and T_{air} is the air frictional torque of the FW (Nm). The rated power P_{rated} of the FW is given by T_{em}, and ω_{max}, the maximum angular speed of the motor shaft (rad/s). The air frictional torque of the flywheel energy storage system developed is given by [13]:

$$T_{air} = 0.1393\, \rho_a^{0.8} \beta_a^{0.2} r^{4.6} (\alpha + 0.33) \omega^{1.8} \qquad (3)$$

where ρ_a is the enveloping gas density (kg/m³), air in the proposed FW, β_a is the dynamic viscosity of the gas (Pa·s), r and h are the radius and thickness of the flywheel rotor (m) and $\alpha = h/2r$.

Depending on the design configuration for the considered bearing supports, the bearing torque equation will vary. In the proposed design, for simplicity, cost constraints and material availability, only mechanical bearings have been used for the FESS design for the PIC MG and the corresponding torque, M_B is given as [13][14]:

$$M_B = 12.2\omega - 25.38 \qquad (4)$$

In the proposed application, the rotation of the FW is 10000 rpm and the used induction motor is 4kW, 4 poles and rated speed of 1500 rpm. The motor is then driven by FOC in flux weakening region and the FOC operation is determined in torque so as to keep a constant DC link voltage between the bidirectional converters, ensuring a constant power storage in the FESS in its charging scenarios and power output to the consumer in the FESS discharging scenario. The DC link voltage has been chosen to be 500 V, which is the voltage of the inverter supplying the FESS.

B. Load Modelling

In considering a typical small Pacific island village with about 10 households, the power installed is realistically assumed to be 0.5 kW per household consisting with a peak power consumption of 5 kW and an average power demand of 2.5 kW/day. The total energy demand, E_{demand} for a 24hr period is approximately 60 kWh/day [15].

Given below is the solar radiation estimation and profile load plot for the island of Taveuni, Fiji, for a 24hr period in the month of January [16]:
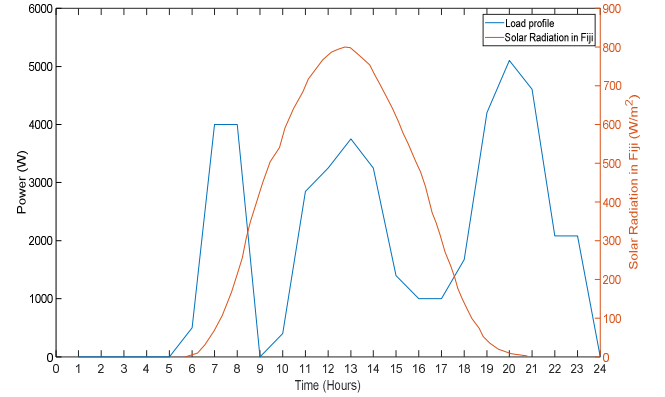

Fig. 3. 24Hrs Solar Radiation Estimation and Profile Load Plot for Taveuni Island for the month of January

C. PV modelling

The PV modelling calculations considered in this section are as described in [7] , The efficiency of the PV system is:

$$\eta_{PVsys} = PR\, \eta_{cabling} = 0.7 \times 0.95 = 0.66 \qquad (5)$$

where PR is the PV module performance ratio, $\eta_{cabling}$ is cabling efficiency. The photovoltaic module sizing is considered under STC, where the conditions are irradiance 1000W/m², solar cell temperature is 25ºC and a radiant spectrum expected for solar radiation at an air mass of 1.5.. The data used in (5) are proposed in [7] as a first approximation.

The total Watt-hours per day needed from the PV modules is calculated as:

$$E_{PV} = \frac{E_{demand}}{\eta_{PVsys}} = 60\text{kWh/d} / 0.66 = \qquad (6)$$
$$= 91 \text{ kWh/d}$$

The nominal power of the PV modules under STC is calculated by using the lowest irradiation of the year G_{min} ($=\frac{4kWh}{m^2}/d$ in June)

$$P_{PV} = \frac{E_{PV}}{G_{min}}\, 1000\, W/m^2 = \qquad (7)$$
$$= \frac{91\ kWh/d}{\frac{4kWh}{m^2}/d}\, 1000\, W/m^2 = 23 \text{ kWp}$$

A panel of 140 Wp has been chosen, resulting in 164 panels, occupying a surface of 192 m²

D. Battery Sizing

The battery sizing calculations considered in this section are as described in [7]. The batteries are sized to accommodate for 2 days of autonomy (n_{days}) with a 0.6 Depth of Discharge (DoD). The battery energy capacity, E_{bat} is therefore calculated as follows (considering a unity battery efficiency):

$$E_{bat} = E_{demand} \frac{n_{days}}{DoD} = \qquad (8)$$
$$= (60 \text{ kWh /Day}) (2 \text{ Days} / 0.6) = 200 \text{ kWh}$$

In determining the Ampere Hour Rating for the batteries, B_{Ah} the DC Bus nominal voltage for the system is considered to be 500V.

$$B_{Ah} = \frac{E_{battery}}{V_{DC}} = 200 \text{ kWh/500V} \qquad (9)$$
$$= 400 \text{ Ah}$$

In considering a 12V Sealed Lead Acid Deep Cycle Battery at 200Ah, there would be a need for 42 x 2 Battery Array, requiring 84 batteries in total.

III. RESULTS

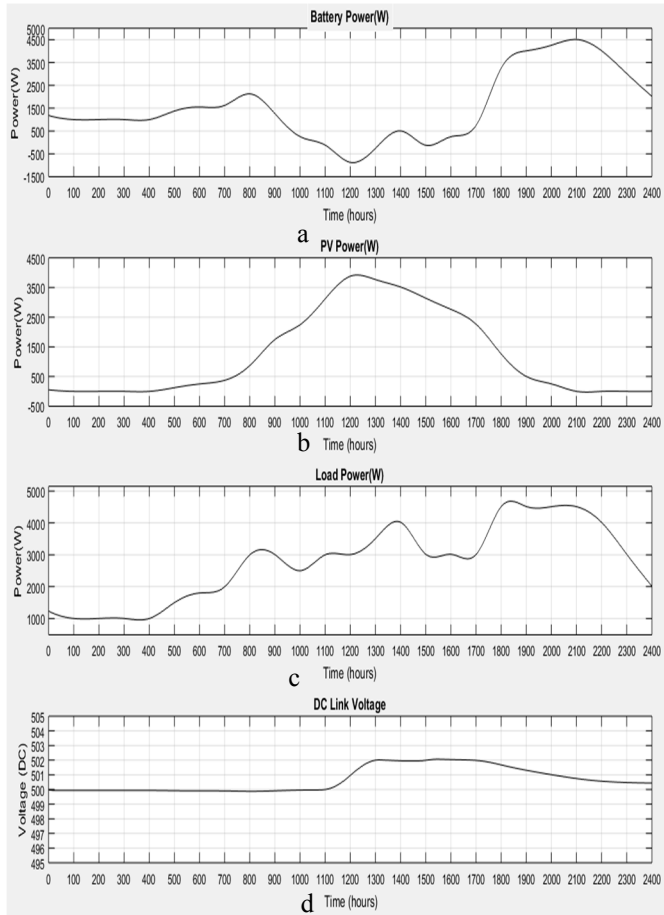The system of fig.4 and 5 has been simulated in Matlab-Simulink® environment.

d

Fig.4. (a) Battery Power, (b) PV Power, (c) Load Power, and (d) DC Link Voltage Plot

Fig 4.a shows the power that is given and absorbed by the battery bank for a 24 hour period. Positive values indicate that the power is injected to the load. Fig 4.b shows the solar energy that is produced in the 24 hour time period by the PV array. Fig 4.c shows the load profile for a 24 hour time period at Taveuni Island in Fiji, and Fig 4.d presents the corresponding fluctuations of DC-link voltage of the micro-grid with PV panels and battery banks. It is observed that the battery bank has been utilized during the night to supply the night loads of the small island community. Once the solar energy is in abundance the battery bank starts charging and it also supplies the local load from 700 h to 1200 h. It is apparent that the charging response of the battery is sluggish and slow. At 1200 h the battery bank is completely charged and can start supplying the daily loads. The characteristic of a Lead Acid battery string is to give constant current with a long time constant, it is unable to supply the rapid fluctuations of the load current: this explains the DC-link voltage fluctuations of as much as 2 V (0.4%) observed in Fig 4.d from 1200h to 2100h. Obviously these fluctuations are minimal at night, since the load is generally constant.
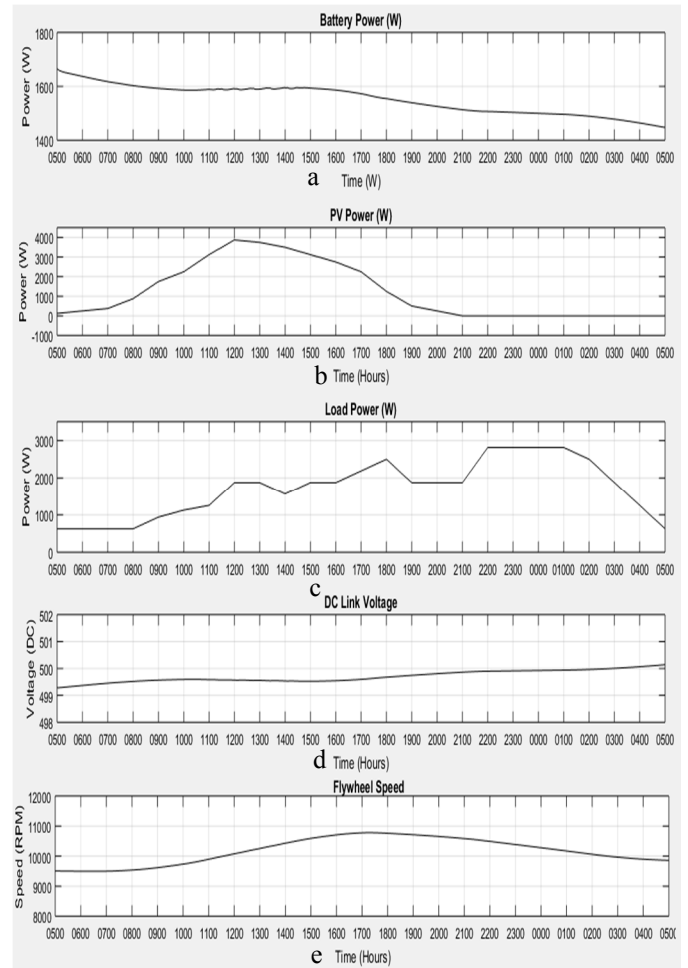

Fig.5. Microgrid with FESS (a) Battery Power, (b) PV Power, (c) Load Power, (d) DC Link Voltage and (e) Flywheel speed Plot

Fig 5 shows the same scenario when the FESS is used. Fig. 5.a shows the battery power oscillations, fig.s 5.b and 5.c are the same as fig. 4.b and 4.c but for the FESS. Fig 5.d presents the fluctuations of DC-link voltage of the micro-grid with PV panels and battery banks together with the FESS, while fig. 5.e plots the rotation speed of the FW. It can be noticed from 5.a that the battery bank discharges much slower than the previous case, since the flywheel is always backing up the power supply to the loads. This reduction of the fluctuations of the battery cycles has the important consequence of increasing the life-span of the batteries. As a consequence also the VDC has smaller oscillations, in particular of 0.5V (0.1%). The fluctuations of the speed show the correct operation of the FESS in the field-weakening region as well as its quick response in meeting the load demand before the battery.

From the proposed scheme, the introduction of the FESS in the MG reduces the power delivery by the battery at the effective peak time 2100hrs, prolonging the life cycle of the batteries in the scheme. Also, the amount of batteries used could be reduced resulting in a more environmentally friendly solution to power storage for isolated microgrids in PICs.

IV. CONCLUSION

This paper has proposed a FOC based FESS at 10000 rpm and with only mechanical bearings to help a battery system in a MG developed for a small village in the island of Taveuni in Fiji. The target has been to show the reduction of the DC fluctuations in comparison to the case of MG with only batteries and the corresponding decrease of the cycles of the batteries, with resulting increase of the life of battery system. The FESS has been simulated by using a real FW designed to be realized in Fiji with local material and competences. Future works is aimed at decreasing the size of battery strings by suitably sizing the FESS. Also, exploring the use of magnetic bearings to extend the operational life of FW.

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