High performance DC-DC buck converter based on Sliding Mode Control

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Abstract
The quality of power conversion represents an important constraint in designing the DC-DC converter for distributed generation (DG) application based on renewable and clean energies. From this point of fact, this paper introduces a full modelling and design steps for a suitable DC-DC buck converter which controlled by a flexible designed sliding mode controller (SMC). Firstly, analyzing, modelling of a buck converter working through a continuous conduction mode (CCM) operation, and collecting the dynamic equations, all are demonstrated in this study. Then, to guarantee a high performance of power conversion function, a new comprehensive steps design of an effective SM controller has proposed to integrate the converter function. The proposed converter with the SMC controller are simulated and tested using Simulink of MATLAB software. The collected simulation results of resistive load voltage, current, and power are harvested for different load levels with varying the input DC link voltage. The shape and levels of load testing parameters through source voltage and load variation are promising and confirming the quality and the effectiveness of the presented converter and controller.

Keywords
Buck converter, Sliding Mode Controller, Buck converter modeling, simulation, MATLAB

1. Introduction
Since 1950s, the traditional alternating current AC power stations are working on generating and transmitting the electrical power to the end use customers. This electrical power is generating and delivering to the load side through a unidirectional centralized process. Most often, fossil fuels are used to move the rotors of big turbines connected to the same shafts of generators. There are many disadvantages associated with this traditional method of generating electrical power, that are in terms of air pollution, power and economic losses as mentioned in Weedy et al. (2012); Abdullah et al. (2020); Ali (2020); Hussain (2020). One of essential disadvantages is represented by the price instability of the generated power due to the instability of the fuel prices, and the unregularly maintenance. Other one is the lack in the control of generation process, especially for the case of unbalance distributed loads.

Another disadvantage is in terms of power or energy losses which are consuming in a serial resistance of the transmission and distribution lines. These losses are proportional with the lines currents and length. The limitation in the network capabilities and infrastructure showing other disadvantage because it reflects the limitation of the traditional power station and network Abdullah et al. (2020); Farhad et al. (2016); Hosham et al. (2018).

The researchers' efforts to avoid or mitigate the above demerits of the traditional AC power grid, since approximately three decades, a new focusing of renewable energy sources have been adopted to replace gradually the traditional AC grid. Working in this direction is also solving the problem of homes far from the electrical grid. For example, a photovoltaic based microgrid can serve as an effective alternative which able to satisfy the power requirements of the remote country houses.

Solar energy system is playing a major role in harvesting the renewable energy. The photovoltaic PV energy system can operate in grid tied mode or standalone mode. The function of this PV system converting the incident solar energy to a proportional electrical power. In addition to avoiding the demerits of the traditional power generation system, the renewable system can export the extra electrical power to the grid, in other meaning, the renewable energy microgrid supports the traditional grid by reducing the electricity demand from it as explained in Hussain (2019); Micheal et al. (2017). The reduction in air pollution level represents an important objective from adopting the renewable energy sources, especially when using in power delivering to electric vehicles, trains, conveyers, and tractors Arellano et al (2013); Galus et al. (2010); Guille and Gross (2009).

Photovoltaic PV panel converts the incident sun light into a proportional electrical power, with different levels of delivered direct current and panel output voltage, the level of delivered power is fluctuated due to the fluctuation in the levels of incident light and ambient temperature that is leading to have fluctuation in output panel voltage and current Hussain (2018); Hussain and Fernando (2019); Hussain and Khaled (2020).

Based on the above, a DC-DC buck converter with a flexible design of a robust sliding mode controller are designed, simulated by MATLAB/Simulink, collected results analyzed, and all the study details and concluded points introduce in this paper. In section 1, the converter equivalent circuits and converter modelling are discussed for the two status of the converter switch, and the dynamic equations are demonstrated as well. Full design steps of the desired robust sliding mode controller are shown in Section 2. In Section 3, Different source voltages and load conditions are tested and analyzed to reflect the effectiveness of the robust controller with the buck converter. Summary of the conclusion is shown in Section 4.

2. Buck Converter: Modeling and Operation

The function of DC-DC buck converter is stepping down and regulating the unregulated direct current DC link voltage. The topology of this converter is represented by inserting an LC circuit to a basic circuit of the converter Attia (2018), Daniel (2011), Rashid (2001). The circuit arrangement and connection of this converter is shown in Figure 1.

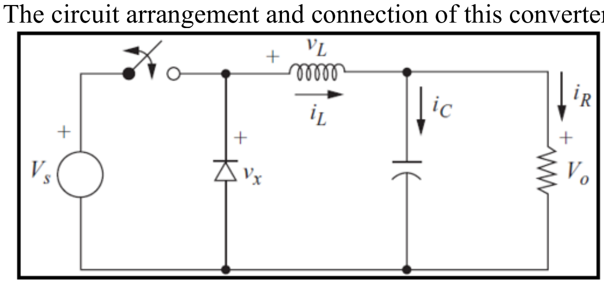


Figure 1. The circuit arrangement of DC-DC buck converter (step-down converter)

In the analysis starting to the operation status of the converter circuit, assume the switch is closed and the input voltage V_S, whereas when the switch is open the input voltage is disconnected from the converter circuit. A continuous current mode CCM of the converter operation is adopted in this study, so, the inductor current remains positive during the switching period and never reaches to zero.

If the switch closing is periodically executed with duty ratio D, the average of the output voltage (V_O) at the LC filter can be calculated by integrating to the input voltage for the duty ratio period divided by the switching time (T):

$$V_o = \frac{1}{T}\int_0^T V_o(t)\,dt = \frac{1}{T}\int_0^{DT} V_s dt \tag{1}$$

For the period ($0 \leq t \leq DT$), the switch is closed:
When the switch is closed for DT, the diode will be in reversed biasing, and the inductor voltage is:

$$v_L = V_s - V_o = L\frac{di}{dt} \tag{2}$$

Or

$$\frac{di}{dt} = \frac{V_S - V_O}{L} \tag{3}$$

The equivalent circuit during $0 \leq t \leq DT$ is shown in Figure 2

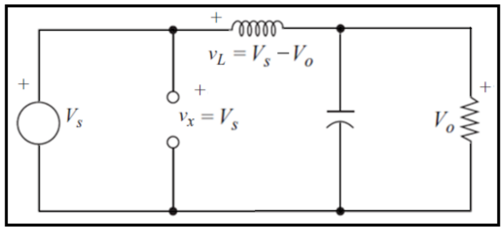


Figure 2. The converter circuit during $0 \leq t \leq DT$ (Switch is closed)

So, the change in the inductor current Δi_L during DT is

$$\frac{di}{dt} = \frac{\Delta i}{\Delta t} = \frac{\Delta i_L}{DT} = \frac{V_S - V_O}{L} \tag{4}$$

Or

$$\left(\Delta i_{L(Closed)}\right) = \left(\frac{V_S - V_O}{L}\right) DT \tag{5}$$

For the period ($DT < t \leq T$), the switch is opened:
When the switch is opened, the diode will be in forward-biased due to the effect of positive direction of the inductor current. The inductor voltage will be

$$v_L = -V_o = L\frac{di}{dt} \tag{6}$$

Or

$$\frac{di_L}{dt} = \frac{-V_O}{L} \tag{7}$$

The equivalent circuit of the converter during $DT <$ t $\leq T$ is shown in Figure 3.

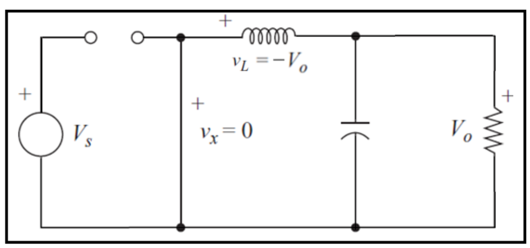


Figure 3. The converter circuit during $DT \leq t \leq T$ (Switch is opened)

The variation of inductor current during the switch opening is

$$\frac{di}{dt} = \frac{\Delta i}{\Delta t} = \frac{\Delta i_L}{(1-D)T} = \frac{-V_O}{L} \tag{8}$$

Or

$$\left(\Delta i_{L(Open)}\right) = -\left(\frac{V_O}{L}\right)(1 - D)T \tag{9}$$

The net variation in inductor current at steady-state operation after completing a full period of switching time is zero, so:

$$\Delta i_{L(Closed)} + \Delta i_{L(Open)} = 0 \tag{10}$$

Or

$$\left(\frac{V_S - V_O}{L}\right) DT - \left(\frac{V_O}{L}\right)(1 - D)T = 0 \tag{11}$$

This yields

$$V_o = V_s D \tag{12}$$

So, the desired output voltage produced from DC-DC buck converter is always less than or equal the input supply voltage that depends on the duty ratio *D* value.

To drive the dynamic equation of di_L/dt for the buck converter, replace *u* instead of *DT* as a duty ratio period in which the switch is closed. 1-*u* can replace the value of *T*(1-*D*) to represent the time period in which the switch is open.

$$\frac{di_L}{dt} = \left(\Delta i_{L(Closed)}\right) + \left(\Delta i_{L(open)}\right) \tag{13}$$

$$\frac{di_L}{dt} = \left(\frac{V_S - V_O}{L}\right) DT - \left(\frac{V_O}{L}\right)(1 - D)T \tag{14}$$

$$\frac{di_L}{dt} = \frac{u\,V_S}{L} - \frac{V_O}{L} \tag{15}$$

On the other side, during the switching ON and OFF the capacitor current is

$$i_C = i_L - i_R \tag{16}$$

So,

$$C\frac{dV_O}{dt} = i_L - \frac{V_O}{R} \tag{17}$$

$$\frac{dV_O}{dt} = \frac{i_L}{C} - \frac{V_O}{RC} \tag{18}$$

The dynamic equations of the inductor current and load voltage in the buck converter can be represented by (15), and (18) respectively.

3. Detailed Design of a Sliding Mode Controller

Sliding mode controller SMC works on driving the switch of the circuit converter, and SMC for buck converter has a sliding surface *S* which is the summation of the error X_1 of the output voltage, and the change of this error X_2. This error X_1 represents the difference between the reference voltage (V_r) and the actual output load voltage (V_o), Ref 19: Guldemir (2011); Guldemir (2005); Trushev et al. (2005); Tahri et al. (2014); Ben Saad et al. (2011).

$$X_1 = V_r - V_0 \tag{19}$$

$$X_2 = \frac{dX_1}{dt} \tag{20}$$

$$X_2 = -\frac{dV_O}{dt} \tag{21}$$

$$S\,(X) = X_1 + X_2 \tag{22}$$

$$S(X) = X_1 + \frac{dX_1}{dt} \tag{23}$$

Replace (19), and (21) in (23) yields

$$S(X) = (V_r - V_0) - \frac{dV_O}{dt} \tag{24}$$

Replace (18) in (24) yields

$$S(X) = (V_r - V_0) - \frac{1}{C}\left(i_L - \frac{V_O}{R}\right) \tag{25}$$

Rearranging (25) yields

$$S(X) = -\frac{1}{C}i_L + \left(\frac{1}{RC} - 1\right)V_o + V_r \tag{26}$$

The target of the SMC is to have zero for the sliding surface *S* and the derivative of the surface $\dot{S}$ Guldemir (2011); Tahri et al. (2014); Ben Saad et al. (2011).

$$S(X) = \dot{S}(X) = \frac{dS}{dX} = 0 \tag{27}$$

On the other side, derivative (26), yields $\dot{S}(X)$

$$\dot{S} = -\frac{1}{C}\frac{di_L}{dt} + \left(\frac{1}{RC} - 1\right)\frac{dV_O}{dt} \tag{28}$$

Replacing in (28) the value of $\frac{di_L}{dt}$ from (15), and the value of $\frac{dV_O}{dt}$ from (18), yields

$$\dot{S} = -\frac{1}{C}\left(\frac{u\,V_S}{L} - \frac{V_O}{L}\right) + \left(\frac{1}{RC} - 1\right)\left(\frac{i_L}{C} - \frac{V_O}{RC}\right) \tag{29}$$

There are two components in the controlling state *u*, the first one is the equivalent component u_{eq}, and the second one is the nonlinear component u_n Guldemir (2011); Tahri et al. (2014); Ben Saad et al. (2011).

$$u = u_{eq} + u_n \tag{30}$$

The sign of the value *S* determines the value of nonlinear component u_n as follows

$$u_n = sign\,(S) \tag{31}$$

On the other side, to have the equivalent component u_{eq}, equaling (29) to zero yields

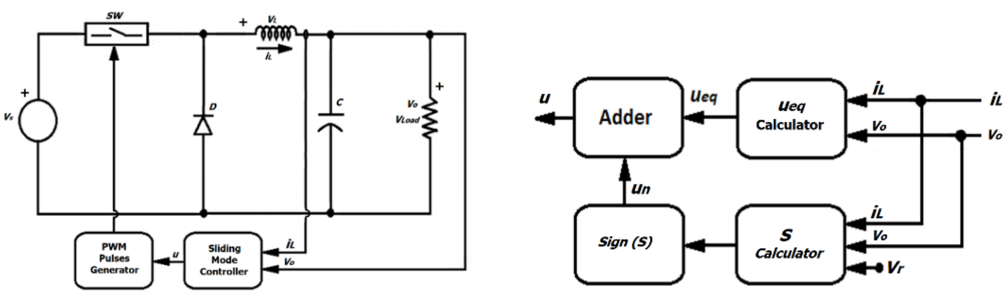
$$u_{eq} = \frac{P_1 i_L + P_2 V_o}{P_3 V_S} \tag{32}$$

where,

$$P_1 = RL(1 - RC) \tag{33}$$
$$P_2 = RC(R + L) - L \tag{34}$$
$$\boldsymbol{P_3 = R^2 C} \tag{35}$$

4. Simulation Results

The electrical components of the buck converter is designed through the steps and relationships shown in Daniel (2011). The selected parameters and components of the converter are shown in Table 1, in which the converter switching frequency is 10 kHz. The converter is controlled through the designed and proposed SM controller. Figure 4 shows the block diagram of the proposed robust SMC with the designed buck converter. The controller with the converter are simulated, and the system performance is evaluated through MATLAB/Simulink simulation of 50 µs sample time as shown in Figure 5. To have precise evaluation to the proposed SMC, different resistive load are connected to the converter during the running time of the simulation. The connected load is started by 15 Ω for 5 seconds of full 15 seconds of simulation time. Additional load resistor 15 Ω is connected in parallel with the first one to have lower load of 7.5 Ω for the other 5 seconds. After that, a third resistor 15 Ω is inserted in parallel connection with the load to have a lower load of 5Ω for the last 5 seconds of the simulation running time. A stable load voltage of differ loads (15 Ω, 7.5 Ω, and 5 Ω) is monitored for different reference voltages 15 V, 20 V, and 30 V.



(a) (b)

Figure 4. Block diagram of the presented controlled DC-DC buck converter;
(a) Converter circuit, (b) designed SM controller

Table 1. Parameters of the designed DC-DC buck converter

Converter Parameter	Parameter Value
Inductor L	4 mH
Capacitor C	1.5 mF
Load resistor R	15 Ω, 7.5 Ω, 5 Ω
Switching frequency f_s	10 kHz

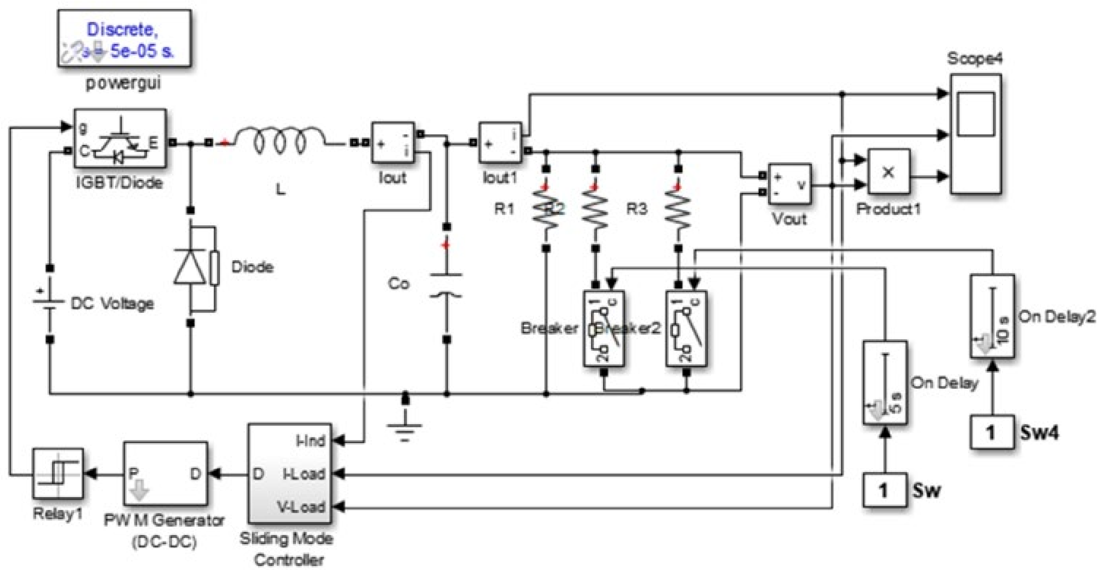


Figure 5. MATLAB/Simulink simulation of the presented SM controlled DC-DC buck converter

Figure 6 shows the load current, voltage and power for different resistive load when setting the reference voltage to 15 V, and how the SMC controller stabilize the load voltage and how follow the reference voltage without any fluctuation in the output voltage during the instants (5 seconds, and 10 seconds) of load variations.
Same effective response from the converter with SM controller is received when selecting another reference voltage V_r = 20 V as shown in Figure 7.

The system performance when reference voltage V_r = 30 V is shown in Figure 8, in which the effectiveness of the designed controller in stabilizing the load voltage in the level of reference voltage. Figure 9 demonstrates a very low voltage fluctuation at the instants of loads variations.

The harvested testing results from the system simulation reflect the importance of applying the proposed controller as a part from the Maximum Power Point Tracking MPPT system to guarantee a smooth response from system converter by avoiding the overshoot in the output voltage and load current during any variation of light intensity and ambient temperature.

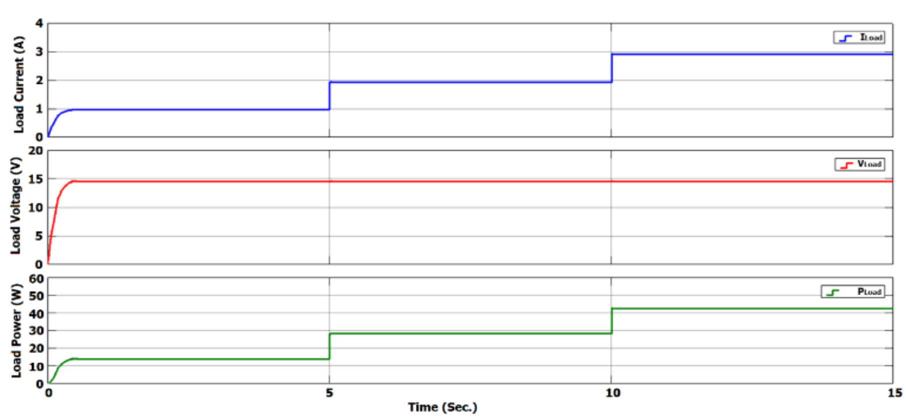


Figure 6. Load current, voltage and power at reference voltage 15 V,
and different loads 15 Ω, 7.5 Ω, and 5 Ω.

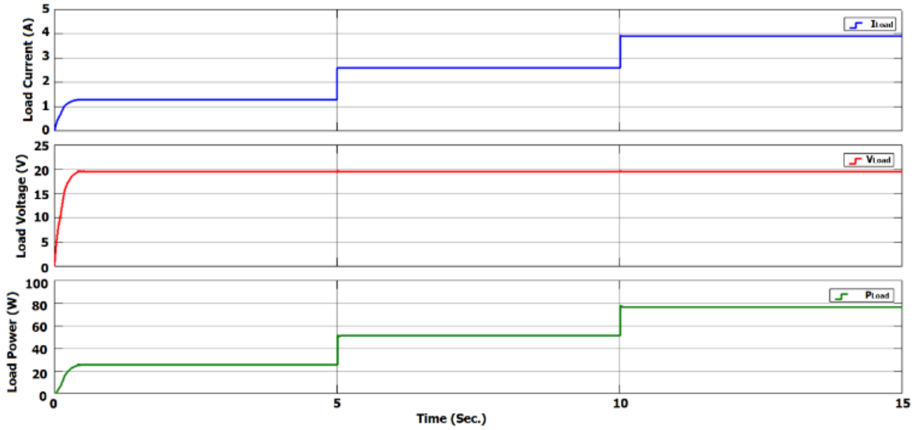


Figure 7. Load current, voltage and power at reference voltage 20 V, and different loads 15 Ω, 7.5 Ω, and 5 Ω.

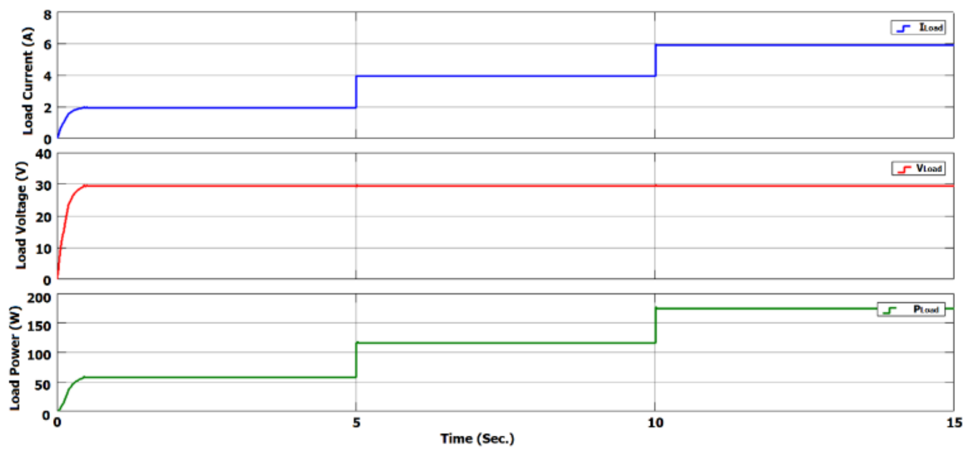


Figure 8. Load current, voltage and power at reference voltage 30 V, and different loads 15 Ω, 7.5 Ω, and 5 Ω.

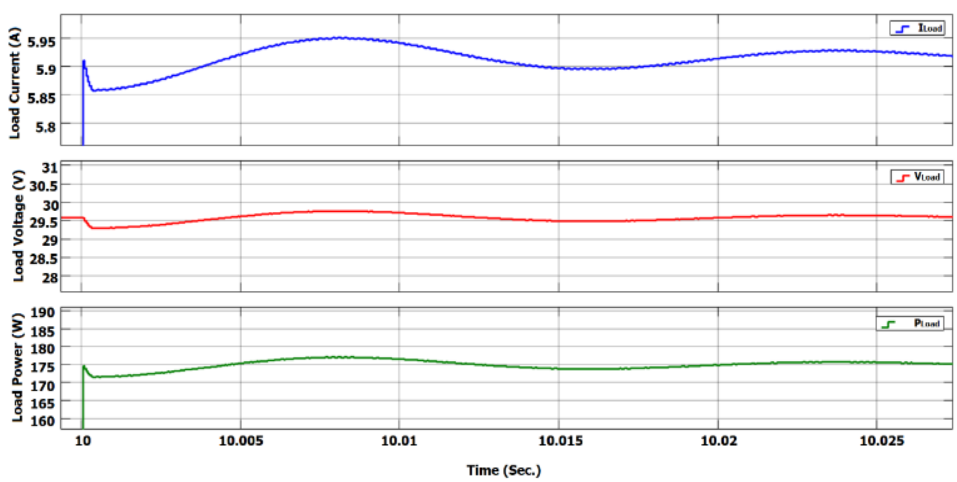


Figure 9. Low fluctuation range in load current, voltage and power at reference voltage 15 V, and load variation from 7.5 Ω to 5 Ω.

5. Conclusion and Future Work

A new design of a robust sliding mode controller for buck converter has presented in this paper; the design has started by determining the dynamic equations of the inductor current and output voltage of the converter through modeling it in continuous current operation mode. After that, a detailed steps of a sliding mode controller SMC have been demonstrated. The system is simulated and evaluated using MATLAB/Simulink. The simulation results confirmed the effectiveness and suitability of the proposed SMC for DC-DC buck converter application in terms of tracking the reference voltage in spite of load variations. For future work, the SM controller can inserted with a Maximum Power Point Tracking MPPT system that to have a smooth response from system converter during any variation in weather conditions, such as light intensity and ambient temperature.

References

Abdullah, H., Razzaqul, A., Nasser, H., Reza, G., Eklas, H. (2020), Survey of smart grid concepts and technological demon striations worldwide emphasizing on the Oman perspective. Applied System Innovation, 3(5), 1-190.

Ali, K. (2020), Design of Smart Power Grid Renewable Energy Systems. United States: John Wiley & Sons Ltd.

Arellano, B., Sena, S., Abdollahy, S., Lavrova, O., Strattonl, S., Hawkins, J. (2013), Analysis of Electric Vehicle Impacts in New Mexico Urban Utility Distribution Infrastructure. Detroit, MI, USA: IEEE Transportation Electrification Conference and Expo (ITEC).

B.M. Weedy, B.J.Cory, N. Jenkins, J.B.Ekanayake, and G. Strbac. (2012). Electric Power Systems, 5th Edition, John Wiley & Sons Ltd.

Danial, H. (2011), Power Electronics. United States: McGraw Hill

Farhad, K., Shamsodin, T., Hamed, T., Edris, P. (2016), Integration of Electric Vehicles Into a Smart Power Grid: A Technical Review. Ottawa, ON, Canada: IEEE Electrical Power and Energy Conference (EPEC).

F. Tahri, A. Tahri, and S. Flazi, 2014, Sliding Mode Control for DC-DC Buck Converter, Third International Conference on Power Electronics and Electrical Drives ICPEED'14, At: University of science and technology of Oran.

Galus, M.D., Zima, M., Andersson, G. (2010), On integration of plug-in hybrid electric vehicles into existing power system structures. Energy Policy, 38, 6736-6745.

Guille, C., Gross, G. (2009), A conceptual framework for the vehicle-togrid (V2G) implementation. Energy Policy, 37, 4379-4390.

H. Guldemir, 2011. Modeling and Sliding Mode Control of Dc-Dc Buck-Boost Converter", 6th International Advanced Technologies Symposium (IATS'11), 16-18 May, Elazığ, Turkey.

H. Guldemir, 2005. Sliding Mode Control of Dc-Dc Boost Converter. *Journal of Applied Sciences* 5(3): pp. 588-592.

Hosham, S., Khalid, F., Raheel, J. (2018), Enhancement of Performance for Steam Turbine in Thermal Power Plants Using Artificial Neural Network and Electric Circuit Design. Hindawi: Applied Computational Intelligence and Soft Computing.

Hussain, A. (2018), Artificial neural networks based maximum power point tracking photovoltaic system for remote park LED lighting applications. International Review on Modelling and Simulations IREMOS, 11(6), 15156.

Hussain, A., Fernando, G. (2019), Stand-alone PV system with MPPT function based on fuzzy logic control for remote building applications. International Journal of Power Electronics and Drive Systems, 10(2), 842-851.

Hussain, A., Khaled, H. (2020), Hybrid technique for an efficient PV system through intelligent MPPT and water cooling process. International Journal of Power Electronics and Drive Systems, 11(4), 1835-1843.

Hussain, A. (2018), A stand-alone solar PV system with MPPT based on fuzzy logic control for direct current portable house applications. International Review on Modelling and Simulations IREMOS, 11(6), 16074.

Hussain, A. (2020), A New Intelligent Power Factor Corrector for Converter Applications. Toronto, Canada: 6th International Conference on Control, Modeling and Computing (CMC 2020).

Hussain, A. (2020), Artificial neural network based unity power factor corrector for single phase DC-DC converters. International Journal of Electrical and Computer Engineering, 10(4), 4145-4154.

Hussain, A. (2019), Supplying DC Electricity to the Isolated Dwellings through MPP Tracked PV System Based on

Artificial Neural Network. Ottawa, Canada: 6th International Conference of Control, Dynamic Systems, and Robotics (CDSR'19).

I. Trushev, N. Mastorakis, I. Tabahnev, and V. Mladenov, 2005. Adaptive Sliding Mode Control for DC/DC Buck Converters. October, https://www.researchgate.net/publication/234806929

K. Ben Saad, A. Sahbani, M. Benrejeb, 2011, Sliding Mode Control and Fuzzy Sliding Mode Control for DC-DC Converters, Research unit LARA, National engineering school of Tunis (ENIT), Tunis, Tunisia. Publisher InTech.

Michael, H., Damir, N., Mariesa, W. (2017), Electric Power Grid Modernization Trends, Challenges, and Opportunities. United States: IEEE Advancing Technology for Humanity.

Rashid, M.H., 2001. *Power electronics*. Handbook, Academic Press, New York, USA.

Biography

Hussain Attia earned his Ph.D. degree in power electronics from University of Malaya, Kuala Lumpur, Malaysia, and M.Sc. degree in electronic engineering from the University of Technology, Baghdad, Iraq. Currently, he is working as a faculty member in Department of Electrical, and Electronic Engineering at American University of Ras Al Khaimah, Ras Al Khaimah, UAE. He served as a technical and organizing member for many IEEE and international conferences such as ICEDSA / 2016, ICECTA / 2017, ICEWES / 2018, and ICECTA / 2019. Hussain's research interests include power electronics, AC & DC Drives, PWM Inverters (single phase & three phases), harmonics reduction techniques, and intelligent control.