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PV Output Power Smoothing Using Flywheel Storage System

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Abstract—**A large penetration of renewable energy sources (RES) characterizes the next generation power grid. Yet the intermittent nature of such resources introduces new challenges in the power grid. In this paper, we explore the employment of flywheels to smooth the output power of a fluctuating energy resource. We introduce an energy management approach that is based on moving average (MA) and linear programming (LP) to optimize the operation of the flywheel storage system to smooth the output of a PV system. The MA is tracked to reduce the fluctuation whereas optimization is used to find the optimal charging and discharging periods that takes into consideration the production forecast. The results demonstrate the ability of the approach to mitigate the output power fluctuation of a photovoltaic system.**

I. INTRODUCTION

As the yearly energy demand grows, there is a great interest in the integration of RES to fulfill this increase in demand. Integration of RES in electric distribution network has become more and more attractive multi-faceted trend as economic and environmental factors drive new technologies to be more efficient and less polluting than other conventional sources. On the other hand, their intermittent nature introduces new challenges to the power system. The fluctuation of RES can be huge such that it jeopardizes the power system. Storage systems can be used to mitigate the effect of output power fluctuation. The storage systems that can be employed in such applications should have a very fast response time and long life that is not affected with frequent charging and discharging.

Traditional power grid design approaches which are based on the considerations of the extreme conditions for peak load and weak load and the assumption that the voltage at the transformer is always higher than at the loads is no longer suitable for the distribution grids with distributed energy resources (DERs). With the concept of smart grid, applications such as Demand Response (DR), Conservation Voltage Reduction (CVR), and VAR Control have been widely used due to the features of intensively using information and communication technologies (ICT) in smart Grids. Economic benefits of DR have been explored in our previous works [1]–[3]. In [4]–[6] we used co-simulation approach to study CVR and Volt/VAR control. In this work, we explored the usage of optimal coordination of flywheel storage unit to reduce the power fluctuation of a renewable energy resource.

Nowadays, there are many types of energy storage systems, these storage units can be categorized depending on the form of energy that used. Batteries are the most common type, which convert the stored chemical energy into electrical energy. Lead-acid battery are the most known rechargeable battery technologies and have been used for more than 50 years. They have low energy to weight ratio and relatively high power to weight ratio and low cost. Therefore, lead-acid batteries can be usually found in vehicles since they can provide high starting current. Therefore, applications such as backup power, off-grid/remote applications, time shifting, power quality and time shifting of renewable generation are suited to this technology. Flow batteries are relatively larger than other types of batteries and have many applications including load balancing in the power grid. Lithium-ion batteries have better characteristics compared to the previous types. They have higher energy-weight ratio and number of cycles. All Batteries have a common characteristic, namely the limited cycle life. This characteristic disqualifies the batteries from being a good candidate for smoothing a fluctuating energy source.

Some of the characteristics of the flywheel storage system are low response time, high power storage and a life time that is not affected by frequent charging and discharging cycles. Therefore, these kind of energy storage are suitable for smoothing RES output power fluctuations. Flywheels can't store a large amount of energy, yet they can provide high power and hence they are suitable for applications that require high power during short-time periods (i.e., from few seconds to few minutes) [7].

The flywheel is a storage element in which it stores the kinetic energy [8]. Charging the flywheel means increasing the speed, therefore, to charge the flywheel a torque should be applied in the same direction of the rotation. The Discharging means reducing the speed, therefore the braking torque is applied in opposite direction of rotation. The amount of energy stored (E) in the flywheel varies linearly with the moment of inertia (I) and quadratically with the angular velocity (ω) as shown in Equation 1

$$E = \frac{1}{2} I \omega^2 \tag{1}$$

The inertia is given by the following Equation 2:

$$I = \frac{1}{2} m r^2 \tag{2}$$

where m is the mass and r is the radius.

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In the charging stage, the electric machine works as a motor and it converts energy from electric to kinetic and when it discharges, the machine works as a generator and it provides electricity.

Flywheels can be classified according to their speed into mainly two groups; (1) low speed and (2) high speed. High-speed systems have much lower weight and smaller size. However, they are more complex and contain sophisticated technologies to reduce friction and increase the speed [9].

The research on controlling flywheel has two main areas. In the first area, the researchers are focusing on high-level energy management approaches and in the second area, the focus is on the low-level control of the electrical machine. Several machines and control algorithms have been discussed in the literature to be used in flywheel systems. This include induction machines, doubly fed induction machines, DC machines, permanent-magnet synchronous machine, etc.

The flywheel storage system can stabilize the output power fluctuation of PV panels due to changes in the sunshine by a charge and discharge of storage energy from the flywheel system. This paper belongs to the first research area. We introduce energy management approach to reduce the PV output power fluctuations.

The rest of the paper is organized as follows. At the beginning, we present some related works in Section II. Then in Section III, we introduce our approach. In Section IV, we provide the simulation environment. In Section V we present a case study where we evaluate the proposed approach. Finally, Section VI concludes the paper.

II. RELATED WORK

Flywheel storage systems can be used in several applications such as smoothing fluctuating energy resources, frequency regulation, Uninterruptible Power Supplies (UPS), etc. [10], [11], [12]. The authors in [13] have introduced the usage of flywheels to reduce the charging and discharging cycles of a battery used to regulate the fluctuations of solar power sources. The authors investigated the effects of introducing a flywheel into a microgrid comprising photovoltaic equipment, batteries, and a load. The authors were able to reduce both the maximum charge and discharge power of the relative frequency of the battery. Smoothing the output power of distributed energy resources is one of the important applications of flywheels. The authors in [14] minimize the variations of the power generated by the diesel generator through a fuzzy logic based supervisor. The work in [14] proposed an approach that is based on the inputs filtering and processing and the feedback control to optimally operating the flywheel. This work aims to smooth the output power of a wind turbine

The work in [15] introduces a smoothing approach that counts on a traditional Inertial Filter. This approach analyses the relationship between capacity allocation and the time constant and its smoothing effect, and combined with Proportional Integral Differential (PID) control to realize power smoothing control of wind power. The smoothing approach employs the wavelet theory in order to realize a multi-layer decomposition of power output in some wind farms. Combining the Battery Energy Storage System (BESS) technologies and the characteristics of the Super Capacitor (SC) construct the power smoothing model based on hybrid energy storage technology The authors in [16] proposed a combination of flywheels with battery storage system in order to form a Hybrid Energy Storage System (HESS). The authors introduce a method to perform power quality analysis and DC voltage ripple quantification in an HESS connected solely to a DC bus. After that, the authors conduct lab testing and verification in order to characterize a flywheel-battery based HESS with different battery contribution levels. The intermittent nature renewable energy resources cause deviations from the nominal frequency in the grid. Frequency regulation is an application aims at holding the frequency very close the nominal frequency. Such an application requires a very short response time. The generators provided a frequency regulation as an ancillary service to improve the stability of the grid. A frequency regulation service to the grid operator can be bought by a power plant. Flywheels are capable of millisecond response times and nearly constant cycling, which make them ideally suited to this application. In [17] an optimized frequency regulation service is provided that offers strategies for a flywheel energy storage (FES) unit to the day-ahead markets and their associated real-time markets. Such offers allow independent grid operator to procures the service competitively. The FES offer strategies are obtained from the deployment of a robust optimization approach, which explicitly considers the uncertain nature of automatic generation control signals and the amount of FES stored energy. A control scheme to coordinate wind generators and flywheel energy storage systems is introduced in [18]. This scheme aims at provision grid frequency regulation services and energy balancing. Temporary backup electrical power can be achieved by Uninterruptible Power Supplies (UPS) Flywheel systems that used mostly everywhere [19], [20]. Flywheels can be used to solve voltage sag problems [21]. The main reason behind voltage sag is load unbalance which causes a decrease in voltage magnitude. This happens when large amounts of power for a short period of time is absorbed by the load, which will decrease the voltage and cause voltage drop problems [22]. In [23] a simple flywheel system is proposed that does not include semiconductor converter which is used as a voltage sag compensator using a capacitor self-excited induction generators.

III. APPROACH

In this section, we introduce our approach that is based on moving average (MA) in combination with linear programming (LP) to optimize the operation of the flywheel storage system. The inputs to the controller are the PV output and state of charge of the battery. The MA is used to reduce the fluctuation whereas the optimization is used to find the optimal charging and discharging periods that takes into consideration the production forecast. This way, the approach tries to maintain the state of charge at a level that is suitable for the future fluctuations. This model is suitable to be applied in the real time operation of a flywheel system. We assumed that a short-term production forecast is available. Forecast methods and its accuracy are beyond the scope of this paper.

A. Moving Average

The controller uses a moving average (MA) method to compute the time moving average for a period of Δ (sec).

The sample mean can be calculated at time `t` as shown in the following Equation 3.

$$MA_t = \frac{P_{PV}(t) + P_{PV}(t-1) + .. + P_{PV}(t-\Delta+1)}{\Delta} \tag{3}$$

where $P_{PV}(t)$ is the PV output power at time `t`.

B. Optimized Operation

We have applied linear programming for optimizing the operation of the flywheel system. We have adventured PV production forecast to preserve the state of charge of the flywheel within optimal limits that take into its account the future PV production. The objective is how to minimize the difference between the average and to prevent unnecessarily charge and discharge and current PV output power.

$$min\{\sum_{t=1}^{T} |P_{PV}(t) - MA(t)| + P_c(t) + P_d(t)\} \tag{4}$$

The flywheel energy balance can be modeled as:

$$FW(t+1) = FW(t) + \eta_c P_c(t) - \frac{P_d(t)}{\eta_d} \tag{5}$$

$$FW^{max} \geq FW(t) \geq FW^{min} \tag{6}$$

Where $FW(t)$ is the state of charge for flywheel at time `t`, $P_d(t)$ indicates power discharged from the battery, $P_c(t)$ is the power charged in the battery, η_c is the charge efficiency in the battery, and η_d is the discharge efficiency of the battery. The storage system is limited with the rated power.

$$P_d^{max} \geq P_d(t) \tag{7}$$

$$P_c^{max} \geq P_c(t) \tag{8}$$

P_c^{max}, P_d^{max} indicates the maximum amount of power allowed to charge and discharge, respectively.

The next set of equations for flywheel is guaranteeing the state of charge and discharge

$$P_d^{max} x(t) \geq P_d(t) \tag{9}$$

$$P_c^{max} (1 - x(t)) \geq P_c(t) \tag{10}$$

$$x(t) \in \{0, 1\} \tag{11}$$

IV. SIMULATION EXPERIMENTS

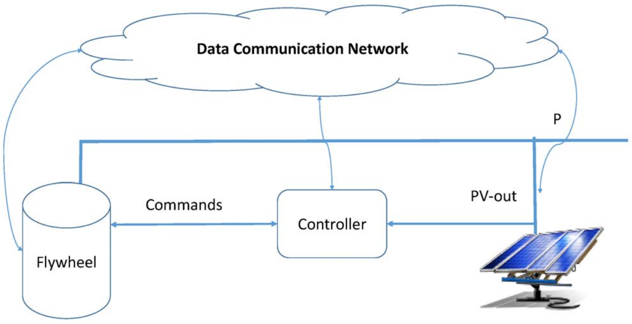


Fig. 1. The structure of the system

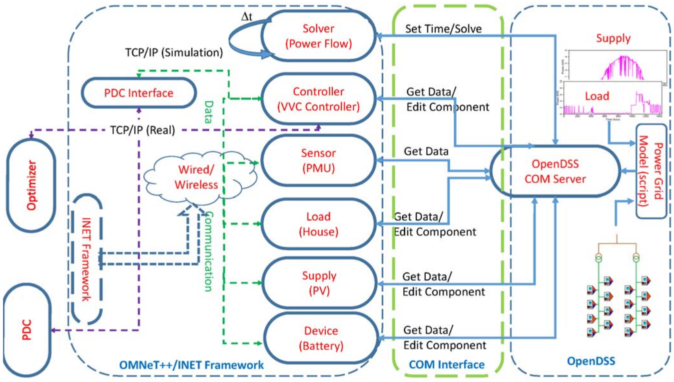


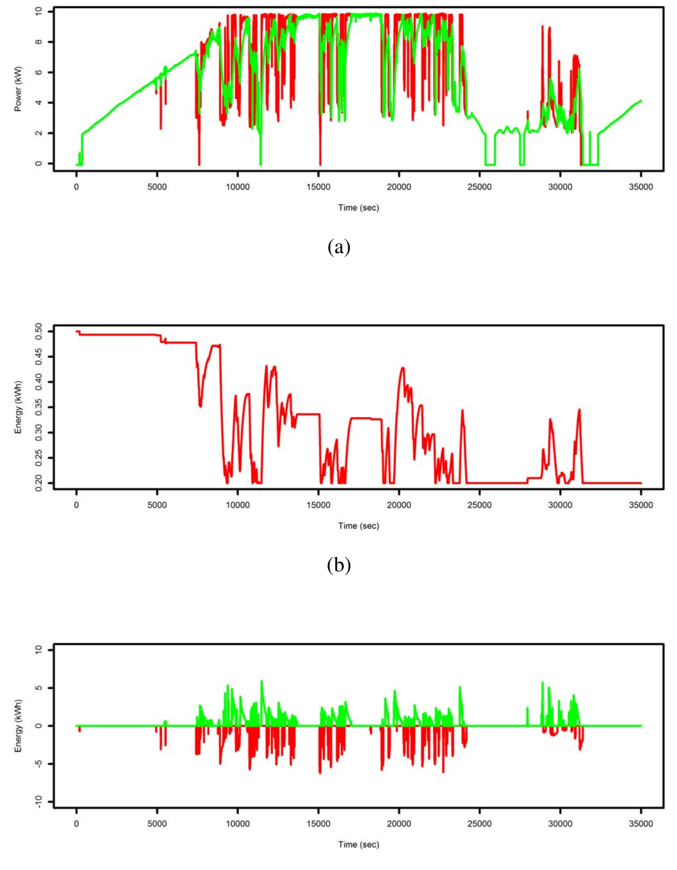
Fig. 2. The structure of SGsim: It illustrates the interconnection between the different components

Exploring Smart grid applications requires dealing with several tools that have the ability of capturing the multi-disciplinary field of smart grid. SGsim [4]–[6] which is multi-simulator framework have been used to evaluate the approach. Mainly, it is based is based on two simulators: OpenDSS [24] to simulate the power grid and OMNeT++ [25] to simulate the data communication grid in addition to controlling the behavior of the different components (e.g. the behavior of the flywheel). OpenDSS offers not only a stand alone software, but also it provides a COM server (DLL) that can be driven from an another program such as matlab or any software. In our case we wrote a dll library (SGsimLib.dll) to access opendss from a C/C++ code written in OMNeT++. several frameworks, such as the mixim and INET framework, have been developed with well-tuned data communications components such as Ethernet, Wireless protocol and many other protocols. Figure 2 shows the components of the SGsim. The Library make it possible to control the run of the circuit such that it is possible to edit/add/remove different components during the run-time. For instance, `RegControl` is designed to emulate a standard utility voltage regulator or LTC control. The following edit command can be used to change the parameters of `regcontrol.TR1` , i.e., set the value of the voltage at the transformer to 228.

```
  edit regcontrol.TR1 transformer=TR1
winding=2 vreg=228
```

This is very useful when simulating time-dependent scenarios. The main components of SGsim can be summarized as follows:

- Power Grid Model (or the circuit): a text file (script) that describes the circuit should be given to the SGsim. Additionally, time-dependent loads and supplies profiles can be provided as csv or text files. The load and supply can be obtained from data bases such as Pecan Street [26]. The database provides load and supply signals with different resolutions (mainly 1 hour and 1-min). The consumption of individual components is also provided.
- Solver: It controls the execution of the OpenDSS through the library (COM interface). It is a very critical component because it ensures time synchronization between the two simulators (i.e. between OpenDSS and OMNeT++).



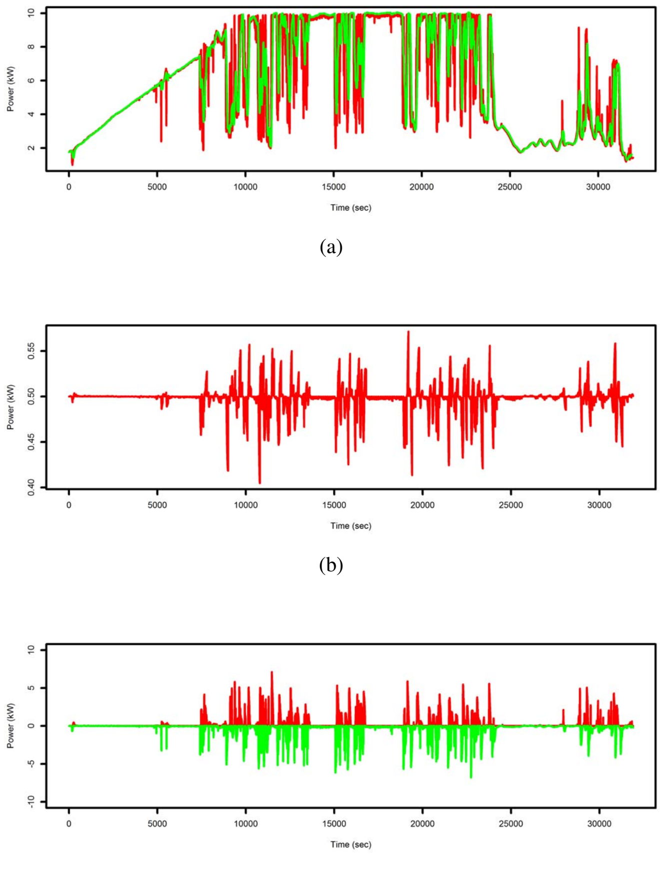
(a)

(b)

(c)

Fig. 3. Results for window size 100 seconds without Optimization: (a) PV output without the flywheel (red) and with the flywheel (green), (b) flywheel state of charge, (c) charge (red) and discharge (green) cycles

- Load: It is an OMNeT++ component corresponds to the load in the electricity network, e.g., a house. Different parameters can be measured at this component which can be used in different smart grid applications. It is also possible to change load parameters during the run-time, e.g., running an elastic load.
- Supply: It is a power generation source in OMNeT++, e.g. distributed energy sources (DER). It is also possible to change the parameters of the supply during the run time, e.g. the output power (active and reactive power).
- Device: it represents power gird devices (eg flywheel, switch, capacitor bank, ...). The COM interface makes it possible to change the parameters, such as the power factor. The flywheel is modeled as a storage element and controlled by the OMNeT++.
- Sensor: It is used to monitor the devices, for instance it can measure the voltage at a particular component (e.g. DER, Storage devices, etc.) and sends the values to other components.
- Controller: Based on the received data and the approach, this component controls the behavior of the system. For example, a moving-average controller can control the flywheel to deliver or absorb the power as required to smooth the PV output power.



(a)

(b)

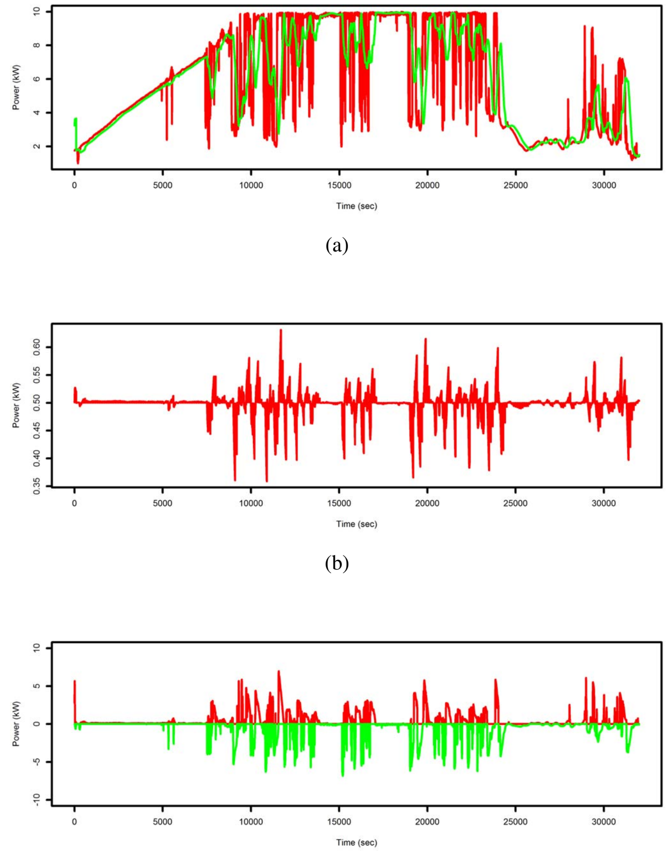
(c)

Fig. 4. Results for window size 100 seconds: (a) PV output without the flywheel (red) and with the flywheel (green), (b) flywheel state of charge, (c) charge (red) and discharge (green) cycles

- PDC interface: This component allows you to visualize the data from the system. It receives simulated TCP/IP packets. It converts it into real TCP / IP packets and forwards them to real software components such as OpenPDC
- Optimization Tools One of the main characteristics of the smart grid is to optimally run the different power grid components. To achieve this goal, optimization tools plays an important role. In the SGsim framework, we integrated the open source optimization tools NLopt [27] and LpSolve [28]. NLopt is an open source nonlinear optimization tool which contains implementations of different algorithms. LpSolve is an open source optimization library to solve mixed integer linear programming. The integration of other tools such as MATLAB [29] and R [30] is also possible.

V. CASE STUDY

We employ the moving average method as well as an optimization approach that have been introduced in section III to smooth the output power of a PV system. The open



(a)

(b)

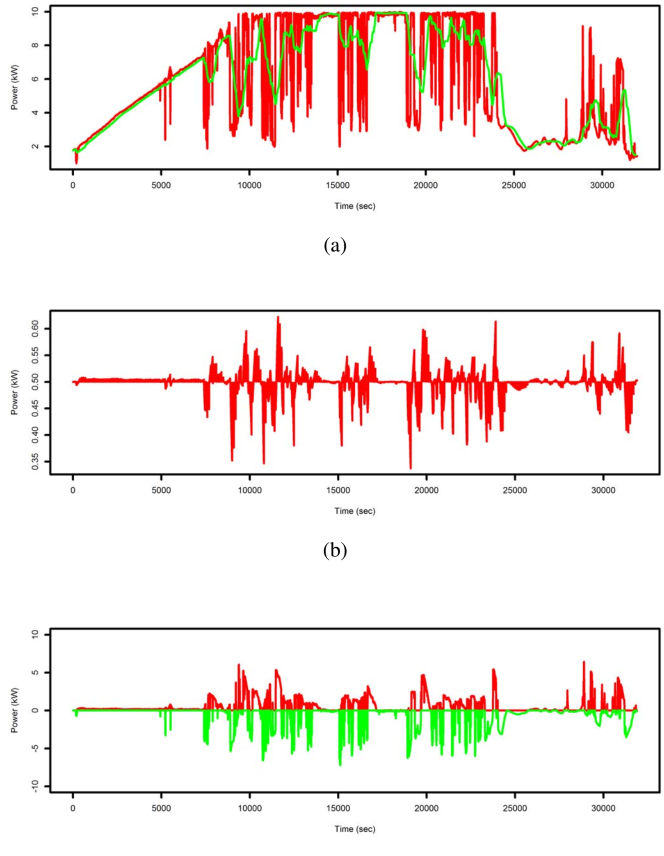
(c)

Fig. 5. Results for window size 300 seconds: (a) PV output without the flywheel (red) and with the flywheel (green), (b) flywheel state of charge, (c) charge (red) and discharge (green) cycles

TABLE I. SIMULATION PARAMETERS

Parameter	Value
PV	10 kW
FW^{max}	1 kWh
FW^{min}	0.2 kWh
P_c, P_d	10
η_c, η_d	0.9
Δ	50, 300, 500 sec
T	100 sec

source simulator SGsim has been used to perform simulation experiments. The system consists of a PV system, flywheel and a controller as shown in Figure 1. The measured PV output is sent to the controller which in turns finds the optimal charging and discharging periods to smooth the PV output. The controller sends the charging and discharging commands to the flywheel. Table I summarizes the parameters that used during the simulation. As listed in the table, the flywheel has a small size storage capacity and high power. We explored the impact of different window sizes. The data are 1 second resolution taken from OpenDSS [31]. The red line in Figure 3 shows the original PV output power. As evident from the figure, the PV output power has very high degree of fluctuation.



(a)

(b)

(c)

Fig. 6. Results for window size 500 seconds: (a) PV output without the flywheel (red) and with the flywheel (green), (b) flywheel state of charge, (c) charge (red) and discharge (green) cycles

Figure3 illustrates the results without utilizing the optimization. The red line shows the output power without smoothing and the green line shows the effect of employing flywheel with the only moving average approach (without linear programming) to smooth the PV output power. The results from Figure 3(a) demonstrate a reduction in the fluctuations. Yet, at some points, the flywheel was not in its optimal state of charge. For instance, it was not charged enough when it was necessary to get power from it at the end of the day as indicated in Figure 3(b).

As expected, when we applied the optimization, the results are getting better as can be found in Figure 4(a). As can be observed in Figure 4(b), the flywheel state of charge has been kept near the 0.5 kWh so that it is possible to charge and discharge the flywheel as necessary.

In the final set of simulation experiments, we explored the effect of increasing the window size. The results for window sizes of 300 and 500 seconds are given in Figures 5 and 6, respectively. As we can see, increasing the window size has a positive impact on the output power.

The charging and discharging cycles are huge in all cases as it is evident in the Figures 3(c), 4(c), 5(c), and 6(c) and hence a normal battery would not be a good choice for such an application.

VI. CONCLUSION

In this work, we explored the usage of flywheels to smooth the output power of a PV system. We introduced an approach that is based on moving average and predictions. A linear programming problem has been introduced to optimize the operation of the flywheel. The approach is simple and hence can be integrated into the controller to run in real time. We have explored the impact of exploiting the supply forecast to optimally operating the flywheel. The results show a substantial reduction in the fluctuations of the output power.

Flywheels have several characteristics that qualify them to be used in many power grid applications:

- Very short response time.
- Long life span which is not affected by the frequent charge and discharge.
- High power rate.

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