Abstract: In this paper, a small standalone solar powered DC microgrid is designed and analysed. The control technique used here is sliding mode control. The common control technique of controlling dc-dc converter is proportional Integral (PI) controller, which is not able to execute well under variations of load. DC-DC converter is nonlinear and time variant system therefore sliding mode controller can be used for dc-dc converter. DC microgrid model is designed and analysed by simulation using Typhoon HIL to observe the system’s dynamic response in view of load impact and battery charging. The buck converter is designed with PWM (pulse width modulation) based sliding mode controller. The tool chain have processor with ultra low latency and unprecedented execution rate for the converter. Dynamic equations associated with the control logic is derived for buck converter. The control technique is tested for step load changes. Sliding mode controller performance is compared with proportional integral (PI) controller. Fast and robust dynamic response of output voltage is obtained.

Keyword: Buck converter, sliding mode control (SMC), PWM (pulse width modulation), HIL (hardware in loop), DC microgrid.

I. INTRODUCTION

Rural areas have abundant renewable energy sources such as: wind, solar, hydro that are cheap and clean energy sources. DC microgrid is best for rural areas because of easy integration with renewable energy sources and storage, availability of DC loads, loss reduction due to less number of conversion stages and low cost in distribution. The power electronic devices which is used in dc microgrid is dc-dc converter. Components of dc-dc converter are high frequency switches, inductors, and capacitors which are used to smooth out switching noise into regulated dc voltages. Applications of dc-dc converters are self-regulation of power supplies, battery charger, laptop, solar charger. Feedback of the converter is taken by connecting a control logic using output voltage of a converter. In a system the feedback control technique should be stable which can manage large input voltage variations and variations in load so that it can ensure stable operating condition and fast transient response [2]. Because of simplicity, several industries use linear control technique such as proportional integral or proportional integral derivative control for controlling dc-dc converters. These controllers are not robust for parameter variations like huge variation in load or input voltage. Hence these control methods are not satisfactory for dc-dc converters. SM control provides fast and stable transient response and high robustness against external variations.

This control scheme is simple to implement and it gives nearly-zero switching losses [4] therefore nonlinear controllers (SM) are suitable for controlling dc-dc converters. Conventional PWM technique is suitable while applying sliding mode control in converters but this leads to the trade-off between the overshoot and speed of output voltage response. This drawback can be overcome by using an integral action in the output voltage error of the system. This control technique gives less settling time and overshoot compare to conventional control technique. In this paper small dc microgrid is modelled using a solar photovoltaic panel which is connected with boost converter, MPPT controller and a battery storage system. The system voltage is managed 48V and this voltage step down to 19V using buck converter. The voltage obtained from buck converter is controlled by PWM technique based SM control. Design method of proposed system is derived in addition to control equations and implemented on the given system. The main focus of this paper is to analyse operations of SM control of buck converter.

II. MPPT BOOST CHARGER

The system consists of PV panel, MPPT controller circuit, boost converter, and battery. PV module considered here contains 72 cells which gives 35V, 192W at irradiance of 1000W/ m². MPPT controller is used to track maximum operating point of PV module. Perturb and observe (P and O) algorithm is used to generate pulses which controls duty cycle of boost converter. In microgrids battery system is used to supply energy needs to the loads at times of low energy generation from renewable energy sources. Battery employed here is the lead acid battery with capacity of 10 ah and nominal voltage of 48V. Battery storage system employed to smoothen voltage variations which occur due to intermittent nature of renewable energy sources.

III. DC-DC BUCK CONVERTER

DC microgrid needs different voltages to connect different type of loads therefore buck converter is required in the system. Buck converter operates in two modes on-state and off-state. Fig. 1 is the circuit of on-state in which current increases through the inductor. Fig. 2 is the circuit in the off-state where energy is changed from inductor to capacitor resulting a decrease in inductor current. Equations are obtained from on-state and off-state operation.
IV. DESIGN STEPS OF SM CONTROL

The sliding mode control used in the model detects the DC voltage from output of boost converter which works as input voltage for further system. Design steps are explained for PWM based sliding mode control in of Buck converter in continuous operating mode of buck converter.

A. System Modelling

The modelling of system for pulse width modulation based SM control for Buck converter starts with state variable matrix $X$. The state variables in system modeling are considered as voltage error, differential of voltage error, integral of voltage error which is denoted as $x_1, x_2, x_3$. $V_{ref}$ is the reference voltage and beta works as feedback network ratio.

$$X = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} V_{ref} - \beta V_0 \\ \frac{d}{dt}(V_{ref} - \beta V_0) \\ \int (V_{ref} - \beta V_0) dt \end{bmatrix}$$

By substituting the $V_0$ variable from equation (2) for the control variable $x_2$.

$$x_4 = \frac{d}{dt}(V_{ref} - \beta V_0) = x_2$$

$$x_1 = -\beta \frac{dV_0}{dt} = x_2$$

$$x_2 = \frac{\beta}{R_L C} \frac{dV_0}{dt} + \frac{\beta V_0 - V_0 u}{LC}$$

$$x_3 = \frac{V_{ref} - \beta V_0}{LC}$$

Matrix form equation,

$$x_{buck} = Ax_{buck} + Bu + D$$

B. Controller design

The Sliding mode control law is entitled as $u$ that follows a switching function, which is represented as:

$$u = \begin{cases} 1, & \text{when } S > 0 \\ 0, & \text{when } S < 0 \end{cases}$$

Here $S$ is considered as instantaneous state variable’s trajectory.

$$S = \alpha_1 x_1 + \alpha_2 x_2 + \alpha_3 x_3 = J^T x$$

Where $J = \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \end{bmatrix}$ and $\alpha_1, \alpha_2, \alpha_3$ represents control parameter called as sliding coefficients.

C. Proof of existence condition

Sliding mode operation exists by satisfying the condition of local reachability. Which is given as:

$$\lim_{\delta \to 0} S < 0$$
This can be expressed as
\[
\begin{cases}
    \dot{S}_{s=0^+} = A^{T}x + B^{T}v_{s=0^+} + D^{T}\dot{x} < 0 \\
    \dot{S}_{s=0^-} = A^{T}x + B^{T}v_{s=0^-} + D^{T}\dot{x} > 0
\end{cases}
\] (6)

Case 1: \( S \rightarrow 0^+, \dot{S} < 0 \)
Substituting \( v_{s=0^+} = u = 1 \) and matrices in equation (6) gives
\[
-\frac{\beta_i}{C} + \alpha_2 \frac{\beta_i}{R_i C^2} + \alpha_2 (V_{\text{ref}} - \beta V_o) - \frac{\beta V_i}{L C} + \alpha_2 \frac{\beta V_o}{L C} < 0
\] (7)

Case 2: \( S \rightarrow 0^-, \dot{S} > 0 \)
Substituting \( v_{s=0^-} = u = 0 \) and matrices in equation (6) gives
\[
-\frac{\beta_i}{C} + \alpha_2 \frac{\beta_i}{R_i C^2} + \alpha_2 (V_{\text{ref}} - \beta V_o) + \alpha_2 \frac{\beta V_o}{L C} > 0
\] (8)

The simplified existence condition is the combination of equation (7) and (8)
\[
0 < -\beta L \left( \frac{\alpha_1}{\alpha_2} - \frac{1}{R_i C} \right) i_c + L C \frac{\alpha_2}{\alpha_2} (V_{\text{ref}} - \beta V_o) + \frac{\beta V_o}{\alpha_2}
\] (9)

V. DESIGN OF SM CONTROLLER FOR BUCK CONVERTER

To design SM controller for buck converter stability conditions should be satisfied. In case of underdamped response converters the desired settling time \( T_s = \frac{\pi}{\omega} \) where \( \tau \) denotes the time constant which can be set by tuning \( \frac{\alpha_1}{\alpha_2} \) using
\[
\frac{\alpha_1}{\alpha_2} = \frac{10}{T_s}
\]

And the desired damping ratio can be set using
\[
\frac{\alpha_2}{\alpha_2} = \frac{25}{\zeta^2 T_s^2}
\]

The equivalent function of control is obtained by equating
\[
\dot{S} = A^{T}x + B^{T}u_{eq} + D^{T}\dot{x} = 0
\]

By solving above equation it yields the equivalent function of control
\[
u_{eq} = -[J^{T}B]^{-1}J^{T}[Ax + D]
\]

Here \( u_{eq} \) is continuous value which varies as \( 0 < u_{eq} < 1 \)
Dividing equation (9) by \( \beta V_i \)
\[
0 < \frac{L}{V_i} \left( \frac{\alpha_1}{\alpha_2} - \frac{1}{R_i C} \right) i_c + \frac{\alpha_2 LC}{\alpha_2 \beta V_i} (V_{\text{ref}} - \beta V_o) + \frac{V_o}{V_i} < 1
\]

By comparing \( 0 < u_{eq} < 1 \) with \( 0 < d = \frac{V_o}{V_{\text{ramp}}} < 1 \)

\[
V_c = -\beta L \left( \frac{\alpha_1}{\alpha_2} - \frac{1}{R_i C} \right) i_c + L C \frac{\alpha_2}{\alpha_2} (V_{\text{ref}} - \beta V_o) + \beta V_o
\] (10)

\[
V_{\text{ramp}} = \beta V_i
\] (11)

Where,
\[
K_{p1} = \beta L \left( \frac{\alpha_1}{\alpha_2} - \frac{1}{R_i C} \right)
\]
\[
K_{p2} = C \frac{\alpha_2}{\alpha_2}
\]

Fig 3. Represents schematic model of the proposed method which is simulated in Typhoon HIL Schematic editor. Control voltage equation is obtained using output voltage and capacitor current. Ramp voltage is obtained by multiplying \( \beta \) with input voltage and an integrator is used in the simulation model to remove variations in input voltage. The control logic is made by comparing control voltage equation (10) and ramp voltage equation (11). When there is a disturbances, the integral term of control variable controls the system, differential term lowers settling time and peak overshoot. Differential term also has the ability to improve transient part not by altering steady state behaviour. These components are helpful to get robust output voltage in load variations. The specification required for converters are considered as

| Table 1 BUCK AND BOOST CONVERTER SPECIFICATION |
|-----------------------------------------------|
| Descriptions | Parameter | Nominal values of buck | Nominal values of boost |
| Input voltage | \( V_i \) | 48 V | 30 V |
| Load Resistance | \( R_L \) | 6Ω, 10 Ω | 6Ω, 10 Ω |
| Inductance | \( L \) | 40mH | 3mH |
| Capacitance | \( C \) | 4µF | 810µF |
| Switching frequency | \( f_s \) | 50kHz | 50kHz |
| Output voltage | \( V_o \) | 19 V | 48 V |

\[
f = \frac{50000}{2\pi} \approx 2500Hz
\]

The switching frequency is considered 50 kHz and this frequency is multiplied by one twentieth in order to recover fast if there are variations in parameters due to disturbance in system.
VI. RESULT AND DISCUSSION

Schematic model is simulated for 3 second and results are observed as shown from figures 4-9. Results are observed by using HIL SCADA panel of Typhoon HIL for given model using SM control and PI control. The waveforms obtained by closing contactor and connecting load 6Ω are shown. A 10Ω resister is also connected to check the discharge current.

Figure 4 and 5 shows output voltage with sliding mode control which gives robust voltage approximately 19V and proportional control gives 23V having ripples. Output current and output power with PI control is also not constant. Hence sliding mode control gives best result than PI control. Figure 6 describes the battery storage system voltage which is shown 48V. Figure 7 and 8 shows load and discharge current with sliding mode control which is constant but there are variations in current with PI control. From all voltage displays, it is observed that the voltages were of constant value, which depicts the proper functioning of the SM control to keep load voltages at the desired voltage levels irrespectively.
Fig 4. Output parameters of buck converter with SM control

Fig 5. Output parameters of buck converter with PI control
Sliding Mode Control of dc-dc Buck Converter using Typhoon Hardware in Loop Software

Fig 6. Load and discharge with SM control

Fig 7. Load and discharge current with PI control

Fig 8. Battery current and voltage
Sliding mode controller is designed to maintain a smooth, constant voltage which is essential for SACDA panel systems. The derived controller is applied with the load. Derivation showed that step equations of sliding mode control technique is applied with buck converter which is directly connected with the load. Sliding mode controller gives smooth constant voltage which is best to connect a load of same voltage. There are less variations in compare to PI controller and fast stable transient response. Hence Sliding mode controller is good for small DC microgrid and dc-dc buck converter applications.

### VII. CONCLUSION

This paper carried out modelling of small DC microgrid with optimal PV panel selection by using waveform generator tool of Typhoon HIL. Battery sizing is calculated according to bus voltage and load requirement. To observe behaviour of sliding mode control technique it is applied with buck converter which is directly connected with the load. Sliding mode controller gives smooth constant voltage which is best to connect a load of same voltage. There are less variations in compare to PI controller and fast stable transient response. Hence Sliding mode controller is good for small DC microgrid and dc-dc buck converter applications.

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