Robust sliding mode controller for buck DC converter in off-grid applications

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ABSTRACT

This paper presents a robust sliding mode controller of DC-DC buck converter for renewable energy applications, such as photovoltaic systems in off-grid configurations. Photovoltaic systems in off-grid configuration are exposed to significant variations in input voltage and power loads. The proposed sliding mode controller presents a simple and efficient method of continuously updating the duty cycle of a pulse width modulation unit (PWM) of a buck converter. The PWM unit is operated at constant switching frequency of 10 kHz carrier signal and varying duty cycle. The differences in input voltage and power load are treated as two bounded uncertainties, thus eliminating the need for input voltage sensor and output current sensors leaving the system with a single sensor required to measure the converter output voltage. That is, measured output voltage is compared with the reference voltage to continuously update the average duty cycle value of PWM unit. Adjustment of PWM duty cycle is performed while maintaining the sliding condition always fulfilled. The simulation results of the proposed controller showed robustness and accuracy against power load fluctuation, changes in desired output voltage, and variations in the input supply voltage that may result from the varying level of irradiance and temperature.

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1. INTRODUCTION

Due to environmental and economic concerns, renewable energy sources, such as photovoltaic (PV) systems, are increasingly being used as sources of energy for household, commercial, and industrial applications. However, such sources inherently exhibit unpredictable output behavior due to many factors that may affect its performance such as, variations due to the nature or type of the source of energy (as in wind energy and solar irradiation), and variation in loads as in standalone systems. Therefore, such sources can't be connected to supply loads directly, since the majority of electric loads require constant levels of voltages and currents. The intermittent behavior of renewable energy sources, such as that experienced in PV and wind sources, mandates the the implementation of converters, such DC converters as front-end power interface devices to regulate and condition the output of such sources [1]. Such converters are usually required to supply constant voltages and/or currents to loads, depending on the type of load being supplied. Substantial differences in power load and voltage input exist in applications such as shipboard power system, therefore DC buck converters are required in order to provide steady power to such electric systems [2]-[5]. This calls for a design of DC buck converter that will exhibit robustness against such variations. Similar scenarios can be found in a wind power generation, where two types of converters could be found; one is usually an AC/DC converter, connected to the wind power generation turbine and provides DC voltage output with wide range varying amplitude. The other converter is a DC/DC buck converter, it has a wide input voltage range and is required to supply constant power to loads that might vary, mimicking the behavior of standalone systems [6].

DC converters are time variant nonlinear devices, thus the application of linear control techniques for such converters is not suitable. Therefore, a small-signal model, linearized around a fixed operating point, is usually used to design a linear controller for such systems. Linear control methods can't achieve satisfactory performance in the presence of large disturbances, such as step change in load or supply [2], [7]-[9]. Additionally, due to the dependence of the linearized model parameters on the converter's operating point, the effect of system parameters difference in DC converter systems cannot be evaded. Therefore, controllers of DC converters must address the nonlinearities and the changes in parameters [10]. Variations and uncertainties in the converter parameters have severe effects on the behavior of such converters and may lead to instability. Therefore, the design and enhancement of robust controllers for power converters have become a major concern in topics of power converters design [11].

Non-linear controllers possess many advantages when compared with linear controllers. Themajor advantage is the guaranteed stability and the robustness against model uncertainties and external disturbances [11], [12]. Many non-linear techniques have been presented, for example, feedback linearization [13], [14], backstepping methods [15], [16], proportional–integral–derivative–based sliding mode controller [17], nonlinear H-infinity fuzzy control [18], and sliding mode controllers [19]-[21], fuzzy logic sliding mode controllers [10], [12], [22], [23]. In off-grid photovoltaic application, as shown in [1] and for energy storage system, as in [9] sliding mode control is used for DC-DC converter. Both systems in [1], [9] proposed a multi-loop control scheme consisting of a proportional integral (PI) controller for outer-loop and a sliding-mode (SM) current controller for inner-loop. As a result, both system's current and voltage sensing were used, in addition to optimizing algorithms, resulting in extra hardware and complexity to the controller systems, thus undermining the sliding-mode control (SMC) simplicity objective [20]. An interesting control law for SM duty ratio controller design for DC-DC converter is proposed in [2]. The controller implementation involved measurements of the input and output voltages and currents, this also resulted in additional hardware complixity to the system.

In this study a novel, simple and efficient SM control law is proposed for a DC buck converter. The control gains are used to avoid input voltage and output current measurement sensors. The control gains of load power and input voltage for DC-DC converter in this study are unknown but assumed to be of known bounds. The proposed SMC is capable of stabilizing the buck converter output voltage over wide range of input voltage and load power variations. Moreover, a pulse width modulation (PWM) unit is used to produce the necessary drive or control signal for DC-DC buck converter upon receiving the average value of the duty ratio, which is generated by the SMC. As a result, this will eliminate the variable switching frequency which is a major disadvantage of the SMC. In this work, a simulation study using MATLAB/Simulink was carried out to examine the operation of the proposed SMC under variations in input voltage and load conditions.

2. MATERIALS AND METHOD

Typically, in basic DC-DC buck converter circuit, the output voltage of the converter is changed by changing duty cycle of the switch S, as in Figure 1. Meanwhile, the system dynamics can be expressed as in (1) and (2),

$$L\frac{di_L(t)}{dt} = d(t)v_{in}(t) - v_o(t) \tag{1}$$

$$C\frac{dv_o(t)}{dt} = i_L(t) - \frac{v_o(t)}{R} \tag{2}$$

where $v_{in}(t), i_L(t), and\ v_o(t)$ are denoting the time average of input voltage, inductor current, and output voltage signals over one switching period, respectively. $d(t)$ denotes the duty cycle of the converter switch. It can be observed that (1) and (2) are non-linear or time varying because of the term $d(t)$ [24]-[26]. Substituting (1) into (2) results in 2nd order non-linear differential equation as in (3),

$$\frac{d^2v_o(t)}{dt^2} = \frac{1}{LC}v_{in}(t)d(t) - \frac{1}{RC}\frac{dv_o(t)}{dt} - \frac{1}{LC}v_o(t) \tag{3}$$

Let $x = v_o(t)$, be the output of the converter, then (3) can be rewritten in a more compact general form as in (4),

$$\ddot{x} = b\,u + f \tag{4}$$

where, $u = d(t)$ is defined as the control input, $b = \frac{1}{LC} v_{in}(t)$ is the uncertain control gain, but of known bounds and can be estimated as $\hat{b}$. Also, $f = -(\frac{1}{RC}\frac{dv_o(t)}{dt} + \frac{1}{LC} v_o(t))$ is the uncertain dynamic function and can be estimated as $\hat{f}$ with some known bounded function such as $F = F(x, \dot{x})$, where $|f - \hat{f}| \leq F$.

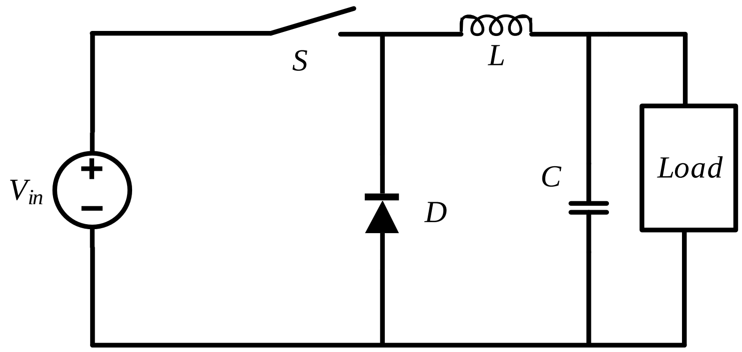

Figure 1. Basic DC-DC buck converter topology

2.1. Sliding surface

The objective of controlling the buck converter is to control the output voltage $v_o(t)$ to track the desired reference voltage $v_{oref}(t)$. According to the sliding mode objective, the control input $u = d(t)$, will be used to regulate or force the output $x = v_o(t)$ to follow certain trajectory such as $x_d = v_{o\_ref}(t)$, hence the tracking error can be defined as in (5),

$$x_e = x_d - x \tag{5}$$

In order to have the system track $x = x_d$, a sliding surface such as $s = 0$ and with the choice of s as shown in (6),

$$s = \left(\frac{d}{dt} + \lambda\right) x_e = \dot{x}_e + \lambda x_e = 0 \tag{6}$$

is selected. Where λ is strictly a positive number that relates to the sliding surface slope. In order for the system to converge to the sliding surface, the condition has to be fulfilled, i.e.:

$$s\dot{s} < 0 \tag{7}$$

The fulfilment of the above condition will guarantee that the system will always be stable and converge to the sliding mode. To ensure that the condition in (7) will always converge, the derivative term $\dot{s}$ must always maintain an opposite sign of s. Therefore, substituting from (4) and (5) into the derivative of (6), gives the equation as shown in (8);

$$\dot{s} = \ddot{x}_e + \lambda\dot{x}_e = x_e = \ddot{x}_d - \ddot{x} + \lambda\dot{x}_e = 0 \text{ or } \dot{s} = \ddot{x}_d - bu - f + \lambda\dot{x}_e \tag{8}$$

To guarantee the convergence of the system, the control input u in (8), is assumed to take the form as in (9),

$$u_{eq} = \frac{1}{\hat{b}}[\hat{u} + k\, sgn(s)] \tag{9}$$

where $\hat{u}$ is defined as $\hat{u} = \left(-\hat{f} + \lambda\dot{x}_e + \ddot{x}_d\right)$. Given uncertainties in the output power (or load R) and the input supply v_{in}, the terms $\hat{f}$ and $\hat{b}$ can respectively be defined as in (10) and (11).

$$\hat{f} = -\left(\frac{1}{\hat{R}C}\frac{dv_o(t)}{dt} + \frac{1}{LC} v_o(t)\right) \tag{10}$$

where $\frac{1}{\hat{R}}$ is defined as the estimated load which may vary between $\frac{1}{R_{max}} \leq \frac{1}{\hat{R}} \leq \frac{1}{R_{min}}$ corresponding to variation in load power such as, $P_{min} \leq P \leq P_{max}$. The estimated value $\frac{1}{\hat{R}}$ is calculated as,

$$\frac{1}{\hat{R}} = \frac{\frac{1}{R_{max}} + \frac{1}{R_{min}}}{2} = \frac{R_{max} + R_{min}}{2R_{max}R_{min}} \tag{11}$$

and,

$$\frac{1}{\hat{b}} = \frac{LC}{\widehat{V_{in}}} \tag{12}$$

where $\frac{1}{\hat{b}}$ is defined as the estimated input voltage which may vary between $\frac{1}{b_{max}} \leq \frac{1}{\hat{b}} \leq \frac{1}{b_{min}}$. The estimated value $\frac{1}{\hat{b}}$ is then calculated as,

$$\frac{1}{\hat{b}} = LC\,\frac{\frac{1}{V_{in\_max}} + \frac{1}{V_{in\_min}}}{2} = LC\,\frac{V_{in\_max} + V_{in\_min}}{2V_{in\_max}V_{in\_min}} \tag{13}$$

2.2. Sliding mode condition

Substituting from (9) and (10) into (8), then the sliding condition can be obtained as in (12),

$$\dot{s} = -\frac{b}{\hat{b}}\left[-\hat{f} + \lambda\dot{x}_e + \ddot{x}_d + k\,sgn(s)\right] + \ddot{x}_d + \lambda\dot{x}_e - f \tag{14}$$

Substituting for $\hat{f}$ and simplifying result in (15),

$$\dot{s} = \left(\frac{1}{R} - \frac{b}{\hat{b}}\frac{1}{\hat{R}}\right)\frac{\dot{x}}{C} + \left(1 - \frac{b}{\hat{b}}\right)\left(\frac{x}{LC} + \lambda\dot{x}_e + \ddot{x}_d\right) - \frac{b}{\hat{b}}k\,sgn(s) \tag{15}$$

in (15) can be used to derive the sliding condition, then k must satisfy the condition in (16), i.e.

$$k > \left|\frac{\hat{b}}{b}\left(\frac{1}{R} - \frac{1}{\hat{R}}\right)\frac{\dot{x}}{C} + \left(\frac{\hat{b}}{b} - 1\right)\left(\frac{\dot{x}}{\hat{R}C} + \frac{x}{LC} + \lambda\dot{x}_e + \ddot{x}_d\right)\right| \tag{16}$$

To guarantee the condition in (16) is fulfilled at all times, the worst-case value for the term $\frac{\hat{b}}{b}$ is taken as $\frac{V_{in\_max}}{V_{in\_min}}$. The gain k in (16) is updated online and it accounts for the amount of uncertainty that will lead to the update of the duty cycle value as estimated by (9). The term in (9) is used to generate PWM gate signals for the DC-DC buck converter. The term λ in (6) represents the break frequency of a filter, therefore it must be selected to be small with respect to the high-frequency unmodeled dynamics, and as well large enough to obtain best tracking performance.

3. RESULTS AND DISCUSSION

To assess the proposed SM buck converter controller, Simulink model was implemented as shown in Figure 2; with the parameters as shown in Table 1. The proposed controller for the DC-DC buck converter was examined for three different operating settings as summarized in Table 2. In the first simulation, the input voltage is changed in a manner to reproduce the behavior of typical PV system operating under varying level of irradiance and temperature. Therefore, the input voltage to the buck converter is initially stepped from V_(in-initial)=0 V at time t=0 sec (representing starting point of the system), to V_(in-min)=120 V (minimum uncertain input) then increased in steps of 20 V every 1 sec to reach V_(in-max)=160 V (representing the maximum uncertain input voltage). The reference or desired converter voltage output is set to 56 V with nominal power (load) at 285.1 W. It can be observed that differences in voltage input have a slight effect on the voltage output as in Figure 3. The output power remained constant at around 285 W with less than ±1 W variation as in Figure 4, due to approximately ±14.5% variation in the input voltage.

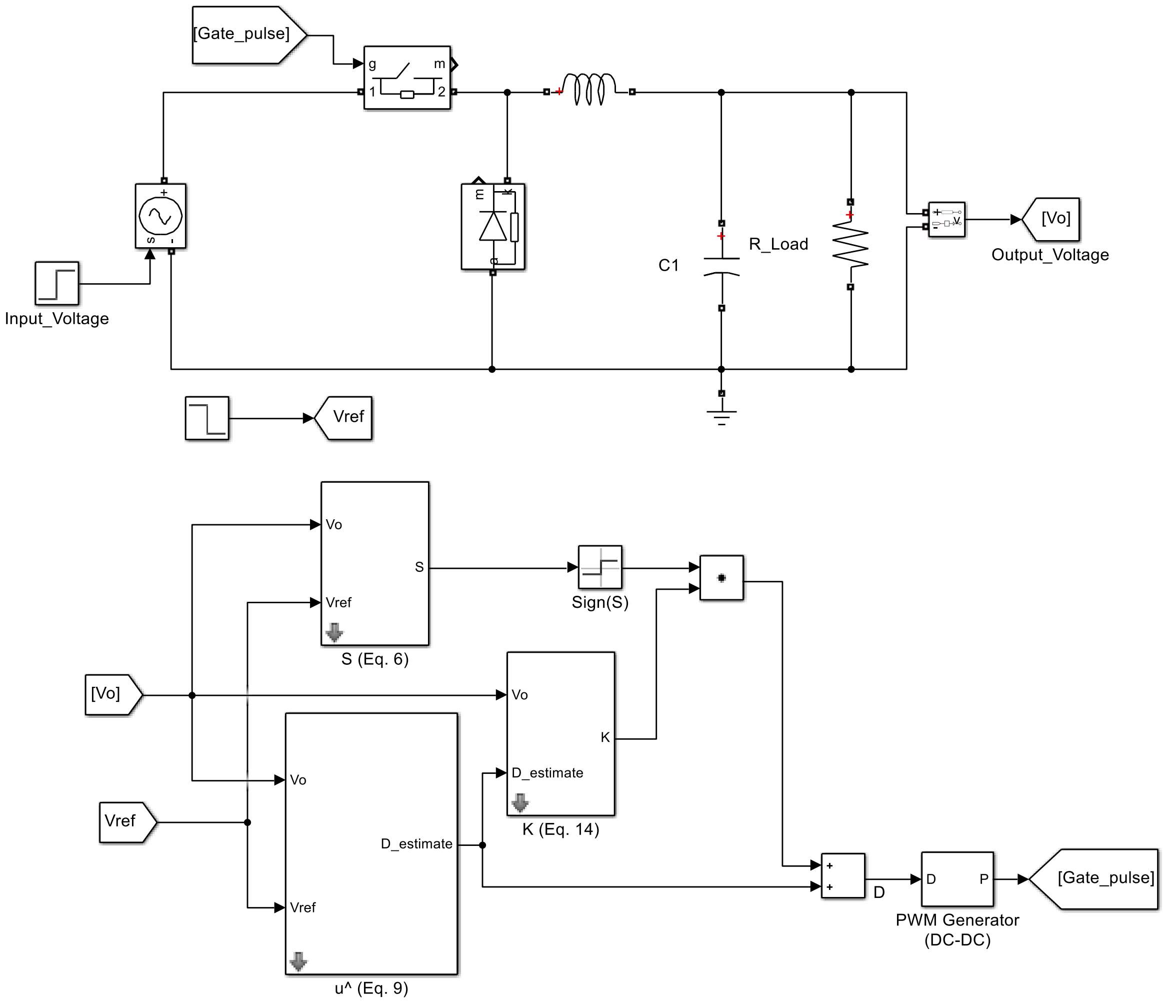

Figure 2. Simulink model of sliding mode DC-DC buck converter

Table 1. Design parameters for buck converter

No.	Parameters	Value
1	Input voltage (V_{in}) range	120→ 160 V
2	Nominal output voltage (V_o)	56 V
3	Nominal load W	285.1 W
4	Inductance L	3×10^{-3} H
5	Capacitance C	2000 μF
6	PWM frequency	10 kHz
7	Sampling time	10×10^{-6}sec
8	Solver	ode8 (dormand-prince)

Table 2. Simulation settings of the buck converter

Sim No.	Variable	Time interval (sec)		
		$0 \leq t < 1$ s	$1 \leq t < 2$ s	$2 \leq t < 3$ s
1	Step change in input voltage (V_{in})	0 → 120 V	120 → 140 V	140 → 160 V
	Desired output voltage (V_o)	56 V	56 V	56 V
	Load (W)	285.1 W	285.1 W	285.1 W
2	Input voltage (V_{in})	0 → 120 V	120 → 140 V	140 → 160 V
	Desired output voltage (V_o)	60 V	56 V	50 V
	Load (W)	327.3 W	285.1 W	227.3 W
3	Input voltage (V_{in})	0 → 120 V	120 → 140 V	140 → 160 V
	Desired output voltage (V_o)	56 V	56 V	56 V
	Load (W)	348.4 W	285.1 W	221.7 W

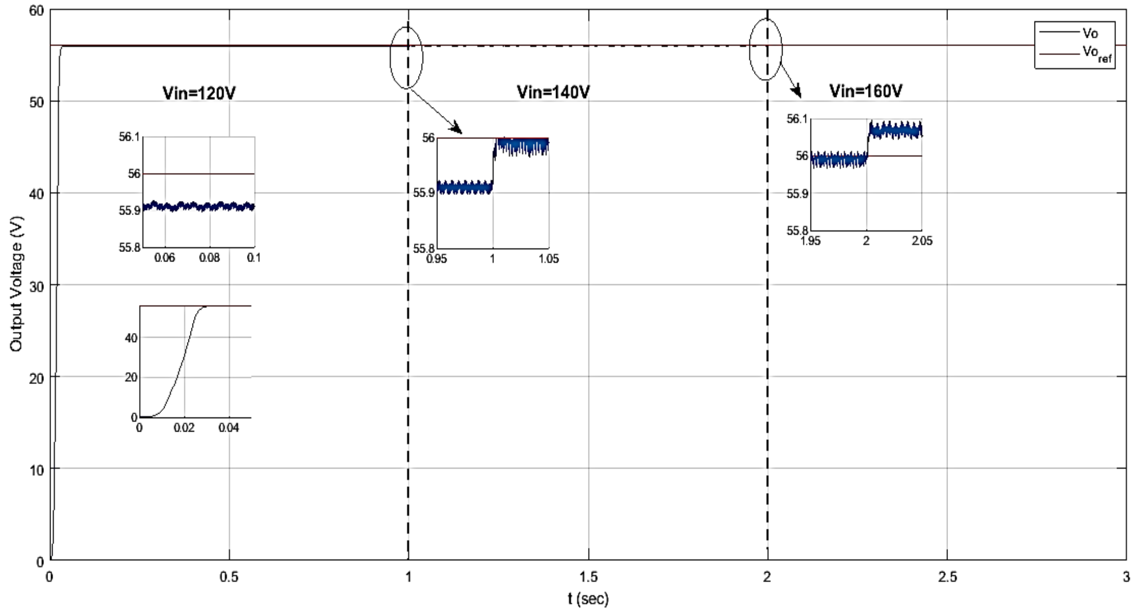

Figure 3. Converter output voltage with varying input voltage (desired output voltage 56 V)

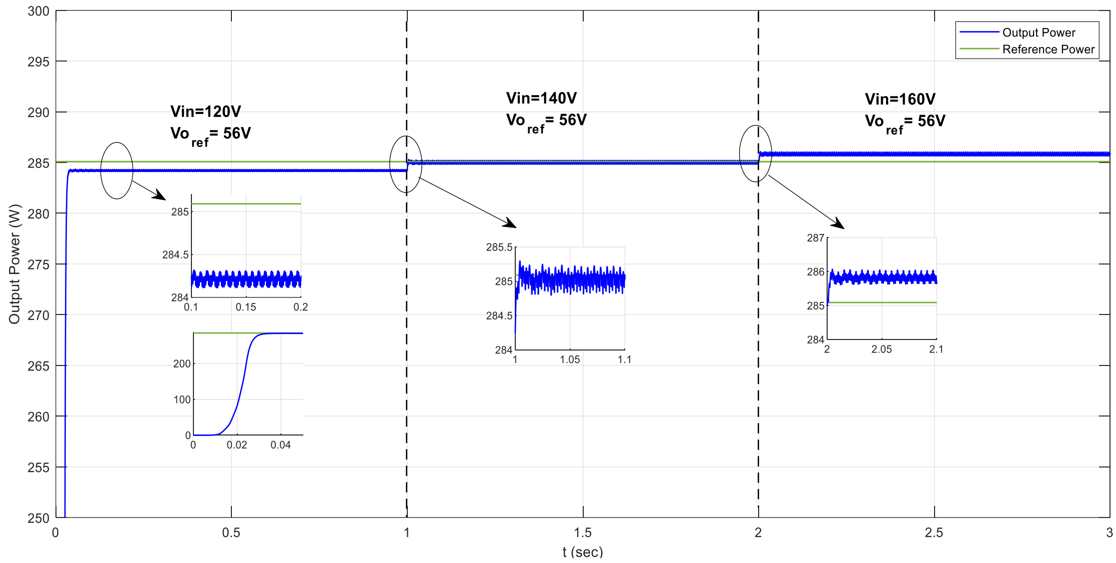

Figure 4. Output power from converter with varying input voltage condition and nominal power load $285.1\ W$

A second simulation is conducted when both the input and output voltages of buck converter are varied. The variation in the input follows a similar sequence as in the first simulation above, while the desired converter output voltage is simultaneously changing according to the sequence in Table 2 to represent worst case conditions. As shown in Figure 5, the converter output voltage was capable of tracking the desired output voltage with tracking error less than ±0.2 V, while the output power, as in Figure 6, showed maximum tracking error of ±1.8 W when the input voltage of the converter varied by ±14.5% around nominal value.

The third simulation is carried out with the input voltage varied as before in Table 2, while the load is simultaneously changing from maximum load to minimum of about ±22.2% around the nominal load value. The converter output voltage is set to 56 volts throughout this part of the simulation. It can be observed that the variations in voltage input together with the power output / load demand have minor effect on the output voltage as in Figure 7. Converter power output tracked the load demand with a maximum of ±1.2 W tracking error as shown in Figure 8.

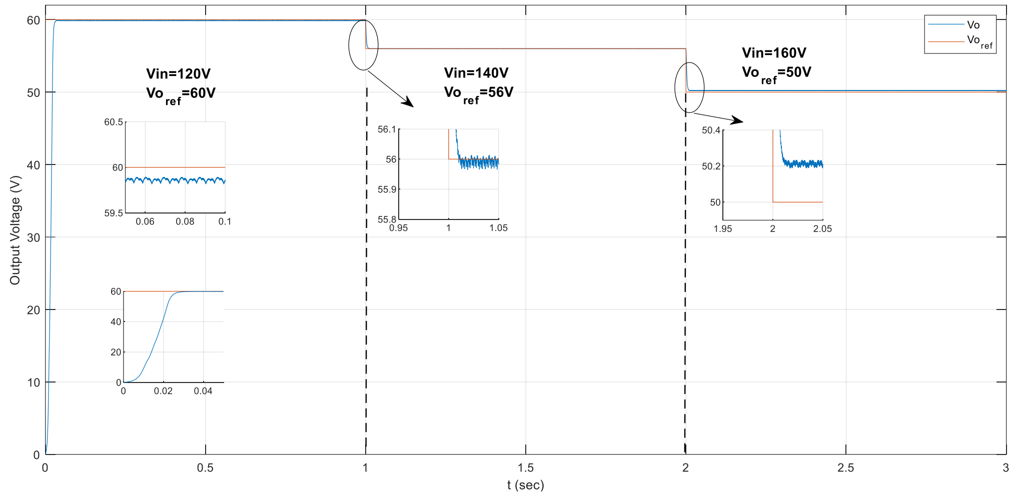

Figure 5. Converter output voltage with varying input voltage and varying desired output voltages

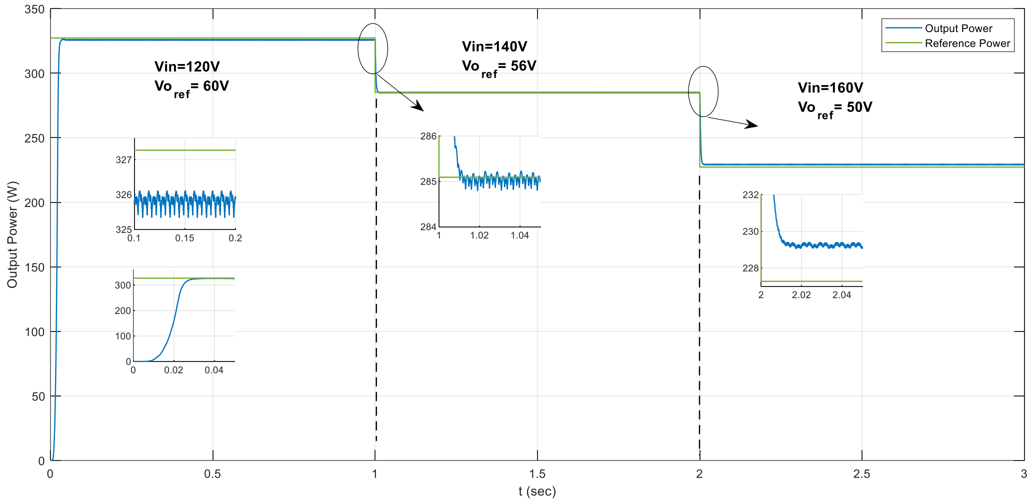

Figure 6. Output power from converter with varying input voltage condition and varying desired output voltages

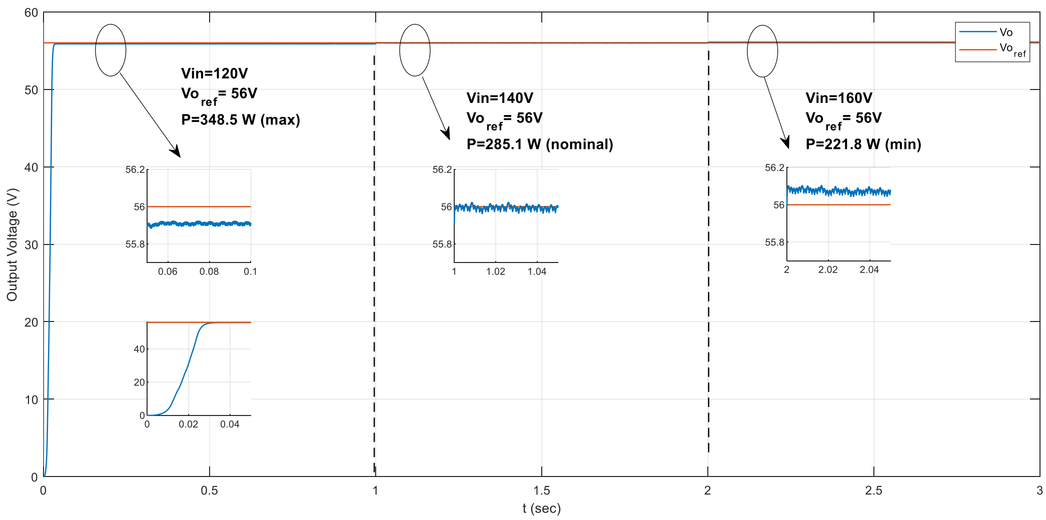

Figure 7. Converter output voltage with varying input voltage and varying power loads

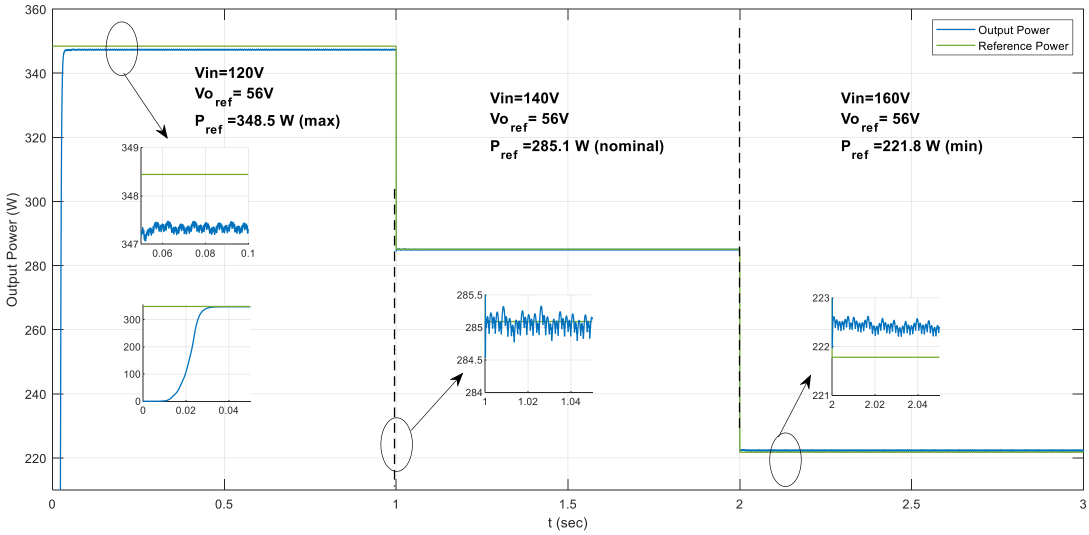

Figure 8. Output power from converter with varying input voltage condition and different nominal power loads

4. CONCLUSION

A simple and robust SM controller for DC-DC buck converter has been developed using a single feedback loop that implements minimum number of sensors for off-grid PV applications with different constant load power conditions. The paper proposed a sliding condition that is updated online to guarantee at all times the convergence of the converter towards the desired operating point. The disadvantages of the variable switching frequency and the discontinuity of the traditional SM controllers have been overcome by updating or the estimated value of the duty cycle using the controller gain to produce an average value of the duty cycle that is fed to PWM unit. Simulation results using Simulink/MATLAB showed excellent behavior in terms of accuracy and convergence of the proposed controller when operated under extreme level of input and power variations and parameters uncertainities.

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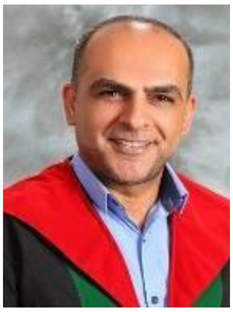

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