ADAPTIVE SLIDING MODE CONTROLLER FOR STABLE DC MICROGRIDS

Adaptive sliding mode controllers can improve the power quality and reduce the ripples.

CONTENTS

Abstract

This paper discusses a strategy to enhance the stability of a system when it is connected to a constant power load (CPL). Generally, the CPL exhibits negative resistance characteristics which affect the power quality and stability of the system resulting in negative damping. This white paper proposes an adaptive sliding mode control technique to address this condition. The controller is designed to automatically assess the output power and input voltage of the system and tune the duty cycle (or) pulse width of boost converter to maintain the grid voltage constant, an adaptive mechanism introduced to update the switching gain in real-time, ensuring large signal stability. The proposed control strategy, validated through simulations, demonstrates superior dynamic regulation performance and robustness compared to a conventional double closed-loop PI control method.

Index Terms	Sliding mode control (SMC)	DC Microgrid	Boost Converter	Constant Power Load

Introduction

DC microgrids offer advantages of high efficiency, seamless integration with renewables, and freedom from issues like frequency synchronization seen in AC microgrids. Notably, constant power loads (CPLs) play a crucial role in DC microgrids, whose features resemble those found in automotive, space, and avionics systems. Ensuring stability and reliability in DC microgrids with CPLs has become a key focus in the realm of electrical energy systems. Maintaining the stability of the DC bus voltage is crucial for a stable DC microgrid.

The challenge arises due to the negative impedance characteristics of the constant power load that decrease the system's damping coefficient. In electric vehicles, DC converters are used to increase or decrease DC voltage; and inverters are used for DC to AC conversion. Since both converts act as constant power loads, they exhibit negative resistance characteristics. In batteries too, the DC-to-DC converter exhibits native resistance characteristics, affecting the system stability.

This paper presents an adaptive sliding mode controller is designed to stabilize the grid.

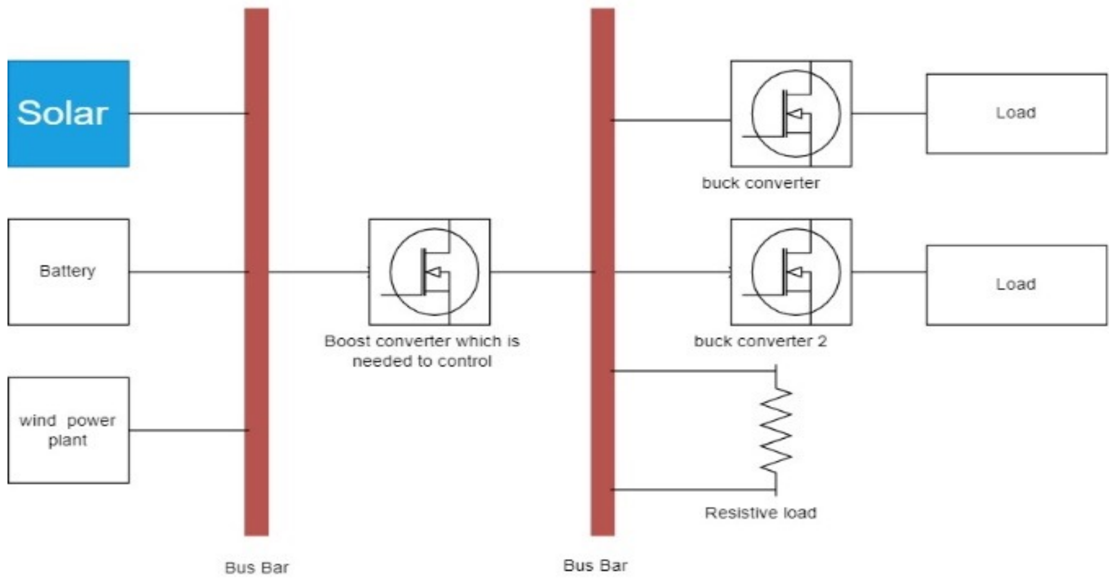

Figure 1 - DC microgrid system

Applications of Sliding Mode Control

- Robotics
- Aerospace Systems
- Power Electronics
- Electromechanical Systems
- Process Control
- Automotive Engines
- Photovoltaic Systems
- Flexible Space Structures
- Biomedical Applications
- Industrial Automation

System Modeling

Equation (1) and equation (2) represent the state equations of the boost converter.

$$\frac{di_l}{dt} = \frac{v_{in} - v_c}{l} - \frac{v_c}{l}d \qquad (1)$$

$$\frac{dv_c}{dt} = \frac{1}{C}\left(i_l - \frac{v_c}{r} - \frac{p}{v_c}\right) - \frac{i_l}{c}d \qquad (2)$$

If i_l is x_1 and v_c is x_2 therefore

$$\frac{di_l}{dt} = \dot{x}_1 \text{ and } \frac{dv_c}{dt} = \dot{x}_2$$

the general state equations are

$$\dot{x} = Ax + bu$$
$$y = Cx + Du$$

Here the control input "u" to boost converter is duty cycle "d"

Input matrix A $\begin{bmatrix} \frac{v_{in} - x_2}{l} \\ \left(x_1 - \frac{x_2}{r} - \frac{p}{x_2}\right) \end{bmatrix}$ and b = $\begin{bmatrix} \frac{x_2}{l} \\ -\frac{x_1}{C} \end{bmatrix}$

Controller Design

The stability of the microgrid is achieved by maintaining constant bus voltage. To maintain constant bus voltage, the duty cycle of a boost converter is tuned such that the inductor current and capacitor voltages are marinated at the rated value. To achieve that let us consider Y as summation of inductor energy and capacitor energy.

$$Y = \frac{1}{2}lx_1{}^2 + \frac{1}{2}cx_2{}^2 \qquad (3)$$

Here x_1 is current through inductor and x_2 is voltage across the capacitor.

$$e = Y_d - Y \qquad (4)$$

Y_d is the summation of desired inductor and capacitor energy where e is the error between desired energy and actual energy.

Let us take sliding surface as s = e.

To maintain inductor current and capacitor voltages at the rated values, the sliding surface must pass through origin (S = 0).

$$s = e \qquad (5)$$

$$\dot{s} = \dot{e} \qquad (6)$$

Here $\dot{s}$ is the derivative of with respective time.

$$V_1 = 0.5s^2 \qquad (7)$$

where $V_1 = 0.5s^2$ is a Lyapunov equation or Lyapunov energy function.

According to Lyapunov, a system is said to stable if, and only if, the derivative of its energy function with respective time is equal to zero.

$$\dot{V}_1 = s.\dot{s} \qquad (8)$$

From equations (3), (4), (6) and (2) V ̇_1 can be written as shown below in eq (9).

$$\dot{V}_1 = s\left(Y_d - l\frac{dx_1}{dt} - x_1 + \frac{x_2}{r} + \frac{p}{x_2} - x_1 d\right) \quad (9)$$

Let's take the duty cycle d in eq (10)

$$d = \frac{Y_d - l\frac{dx_1}{dt} - x_1 + \frac{x_2}{r} + \frac{p}{x_2} + €_1 sign(s)}{x_1} \quad (10)$$

and substitute eq (10) in eq (9) to get eq (11).

$$\dot{V}_1 = -s\big(€_1 sign(s)\big) \qquad (11)$$

Thus, Lyapunov theorem is proved.

Here choosing of the constant $€_1$ is an important factor and it must be chosen such that it is always greater than zero.

Now the controller is perfectly ready to control, but it is not adaptive.

To make it adaptive in nature let's take another constant $€_1$

Where $€_1$ is the adaptive constant which is represented as shown in eq (12).

$$\hat{€}_1 = \mu \int_0^t |s|\, dt \qquad (12)$$

Here μ is constant, μ>0.

Let's check the reachability law $s\dot{s}<0$

$$s\dot{s} = -\mu \int_0^t |s| sign(s) s\, dt \quad (13)$$

$$s\dot{s} = -\mu \int_0^t |s|\, dt|s| \qquad (14)$$

$$s\dot{s} < 0 \qquad (15)$$

So the new control equation is shown in eq (16).

$$d = \frac{Y_d - l\frac{dx_1}{dt} - x_1 + \frac{x_2}{r} + \frac{p}{x_2} + \hat{€}_1 sign(s)}{x_1} \quad (16)$$

$$V_2 = V_1 + \frac{1}{2\mu}\left(€_1 - €_1\right)^2 \qquad (17)$$

$$\dot{V}_2 = -s\left(\dot{€}_1 sign(s)\right) + \frac{1}{\mu}(\hat{€}_1 - €_1)\dot{\hat{€}}_1 \qquad (18)$$

$\dot{V}_2$ is less than zero if and only magnitude of $\hat{€}_1 - €_1$ so by properly choosing the *μ* value it is possible.

finally

$$\dot{V}_2 < 0 \quad (19)$$

Lyapunov's theorem is verified, so it can be concluded that the system is stable.

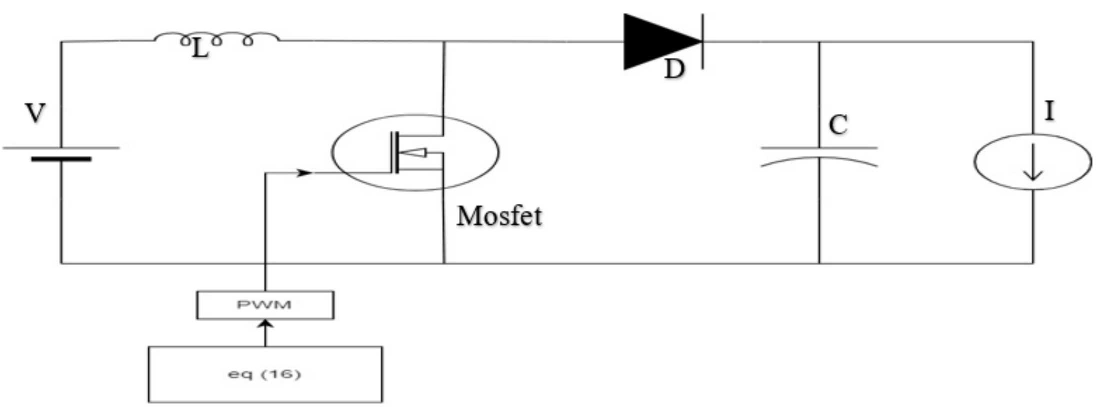

Figure 2 - Circuit diagram for the proposed controller

Simulation Results

A detail simulation is done on the MATLAB Simulink platform as shown in Fig 3, and the parameters used for simulation are Vin = 50, L = 143.999μH, C = 40μF and f = 50kHZ. The control parameters are set as μ = 15.

The detailed results of simulations are provided in Fig 3, where it is observed that even if power is changed suddenly from 50w to 25w and 225w at 0.3 sec and 0.6 sec respectively, the voltage has a small ripple, but it attains constant to 100V within very little time. It is observed that the proposed controller has less overshot and faster response and faster settling time compared to the PI controller.

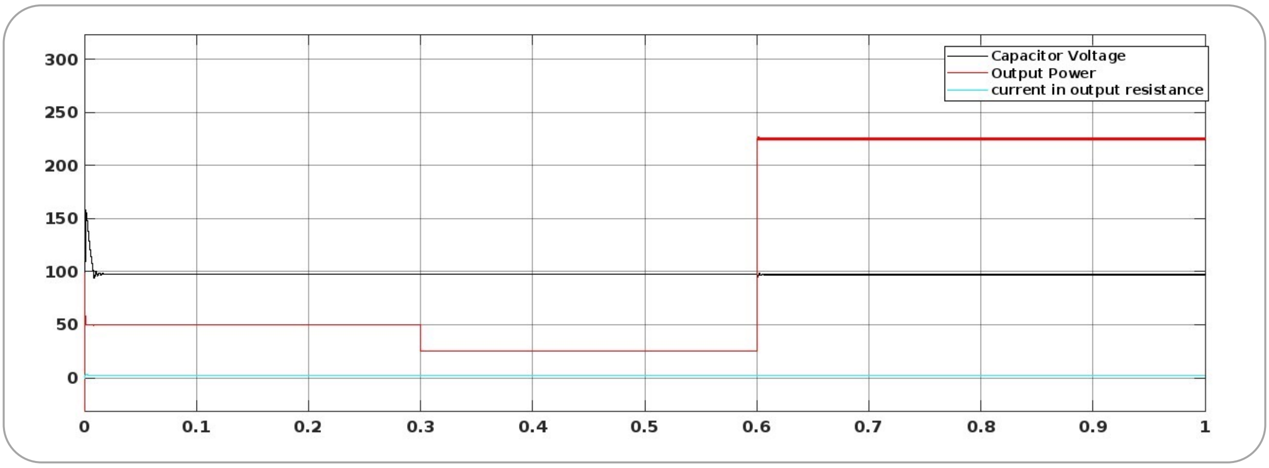

Figure 3 - Capacitor voltage, power, and inductor current for the proposed controller when power changes.

From Fig 4 it is observed that even the output resistor suddenly rises from 50omh to 550 ohm and 1110 ohms at 0.3sec and 0.6sec respectively. At that time even though output voltage experiences some peak overshoot it attains constant within very little time.

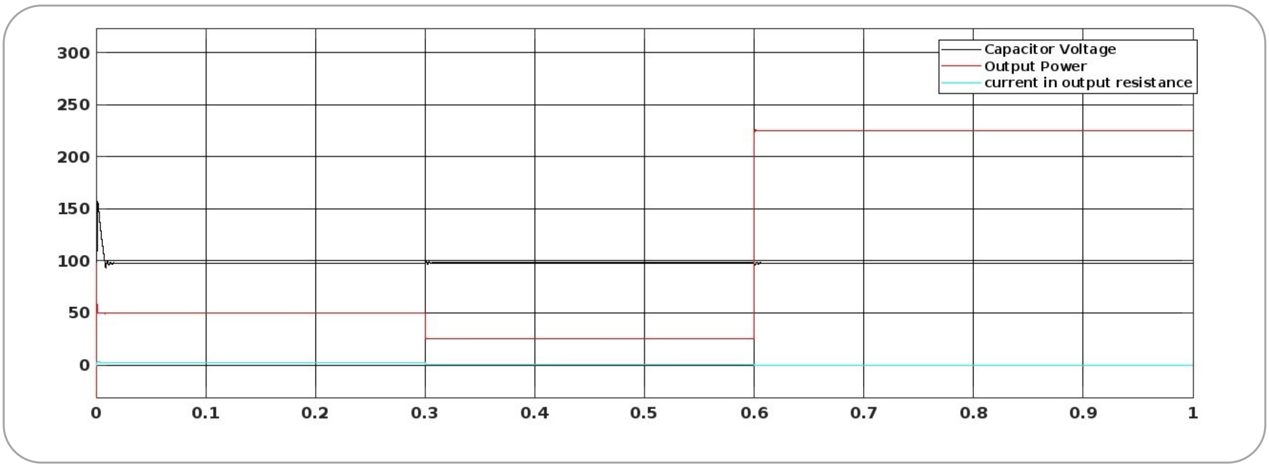

Figure 4 - Capacitor voltage, power, and inductor current for the proposed controller when resistor changes.

The detailed results of simulations provided in Fig 5 are obtained from the PI controller. Here, it is observed that even if power is changed suddenly from 50w to 25w and 225w at 0.3 sec and 0.6 sec respectively the initially voltage has a ripple, but quickly attains constant to 100V.

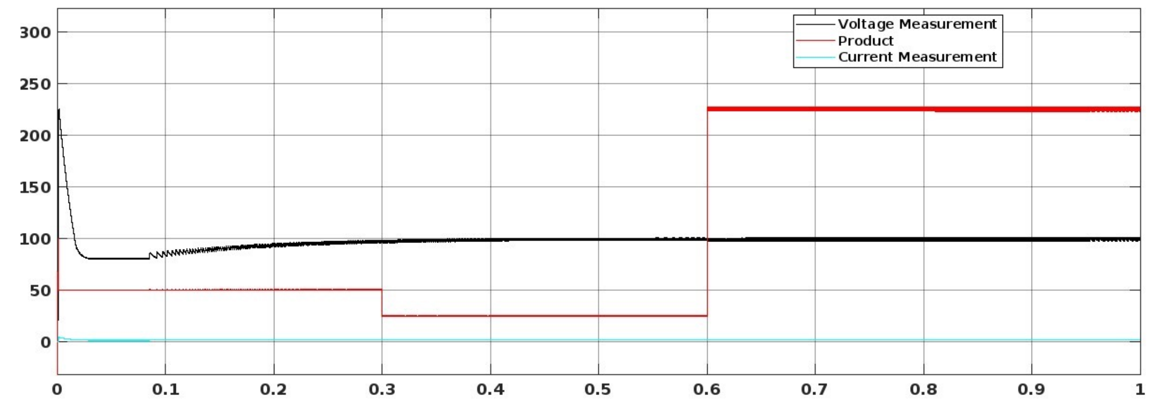

Figure 5 - Capacitor voltage, power, and inductor current for PI controller when power changes.

Fig 6 shows that even the output resistor suddenly rises from 50omh to 550 ohm and 1110 ohms at 0.3sec and 0.6sec respectively. At that time output voltage experiences some peak overshoot and attain constant after some time.

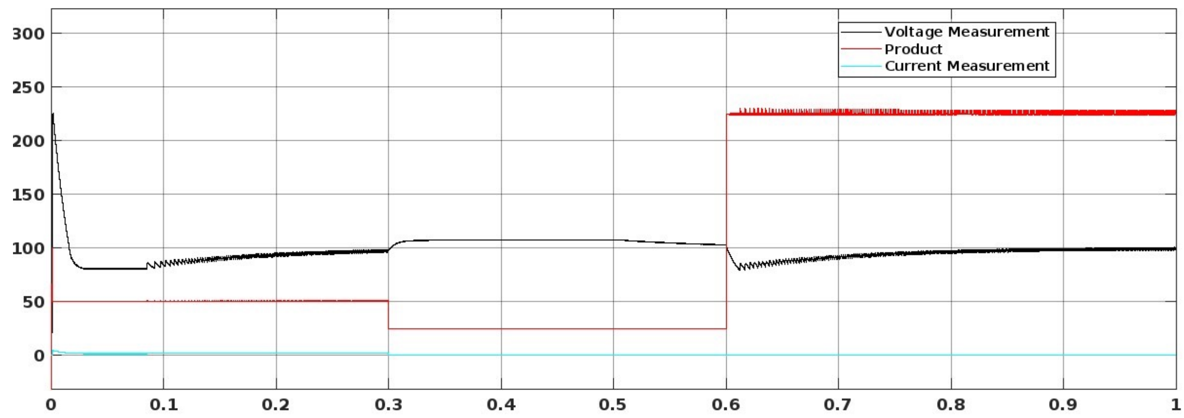

Figure 6 - Capacitor Voltage, Power, and Inductor current for PI controller when Resistor changes.

From Fig 3 and Fig 5, it observed that when load changes suddenly the proposed controller will give less voltage ripples compared to PI controller.

From Fig 4 and Fig 6 it observed that when output resistance changes the proposed controller performing well compared to PI controller.

Conclusion

The sliding mode controller is combined with the adaptive control technique to form the adaptive sliding mode controller. The sliding mode controller is a robust controller and the adaptive control technique by nature can easily change to gain constant according to the system configuration. The advantage of this proposed controller is that it can combine both techniques ensuring the proposed controller acts as a robust adaptive controller. Observing results of simulations done in MATLAB Simulink it is seen that the proposed controller gives superior results compared to conventional PI controllers. So, it is clear that this proposed controller will keep the DC microgrid safe under constant power load conditions too.

Going ahead, an observer will be designed to estimate every state of the system and give feedback to the controller to increase the accuracy and speed of the system.

About the Author

Paidi Ravi specializes in control systems. He has gained valuable industry experience as an electrical schematic engineer over the course of three months. With a curious mind and drive for excellence, he is poised to make meaningful contributions to the world of control systems engineering.

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