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Optimal Energy Management Using Sequential Quadratic Programming Algorithm for Stand Alone PV System

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Abstract

The operation of the standalone photovoltaic (SAPV) system predominantly depends on solar generating units and battery storage systems (BSS). This paper proposes the utilization of Sequential Quadratic Programming (SQP) algorithm for achieving optimal energy management and also for supplying energy continuously to critical loads. The stand-alone PV system is modeled and the SQP algorithm is implemented on the same. Different test cases are evaluated and validated.

Keywords— SQP Algorithm; Stand-Alone PV; Energy Management

<u>Nomenclature:</u>

I_L photo generated current

I_0 dark current

R_s series resistance

R_p shunt resistance

V_{mpp} maximum power point voltage

V_{ocg} open circuit voltage of PV generator model

K_1 constant based on material

Q amount of current stored by the battery at a given time

C battery capacity

I_{10} required current for discharging battery bank in 10h

I_B battery current

ΔT temperature difference between battery temperature and 25C

η_B Battery Faraday Efficiency

I_{DC} Direct current

I_{AC} Alternating current

V_{DC} Direct voltage

V_{AC} Alternating voltage

η_{inv} Inverter Efficiency

a_1 logic signal from priority control algorithm

a_2 logic signal from load schedule

INTRODUCTION

Micro grids operate in two modes: Grid connected and Islanded mode[1]. In islanded mode, alternative energy sources are employed to meet the load demands in the network. Photovoltaic (PV) Solar energy is the most commonly used energy source in the microgrid [2-5]. The SAPV acts only in islanded mode and demands an energy storage device which involves significant cost. The sizing of solar generating unit and BSS are critical for any SAPV system [6-8]. A better energy management along with the efficiency may be achieved by optimal control of BSS and the loads in the network.

The loads are classified based on priority as: emergency, critical, essential and convenient loads [9-11]. The BSS may be allotted a variable priority based on state of charge (SOC) of the battery. This problem is formulated mathematically by considering the specified priorities of the loads. Dynamic programming is utilized to identify the optimal solution for the same. In this paper, Section II provides details of SAPV specification and modeling. Section III elaborates the SQP Algorithm. Section IV considers suitable test cases that validate the operation of SQP Algorithm on the SAPV system. Section V presents the conclusion of the paper.

SAPV Specification And Modelling

The SAPV system is modeled in Matlab/Simulink software. This stand-alone PV system is having PV panel, Battery, regulator, inverter and the load. The modeling of all the components is explained.

The different models include:

i) PV Generator Model

The PV generator model is based on the equivalent circuit of a solar cell and is given as (1). The simulation considers solar radiation and temperature data.

$$I = I_L - I_o \exp\left(\frac{e(V+IR_s)}{mkT} - 1\right) - \frac{V+IR_s}{R_p} \qquad (1)$$

Maximum Power Point Tracking (MPPT) Model

If MPPT is not available in SPVA system, then usually the system behavior is influenced by the battery behavior. In this paper a MPPT model is considered so as to decouple the PV generator and the battery bank, thereby providing MPPT voltage to the PV generator. An 'Open Circuit Voltage PV generator model' is considered for analysis as indicated in (2).

$$V_{mpp} = K_1 V_{OCG} \tag{2}$$

ii) Battery Storage Model

Primary equations are initially defined for discharge, charge and overcharge conditions of batteries. The state of charge, amount of currents stored by the battery, battery capacity and faraday efficiency are given by (3), (4) and (5) respectively.

$$SOC = \frac{Q}{C} \tag{3}$$

$$Q = \eta_B I_B \Delta t \tag{4}$$

$$C = \frac{1.67 C_{10}}{1 + 0.67\left(\frac{I_B}{I_{10}}\right)}(1 + 0.005\Delta T) \tag{5}$$

$$\eta_b = 1 - \exp\left[\frac{20.73(SOC - 1)}{\frac{I_B}{I_{10}} + 0.55}\right] \tag{6}$$

iii) Regulator Model

This model aids in protecting the batteries from over discharge and also enables in reconnecting the recovered batteries into the network. And also the regulator is used to protect the battery from being over charged when it is connected to the solar panel. Based on the State of Charge (SOC) of the battery level, the disconnection from the solar and reconnection occurs.

iv) Inverter Model

The output of this model is a constant rms voltage signal. The AC load extracts DC current indicated as (6).

$$I_{DC} = \frac{I_{AC} V_{AC}}{\eta_{inv} V_{DC}} \tag{7}$$

v) Load Model

In this work, a simple resistor is considered as load .The equation (8) which governs ohm's law explains the current taken from load: [11]

$$I_{AC} = \frac{V_{AC}}{R_L}(a_1 * a_2) \tag{8}$$

Where a_1 and a_2 are known as the signals from the algorithm and the load schedule.

The loads are classified based on its priority requirement as follows: battery based on its SOC, emergency loads, critical loads, essential loads and the convenient or sophisticated loads.

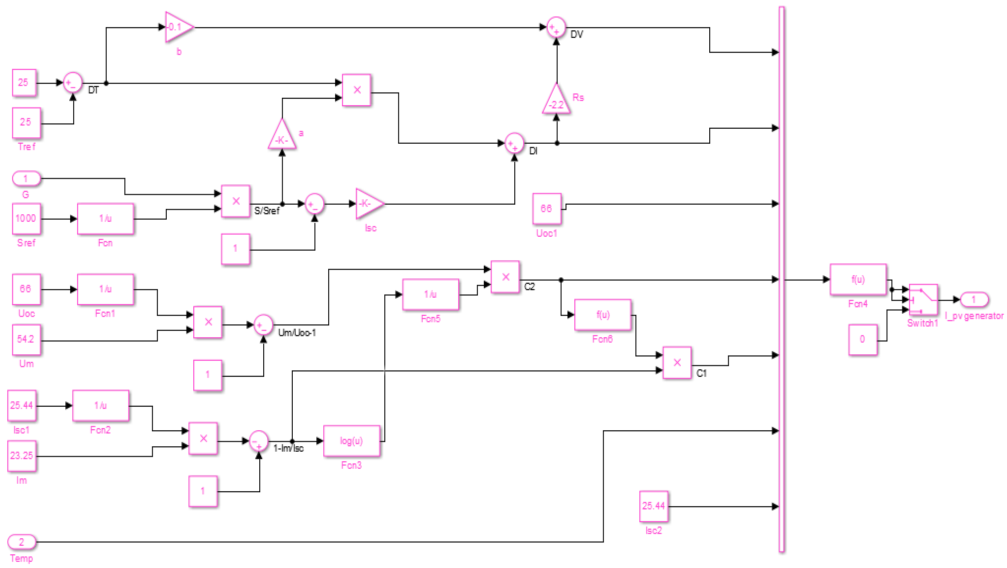

Figure 1: Simulink model of Solar panel

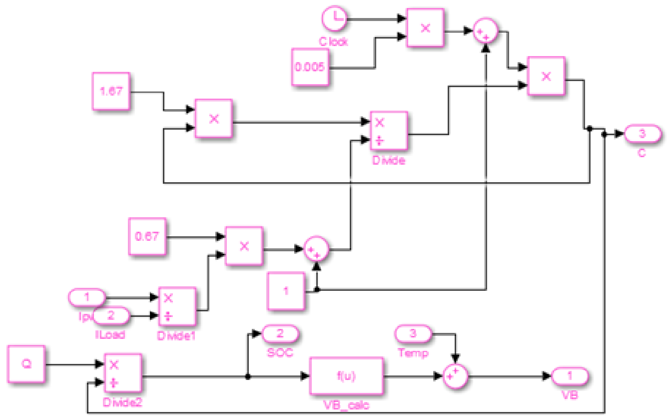

Figure 2: Simulink model of battery

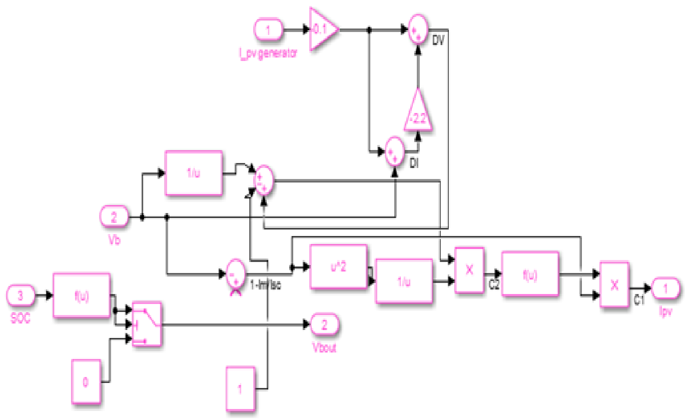

Figure 3: Simulink model of regulator

Load control technique

Due to the intermittent nature of the renewable energy sources, the use of energy storage devices such as battery is mostly needed to store the excess energy. But still the batteries may get over charged or over discharged when it is connected with the sources and loads. Many researches are going in the controller development that can do the proper energy management, load shedding etc. The load management also called as the Demand Side Management (DSM) is also the efficient way of controlling the power from the sources. The loads can be prioritized based on the importance of the loads on its application. This categorization is mainly done to protect the battery being over charged or over discharged. The algorithm followed in this paper is based on the work from Groumpous and Khouzam [13, 14]. The loads are classified as convenient, essential, critical and emergency loads [12]. The solution is given as the maximization of the objective function that depends on the priority of the load and the availability of energy supply.

The optimization function can be expressed as:[12]

$$\text{Maximize} \left(\sum_{i=1}^{n} \sum_{j=1}^{m} R_{ij} X_{ij} + R_B X_B \right) \quad (9)$$

Subject to the inequality constraint

$$\sum_{i=1}^{n} \sum_{j=1}^{mi} P_{ij} X_{ij} \Delta t + P_B X_B \Delta t + E_{UCL} < E_{PV} + E_B \eta_B (SOC - SOC_{\min}) \quad (10)$$

For all i,j $0 \leq X_{ij} \leq 1$, $0 \leq X_B \leq 1$ (11)

where $R_{ij} = r_{ij} P_{ij} \Delta t$ & $R_B = r_B E_B (1-SOC)$, $r_B = 5(1-SOC)$

SQP Algorithm

The Sequential Quadratic Programming is widely used to solve any nonlinear problem of optimization. This algorithm mainly depends on a fundamental theoretical basis and gives potential algorithmic rules to prevail optimal solution for large scale engineering problems.

The basic idea of sequential quadratic programming is to model the nonlinear programming problem at a given approximate solution, say $x^{(k)}$, by a quadratic programming sub problem, and then to use the solution to this sub problem to construct a better approximation $x^{(k+1)}$. This process is iterated to create a sequence of approximations that will converge to the optimal solution x^*. The principal idea of sequential quadratic programming is the formulation of a quadratic programming sub problem based on a quadratic approximation of the Lagrangian function of $\Gamma(x,\lambda)$ and by linearizing the nonlinear constraints of the proposed system.

The optimization problem can be expressed as

$$\text{Minimize } f(x) \quad (12)$$

Subject to

$$h_i(x) = 0, \quad i = 1, \ldots, m_e,$$

$$h_i(x) \leq 0, \quad i = m_e + 1, \ldots, m,$$

Where x can be defined as the vector of n design parameters, f(x) is the objective function to be optimized, me is the total number of equality constraints, m-me is the number of inequality constraints.

$$\text{Minimize } f(s) = \frac{1}{2} s^T.H..s + \nabla f(x^{(k)})^T.s \quad (13)$$

Subjected to

$$\nabla g_i(x^{(k)})^T.s + g_i(x^{(k)}) = 0, \qquad i = 1,....., m_e, \quad (14)$$

$$\nabla g_i(x^{(k)})^T.s + g_i(x^{(k)}) \le 0, \qquad i = m_e + 1,.....,m, \quad (15)$$

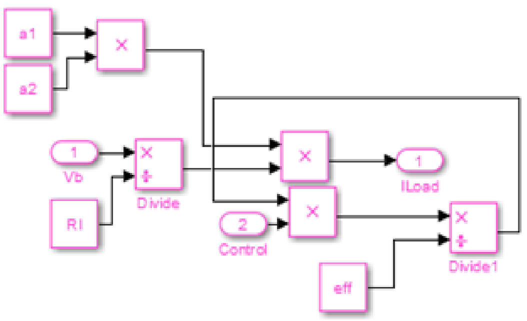

Figure 4: Simulink model of inverter and the load

The quadratic programming sub problem (16) to (18) is solved using the active set method. The solution of the quadratic programming sub problems of (13) to (15) is then used to form a new approximation as follows:

$$x^{(k+1)} = x^{(k)} + \alpha^{(k)}.s \quad (16)$$

where $\alpha^{(k)}$ is the step length parameter, which is determined by the line search procedure.

In this work, the x is taken with the parameters of the current from the PV module, Voltage from the battery, state of charge of battery and the battery capacity. The optimum values of all the above parameters are determined from this SQP algorithm and based on the load priority and the SOC of the battery.

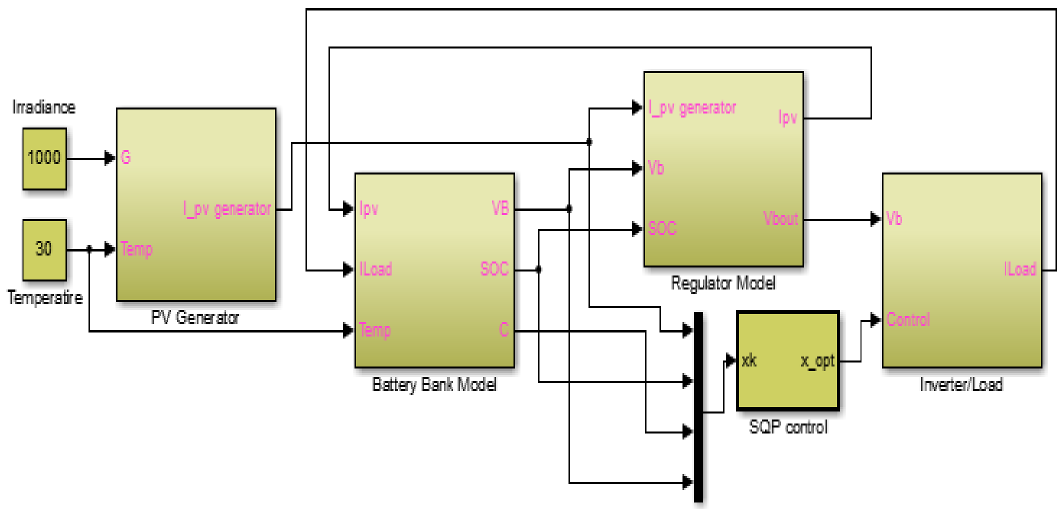

Figure 5: Simulink diagram for the stand alone PV system

In order to validate the SQP algorithm in the system, two scenarios were considered. In both scenarios, the ratings of the solar panel, the capacity of the battery are taken different. Only the initial SoC of the battery is assumed to be same in both cases. For a 24 hour load profile with constant and variable loads, the simulation is carried out using SQP and the priority load control algorithm. The results were discussed in the next chapter.

RESULTS AND DISCUSSION

The simulation has been done for 24 hours' time period. The base load is taken as 150W in the system. The constant load value is taken as 545W. The variable load pattern for 24 hours is shown in the figure 6.

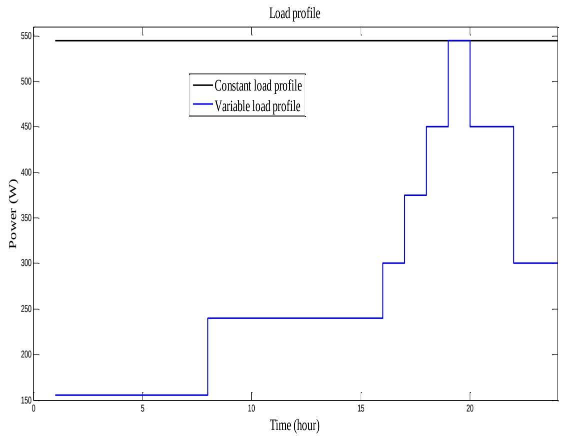

Figure 6: Load profile of the system

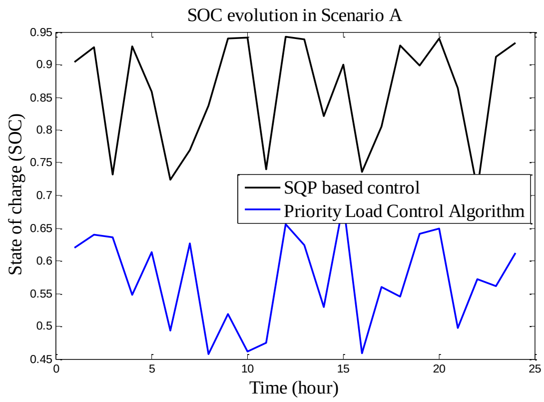

Figure 7: Evaluation of battery SoC for constant load profile

The evaluation of the objective function mentioned has been done for both the scenarios using priority control algorithm and SQP algorithm. The figure 7 and 8 are showing the results for the cases considered. It is observed that the proposed SQP algorithm in this system is giving better results for the objective function considered.

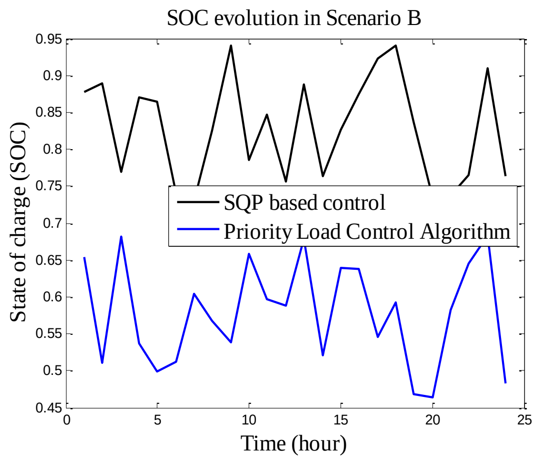

Figure 8: Evaluation of battery SoC for variable load profile

CONCLUSION

The stand-alone PV system is considered as the test system. The prioritization of the load is done based on the importance of the load in the application. The constant load and variable load is considered for the validity of the algorithm in the test system. Two scenarios are considered and the priority control algorithm and SQP algorithm have been implemented in the system. From the results, it is understood that the given Sequential Quadratic Programming algorithm is giving the optimum solution for the objective function.

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