Control Strategies and Hybrid Optimization Scheme for an Electric Power Grid

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Abstract

Energy infrastructure development in rural and remote areas of the planet is key to sustaining human development. This study establishes an optimal control strategy that can efficiently manage an electric grid comprised of various renewable and non-renewable energy sources for a medium sized community. Simple power dynamics are modeled and used for representing the components present on the grid. A hybrid model predictive control scheme is implemented for choosing an optimal mode and set of inputs for the system for tracking both a constant and load-varying power demand profile.

Index Terms: hybrid, power, supervisory, model predictive control, smart grids

1 Introduction

Securing sustainable energy has been of prime importance amidst climate change, diminishing fuel supply and global warming concerns. The growth of the energy sector faces a two-fold challenge[1]: provide more energy at affordable prices so as to meet growing power demands and to increase efficiency through the use of more environmentally sustainable energy sources .

Even more challenging is the energy infrastructure development in rural areas of the planet which is key to sustaining human development. Recent advances in technology have made the use of micro-grids more economical. Hence it becomes imperative to harness and optimize power generation through the use of locally abundant sources such as bio-waste, fast moving water bodies etc. along with other renewable sources such as wind, solar and tidal farms to form a grid powered by multiple renewable sources. This allows for a myriad of architectures that can be tailor fit for specific regional situations.

The analysis of microgrids is discussed in [4, 5] and an economic dispatch method is discussed in [6]. This paper differs in the regard that analysis and control of the microgrid is done from a supervisory controller's standpoint. The inherent stochastic nature of the power generation is not considered to allow for a simpler implementation. The current formulation assumes a microgrid in island mode, i.e. not connected to an external power grid.

The main focus of this study is to develop a supervisory power controller that determines the power split between an energy storage system and a Diesel Generator (DG) in meeting a Reduced Power Profile (RPP). This report is structured in the following manner: Subsection 2 explains the system being considered, the advantages of a power control strategy, power command hierarchy and the selection of the power profile. Subsection 3 explains the model and the formulations for Model Predictive Control (MPC) and the subsequent results. Subsection 5 outlines the solutions developed to circumvent the issues faced whilst implementation. Subsection 6 summarizes the project and the outlines the future activity in this regard.

2 System Model Development

2.1 Power Grid Architecture

Figure 1 depicts the system containing 3 energy sources: a solar farm, a Storage System (SS) and a Diesel Generator(DG). The 50kW solar farm is representative of renewable energy sources used. This could be substituted for two or more other renewable energy sources which directly feed to the power grid. The SS could be a battery bank composed of recycled lead acid or Li-based cells or water tanks/reservoirs where water is pumped for the purpose of irrigation and power generation. The SS has been approximated for a maximum storage capacity of 800kWh using a energy/power flow model with self-discharge depicting the losses incurred with the storage of energy. The hybrid nature of the model stems from the charging and discharging of the storage bank, which allows for bi-directional power flows to/from the microgrid. The DG considered is a commercially available 150kW diesel powered generator whose usage is to be kept at a minimum.

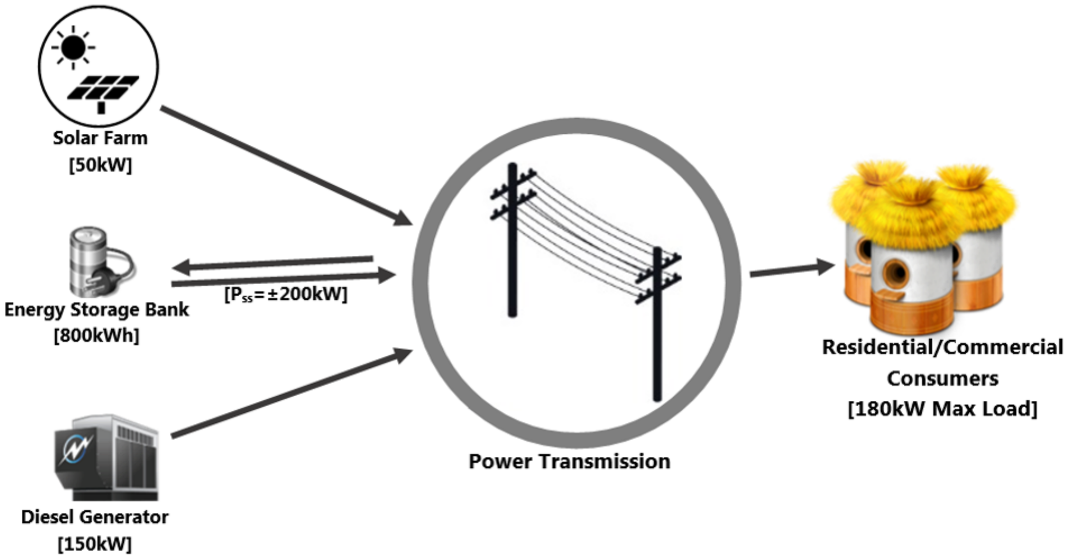

Figure 1: Microgrid comprising of 3 power sources and a load

This hence leads to a power-balance equation given by Eq.1,

$$P_{solar} + P_{ss} + P_d = P_{load} \tag{1}$$

2.2 Solar Farm

The solar farm considered is a medium-sized photo-voltaic cell farm that consists of 221 solar panels, see Fig. 2.


Figure 2: 50kW Solar Farm, [2]

The power output of the solar farm for a typical day is illustrated in Fig 3. Variations in power output due to solar geometry, temperature changes, efficiency changes, wear etc. are neglected and assumed to be captured by this output power profile. This is a valid assumption for the purposes of hourly scheduling of power delivery by a supervisory controller as solar farms often contain energy storage units that can buffer energy. Such a buffering allows for minor deviations due to photo-voltaic cell output while major deviations can be readjusted in the power profile provided to the supervisory controller on a timely basis. The power output of the solar farm is considered as $P_{solar}(t)$.

2.3 Storage Systems (SS)

A 80kWh storage system is considered. While the type currently considered is for a battery bank, this can substituted for any storage system. The model is obtained from [6] where a self-discharge is also considered.

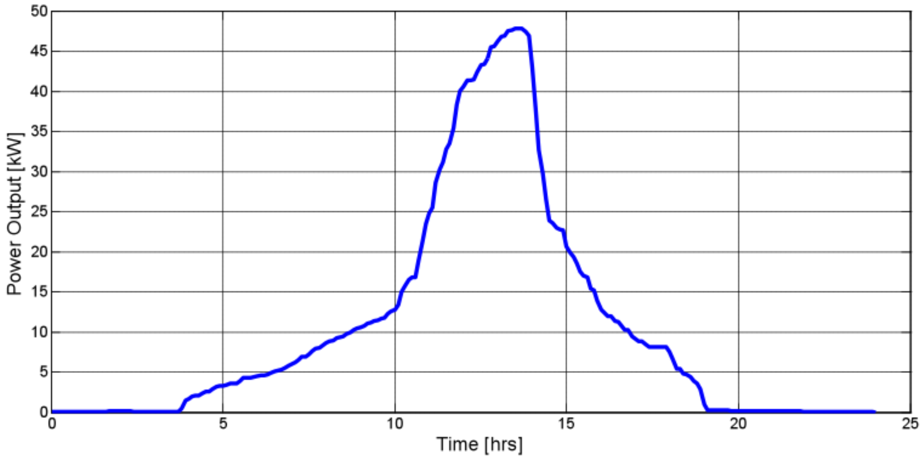

Figure 3: Solar Farm Power, [6]

The state of charge (SOC) of the battery is the ratio of the residual energy to the total energy of battery. It is important to know the SOC of the battery for accurate control of the microgrid. The equation for the charging dynamics of the SS is given by Eq.2

$$\dot{E}_{ss} = -\delta_{ss} E_{ss} - \frac{P_{ss}\eta_{chrg}}{E_{ss}^{max}} \tag{2}$$

where, E_{ss} is the current SOC which is representative of the energy content in the battery, P_{ss} is the power entering the battery in kW, η_{chrg} is the charging efficiency of the battery and E_{ss}^{max} is maximum storage capacity of the battery in kWh.

The equation for the discharging dynamics of the SS is given by Eq.3

$$\dot{E}_{ss} = -\delta_{ss} E_{ss} - \frac{P_{ss}}{E_{ss}^{max}\eta_{dis}} \tag{3}$$

where , η_{dis} is the discharging efficiency of the battery.

2.4 Storage System Power

The storage system power dynamics are modeled using first-order lag dynamics represented by Eq.4. The equation represents the lag between the power command and delivery and is modeled after the power dynamics equation presented in [7]. This modeling approach was considered sufficient at the supervisory level. Detailed dynamics of the SS and it's power delivery can be considered in a local-level controller.

$$\dot{P}_{ss} = -\frac{1}{\tau_{ss}} P_{ss} + \frac{U_{ss}}{\tau_{ss}} \tag{4}$$

where, τ_{ss} is the average delay incurred between power command and delivery in sec, U_{ss} is the power commanded by the supervisory controller in kW.

2.5 Diesel Generator

[7] considers a first-order lag equation to describe the dynamics of the diesel engine. Since the dynamics of the generation system attached to the diesel engine is faster than the diesel engine and hence the overall power dynamics can be assumed to be mostly dependent on the diesel engine's dynamics. Hence, Eq.5 sufficiently describes the power output dynamics of the diesel generator at a supervisory level. The supervisory controller provides a power output command to the Diesel Generator. A local controller capable of following this commanded output is assumed and provides the required control inputs to meet the commanded power output.

$$\dot{P}_d = -\frac{1}{\tau_d} P_d + \frac{U_d}{\tau_d} \tag{5}$$

2.6 Reference Power Profiles

The load reference profile obtained from [6] for a 24hrs time horizon and is presented in Fig 4. This power demand profile reflects real world characteristics and has a peak power demand of 180kW.

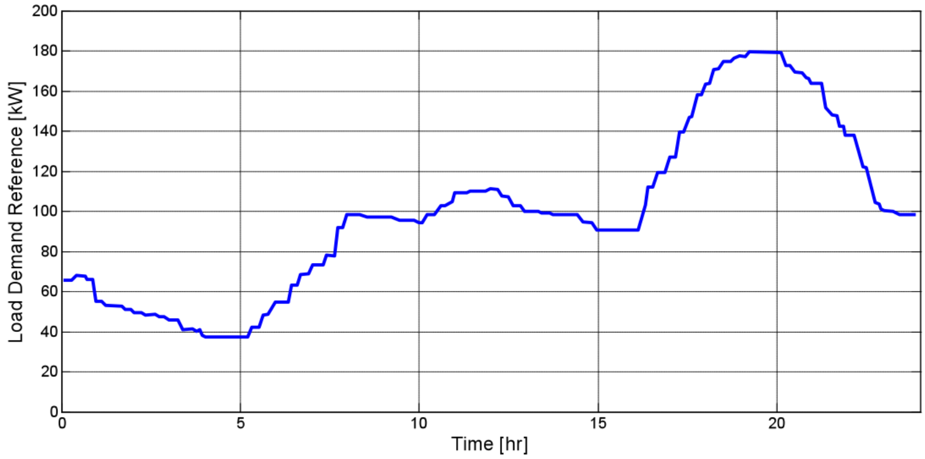

Figure 4: Consumer Load Power, [6]

In this order of ideas, the reference to be tracked is modeled as in Equation 6, where the power from the solar farm is subtracted from the consumer load to provide the full reference power that the electric grid will need to deliver. Other renewable energy sources can at this point be used to further reduce the power levels of the demand profile.

$$P_{ref} = P_{load} - P_{solar}(t) \tag{6}$$

2.7 Control Scheme

Fig 5 depicts the control hierarchy of the hybrid system, where the supervisory controller provides control commands to the various components on the electric grid. The main objective is to make maximum use of the renewable power source, i.e. the solar farm, while using the least amount of power from the diesel generator.

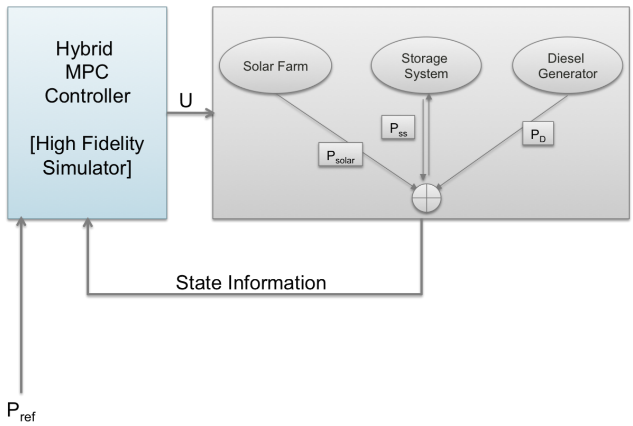

Figure 5: Controller and Power Grid Implementation

The supervisory controller doesn't directly control the operation of the solar farm, but allows for the maximization of the solar power usage by tracking a reduced power profile given by Eq.6.

The state information fed back to the controller consists of information on the power delivery by the DG, SS and it's current energy level along with power output by the solar farm. The controller uses a High Fidelity Simulator that solves the system as a continuous system given a time horizon and selects piece-wise optimal mode sequences and control inputs. The controller then send the power commands U to the respective systems on the power grid.

The current state information is then returned from the systems back to the controller to reduce the cumulation of modeling errors and the controller increments it's prediction horizon. This process is repeated iteratively for each partition during the prediction horizon. Section 5 provides a detailed explanation of the implementation of this control logic.

3 Control Problem

The problem at hand is to perform an optimal power reference tracking problem, where the consumption of energy from the diesel generator is minimized, while maximizing the efficiency of the storage bank.

Subsection 3.1 explains the formulation and implementation of the model predictive control (MPC) on the system, where a convex analysis is enforced on the mode switching, to guarantee autonomy and best performance from the controller and the optimization algorithm. All programming was performed using Matlab.

3.1 Implementation of the MPC

The assumptions, cost function, system dynamics, constraints and subsequent MPC treatment are listed below:

1. **Assumptions**
   - Generator, SS charge/discharge efficiencies assumed to be constant
   - Power Transmission Line loss assumed as part of reference load profile

2. **System Dynamics**
   Let x represent the state variables and u the control inputs

$$x = \begin{bmatrix} E_{ss} \\ P_{ss} \\ P_d \end{bmatrix} \qquad u = \begin{bmatrix} U_{ss} \\ U_d \end{bmatrix}$$

   Then, the hybrid system is modeled as a continuous linear time-invariant system with three states variables and two control inputs as follows:

$$\dot{x} = A_\sigma x + Bu \qquad \sigma = 0, 1 \tag{7}$$

   where each hybrid mode is represented by a different dynamics stated in the matrix A:

$$A_{\sigma=0} = \begin{bmatrix} -\delta_{ss} & -1/(\eta_{dis} \cdot E_{ss}^{max}) & 0 \\ 0 & -1/\tau_{ss} & 0 \\ 0 & 0 & -1/\tau_d \end{bmatrix} \qquad A_{\sigma=1} = \begin{bmatrix} -\delta_{ss} & -\eta_{chrg}/(E_{ss}^{max}) & 0 \\ 0 & -1/\tau_{ss} & 0 \\ 0 & 0 & -1/\tau_d \end{bmatrix}$$

   The inputs are related to the states through the B matrix, which remains the same regardless of the mode operation

$$B = \begin{bmatrix} 0 & 0 \\ 1/\tau_{ss} & 0 \\ 0 & 1/\tau_d \end{bmatrix}$$

3. **Performance Index/Cost Function**
   The optimization problem is formulated as shown in Equations 3.

$$
\begin{aligned}
\underset{u_{\sigma=0},\, u_{\sigma=1},\, v}{\text{minimize}} \quad & \int_{t_0}^{t_f} w_1 \cdot P_d^2 + w_2 \cdot \left(E_{ss} - E_{ss}^{nom}\right)^2 \\
& + w_3 \cdot \left(P_d + P_{ss} - P_{Load}^{ref}(t)\right)^2 + \Psi(x) \\
\text{subject to} \quad & \dot{x} = \hat{A}x + B\hat{u} \\
& \underline{x} \le x \le \overline{x} \\
\text{where,} \quad & \hat{A} = v \cdot A_{\sigma=0} + (1-v) \cdot A_{\sigma=1} \qquad v \in [0,1] \\
& \hat{u} = v \cdot\ u_{\sigma=0} + (1-v) \cdot u_{\sigma=1} \\
& \Psi(x) = (x < \underline{x}) \cdot (x - \underline{x})^2 + (x > \overline{x}) \cdot (x - \overline{x})^2
\end{aligned}
$$

where w_x are tracking weights, $w_1 = 5$, $w_2 = 2$ and $w_3 = 40$. The optimizer solves this problem as an embedded problem where $v \in [0,1]$. These are then projected based on the algorithms described in 5

4. **State Constraints**
In an attempt to model the system to be able to deliver a realistic power load, it is very important that the storage bank be protected from deep discharge and overcharge. This implies that the net energy in the storage bank should be constrained for efficient usage of the battery. Furthermore, the power input/output from the battery needs to accommodate the maximum and minimum capacities.

The constraints on the diesel generator are strictly determined by the model used. Equations **??** are used to enforce power and energy constraints.

$$
\begin{bmatrix} E_{ss}^{min} \\ P_{ss}^{min} \\ P_d^{min} \end{bmatrix} \le \begin{bmatrix} E_{ss} \\ P_{ss} \\ P_d \end{bmatrix} \le \begin{bmatrix} E_{ss}^{max} \\ P_{ss}^{max} \\ P_d^{max} \end{bmatrix}
$$

Furthermore, both the initial state, initial time and final time are fixed, while the final state is free. So that:

$$
E_{ss,t_0} = E_{ss,nom}
$$

5. **Projection of Logic**
The control outputs from the MPC depend on the current mode of operation of the system, v. These outputs are determine by using two different approaches using the embedded value of v provided by the optimization algorithm:

   - **Logic projection**
   The hybrid mode v is computed as a continuous state ranging from $[0,1]$. Once a value has been assigned, this is projected to either mode 0 or mode 1 satisfying the following logic:

$$
\begin{aligned}
\text{if} \quad v \quad &> \quad 0.5 \quad \text{then} \quad v = 1 \\
\text{else} \quad v \quad &= \quad 0
\end{aligned}
$$

   - **Projection based on U_{ss}**
   In this case, the sign of the control input U_{ss} determines whether the system goes to charging or discharging mode. i.e.,

$$
\begin{aligned}
\text{if} \quad U_{ss} \quad &> \quad 0 \quad \text{then} \quad v = 0 \\
\text{else} \quad v \quad &= \quad 1
\end{aligned}
$$

From either logic, an optimal sequence of control inputs is obtained for the total time horizon, which minimizes the power delivered from the diesel generator, while maximizing the efficiency of the storage bank.

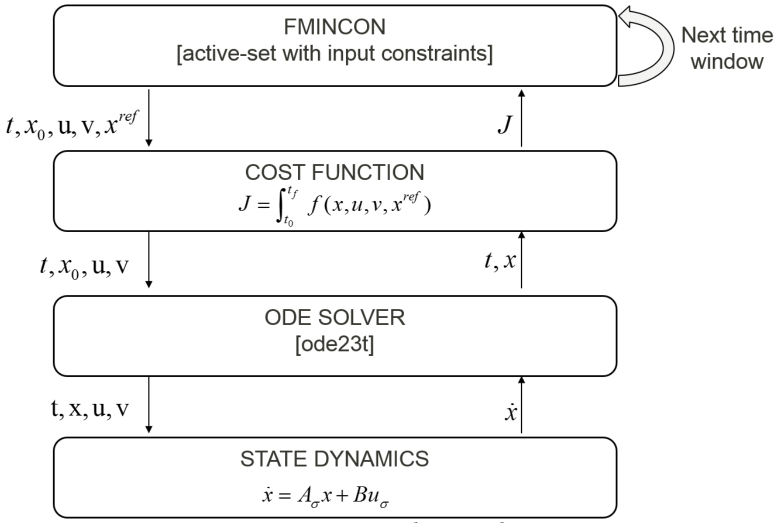

Figure 6: Power Flow Outline [6]

Software Implementation
The above problem was solved using matlab's inbuilt *fmincon* function as shown in Fig. 6
fmincon performs the optimization by calling on a cost function. The cost function enforces the penalty on both the states. Furthermore, the states are propagated within the cost function using numerical integration through matlab's inbuilt *ode23t* function. This integration is performed subject to the dynamical equations provided to the integrator via the system dynamics function.

The whole process is repeated for each time window, until the total simulation time has been spanned. Each iteration produces an optimal control output and optimal hybrid mode, which can then be compiled into the optimal sequences show in the figures in section 4.

4 Results

Two sets of power reference profiles were tracked by using the parameters listed below:

Parameter Name	Value
δ_{ss}	.04 %/hr
η_{chrg}, η_{dis}	0.9
τ_{ss}	0.1sec
τ_d	0.3sec
$[E_{ss}^{min}, E_{ss}^{max}]$	[400, 800] kWh
$[P_{ss}^{min}, P_{ss}^{max}]$	[-200, 200] kW
$[P_d^{min}, P_d^{max}]$	[0, 150] kW

All examples were run using the same set of initial conditions. Figures 7 and 8 show the 3 set of inputs commands obtained from tracking a $50kW$ power reference load, and the trajectory followed by the state variables respectively. The simulation was run for a total time of 24 seconds, and as it is seen from the plots, the power produced by the diesel generator does oscillate about a constant value of $50kW$, as it is trying to follow the reference.

Furthermore, we see that as the diesel generator tries to stabilize, the hybrid state continues to switch from one mode to another, as it is expected since the system is trying to find the correct balance between the two sources.

Next example (see Figures 9 and 10) was performed in hours for a total of 8 hours spanned. In this case it is clear how as the diesel generator is delivering the required power, the power produced by the energy storage system drops. These results are consistent with the dynamics of the hybrid system, and it is exactly what we expect the system to behave like.

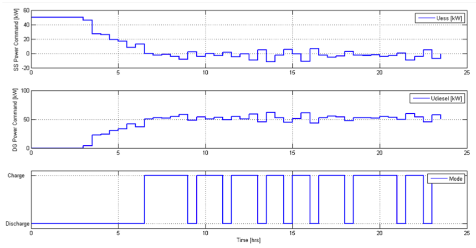

Figure 7: Inputs, Test Case 1, 50kW Reference

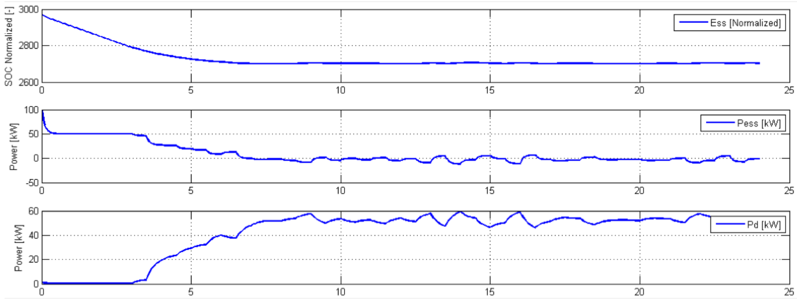

Figure 8: States, Test Case 1, 50kW Reference

Also note that as the system is run in time-step units of hours instead of seconds, the state of charge of the battery reaches its nominal value at a much faster rate.

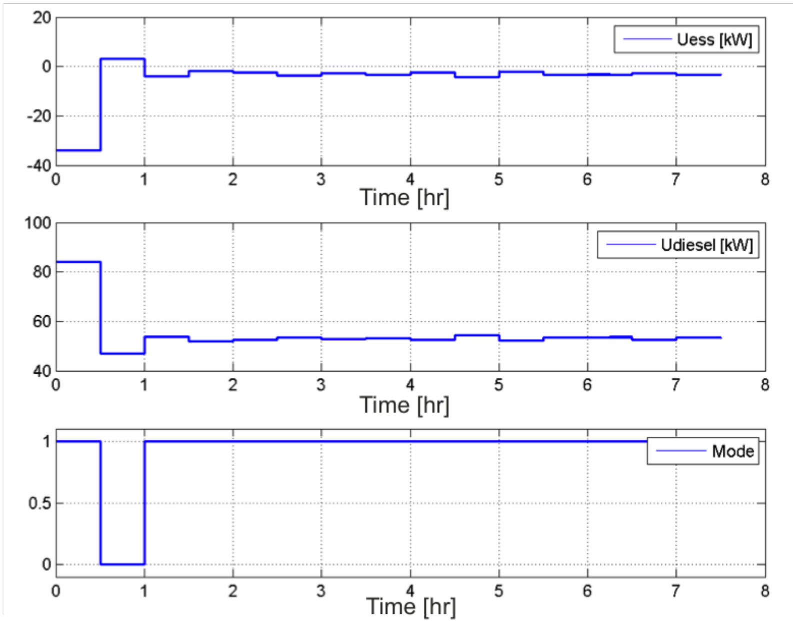

Figure 9: Inputs, Test Case 2, 50kW Reference

To further assess the robustness of the hybrid controller, a load reference profile is used instead of the 50kW constant load. Figures 11 and 12 show the performance of the system when subjected to this inputs. Just like in the previous cases, the power required to deliver such reference profile is a combination of both the diesel generator and the storage bank. While the diesel generator is providing most of the power, it reaches its maximum capacity after about 20 hours, time at which a mode switch is needed, and the rest of the power needs to be provided by the battery. However, the battery capacity is not enough to provide the 30kW left to deliver the required power load.

This is one of the cases where the reference profile load is being well tracked, but due to the limitations on maximum power delivered by the energy sources, the full power demanded by the load cannot be met.

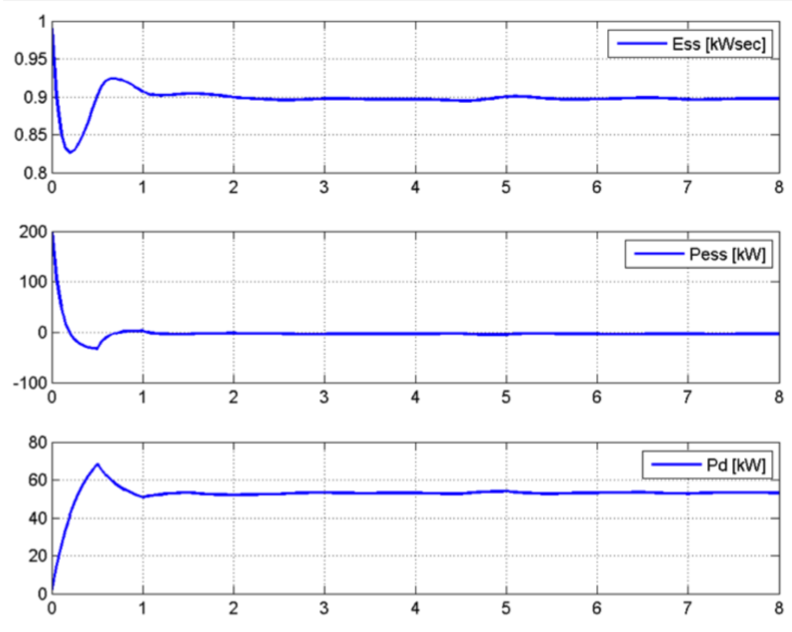

Figure 10: States, Test Case 2, $50kW$ Reference

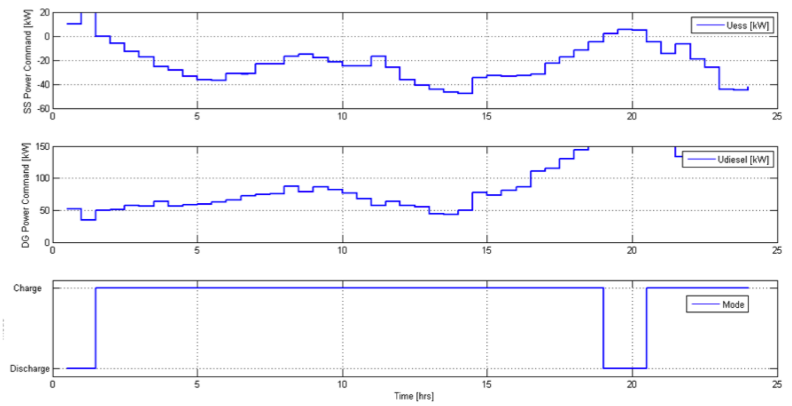

Figure 11: Inputs, Test Case 3, Load Profile Reference

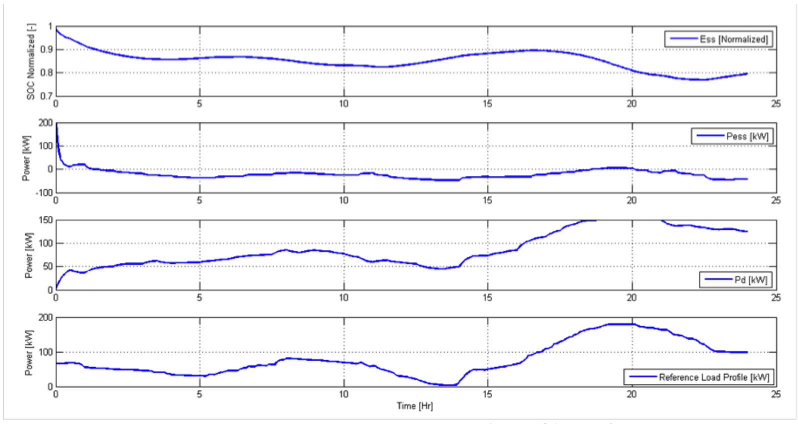

Figure 12: States, Test Case 3, Load Profile Reference

5 Implementation Challenges

While *fmincon* is a powerful optimization tool, it can still be very sensitive to numerical accuracy. This is the case when the orders of magnitude used in the system models for the A and B matrices, Equations 7, differ significantly. In such cases we note that:

- The stability and controllability of the hybrid system is highly affected by the time delays driving the

- dynamical equations, as MPC computation time depends on whether the power reference is being tracked in time horizons spanned in seconds or in hours.
- The reference power profile is not always met due to the limitations on the maximum power that can be delivered by the energy sources chose in this application (see Fig. 12), as well as the restrictions on storage capacity of the battery.

6 Conclusions

Dynamical equations were modeled to simulate the behavior of the power produced by a diesel generator and an energy storage system. These models reflect realistic bounds on the maximum and minimum power deliver by each source, based on today's technology.

A hybrid model predictive control (MPC) algorithm was implemented to track the power transmitted to an electric grid, as it follows a pre-specified reference power profile that it is assumed to capture all variations seen in real world due to solar geometry and weather, among other factors.

The main objective of delivering power to a consumer load from two different sources of energy was accomplished by a hybrid switching between charging and discharging modes of the storage system, as well as a convex logic implemented on the control inputs, that maximized the efficiency of the storage bank and minimized the consumption of energy from the diesel generator. State and inputs bounds were successfully enforced using an added penalty in the cost function.

A projection logic was also implemented and tested to perform well for these sorts of applications, where the mode switches are driven by the current value of the control inputs.

In summary, successful results were obtained for tracking both a constant and a time-varying load reference power profile, using two different approaches to perform the hybrid switching, while optimizing a cost function that guarantees minimum usage of non-renewable energy sources as it maximizes the consumption of power delivered by a renewable energy source.

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