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Voltage Controlled Boost Converter-Inverter System for Photovoltaic Applications

Zeynep Bala DURANAY[1*], Hanifi GULDEMIR[2]

Firat University, Technology Faculty, Department of Electrical Electronics Engineering, Elazig, Turkey
[1]zbduranay@firat.edu.tr, [2]hguldemir@firat.edu.tr

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Abstract: Photovoltaic electric energy generation systems are attractive for the places far from the electric grid system and for small scale applications. Off-grid inverters are widely used in renewable energy applications. Most of the applications such as home appliances require constant voltage. Thus, the voltage of the inverter needs to be kept constant. In this paper, the analysis, modelling, control and simulation of a photovoltaic module fed boost converter-inverter system is studied. The PV fed boost converter provides dc link for the inverter. The cascade connection of boost converter and an inverter provides sinusoidal voltage to the ac loads. A conventional proportional+integral (PI) controller is used to obtain a constant dc link voltage even with input voltage variations. Matlab-Simulink programming environment is used for the modelling and simulations. The simulation results are presented.

Key words: Boost converter, dc link control, inverter, off-grid inverter, voltage regulation.

Fotovoltaik Uygulamalar için Gerilim Kontrollü Yükseltici Çevirici-Evirici Sistemi

Özet: Fotovoltaik enerji üretim sistemleri elektrik şebekesinden uzak yerlerdeki küçük çaplı uygulamalar için oldukça caziptir. Şebeke bağımsız olarak çalışan eviriciler yenilenebilir enerji uygulamalarında yaygın olarak kullanılmaktadır. Ev aletlerinde olduğu gibi birçok uygulama sabit gerilim gerektirmektedir. Bu nedenle bağlı olduğu evirici geriliminin sabit tutulması gerekir. Bu çalışmada bir fotovoltaik modül beslemeli yükseltici çevirici-evirici sistemin analizi, modellenmesi, kontrolü ve benzetimi yapılmıştır. Fotovoltaik modül beslemeli yükseltici çevirici, evirici için gerekli dc gerilimi sağlamaktadır. Kaskad bağlı yükseltici çevirici ve evirici ise ac yükler için gerekli sinüsoidal gerilimi oluşturmaktadır. Giriş gerilimlerinin değişmesi durumunda da sabit bir dc link gerilimi elde etmek için geleneksel PI denetleyici kullanılmıştır. Modelleme ve benzetim için Matlab/Simulink programlama ortamı kullanılmış ve benzetim sonuçları sunulmuştur.

Anahtar kelimeler: Yükseltici çevirici, dc link kontrol, evirici, şebeke bağımsız evirici, gerilim kontrolü.

1. Introduction

New energy resources such as wind power, fuel cell and solar power have been started to be used in home appliances [1] as well as industrial [2] and agricultural [3] applications. The use of solar power, which is one of the most popular renewable energy resources, for generation of electricity [4] is becoming very attractive over the years because of sustainability. The energy obtained from solar photovoltaic (PV) power has vital importance especially for the places where the access of electricity is impossible or it is too difficult in every means to access it [5-6]. In this case off-grid or standalone PV energy generation systems are used [7-9].

PV panels generate DC power. Because the voltage produced by the PV panels is low in magnitude it is required to be increased either using more panels or dc-dc boost converter [10]. This dc voltage has to be inverted to the mains values both in voltage level and frequency. A step up transformer or a boost inverter can be used to bring the voltage level and frequency to mains level. Mostly, inverters are preferred to transformers due to reliability and efficiency.

As the voltage produced by panels change by the climatic conditions such as temperature, irradiation, shading and clouding, the constant voltage level has to be maintained to prevent failures of the connected devices due to voltage oscillations. Dc-dc converters can be used to keep constant dc link voltage for the inverter. This time a converter need to be used together with the inverter causing decrease in efficiency, increase in circuit size and complication in control system structure.

* Corresponding author: zbduranay@firat.edu.tr. ORCID Number of authors: [1] 0000-0003-2212-5544, [2] 0000-0003-0491-8348

In this paper, a classical PI controller is used to keep the dc bus voltage constant and not affected by the dc source voltage changes. To achieve high precision, a control system which compensates the dc link voltage variations using boost converter and an inverter to perform a power conversion with a constant output voltage is studied.

The system can be used in applications where an ac voltage is required to obtain from a low dc voltage source such as photovoltaic applications or electrical vehicles.

2. Single Phase Inverter

An inverter is a vital interface between renewable energy source and an ac load, providing an ac power required by ac loads. A few kVA rating low power applications use single-phase inverters which have two types of structures. One of the single phase inverter structure as shown in Figure 1, is the half bridge inverter which is used for low cost applications. Two capacitors are used for the dc link in this structure and the load is connected to the connection point of these capacitors. The output voltage value can be between half of the negative and positive dc bus voltage i.e. between the values of –E/2 and E/2. In this topology the capacitors are charged by the load current causing dc bus voltage fluctuation. To decrease the output voltage ripples produced by this voltage fluctuation and to increase the performance of the system, these dc bus capacitors need to have a large capacity.

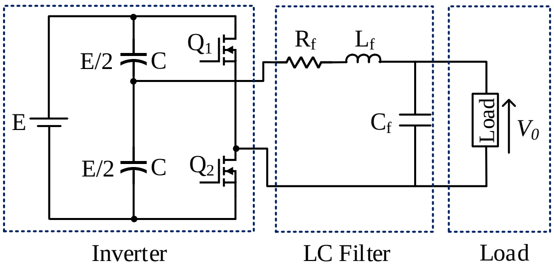


Figure 1. Half bridge single phase inverter.

The other type of the single phase inverter is the full bridge single phase inverter which has two legs to control the output voltage as shown in Figure 2. When compared with the half bridge inverter the dc bus capacitors have smaller capacity than those of the half bridge inverter capacitors as the connection point of these capacitors is not used for load. The output voltage can take the values between the negative and positive dc bus voltage values i.e. between –Vdc ~ +Vdc. These type of inverters are mostly used in high performance and high power applications.

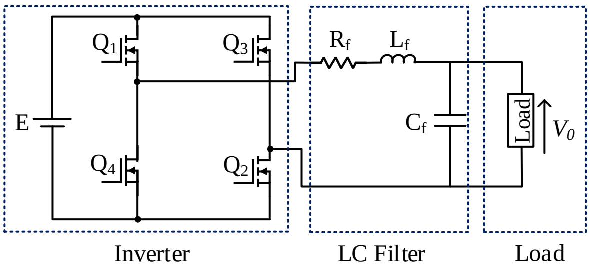


Figure 2. Full bridge single phase inverter.

If the half bridge inverter structure is planned to be used for a 220V utility application, then 800V dc bus voltage is needed. This voltage is reduced to 400V if full bridge single phase inverter is used.

Fast change of voltage (dv/dt) in the inverter results over voltages applied to load. This further creates additional problems such as increase in bearing currents, eddy current losses in the core and skin-effect losses in the windings if the load is an induction machine [11]. One of the solutions to reduce the dv/dt is to use a filter with passive elements at the inverter output [12, 13]. LC type filters are the most used filters [14]. The electrical circuit of the AC inverter shown in Figure. 2 includes an H-bridge inverter and an LC harmonic filter [15, 16].

An open loop PWM controller is used for the output voltage of the inverter. The LC filter is used for suppressing the higher-order current harmonics because of high frequency switching to reduce total harmonic distortion (THD) and also to reduce high dv/dt [17]. The design of the LC filter can be made with the equations presented in [18-20].

The single phase inverter applications require a power up to 5 kW and a dc voltage level of 400 V [21]. They are one of the main element of the off-grid residential PV applications.

3. Dc-Dc Boost Converter

If photovoltaic panels or battery groups are used to obtain a dc bus voltage for the inverter, then the dc output voltages of these PV panels or batteries need to be increased to required level. For this purpose, a dc-dc boost converter is used.

A dc-dc boost converter produces a higher output voltage from a low value dc input voltage by periodically making the switch in the circuit to be on and off.

The circuit diagram of a boost converter is given in Figure 3, where E represents the dc input voltage, S, L, C, D and R are the switch, inductor, filter capacitor, diode and the load respectively.

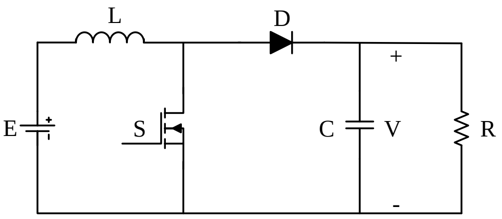
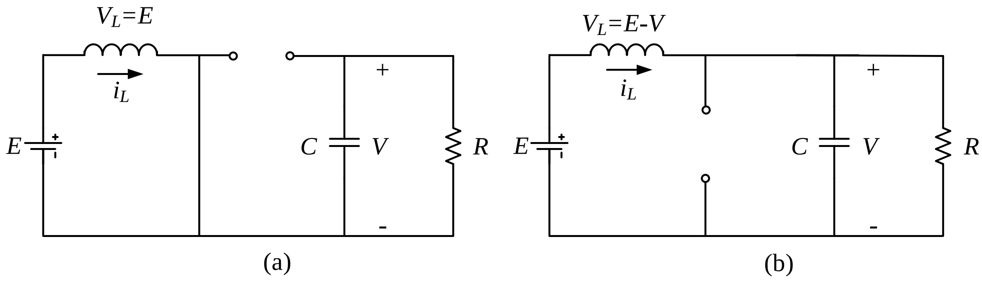


Figure 3. Dc-dc boost converter.

The analysis of the boost converter is made by examining the inductor current and voltage during a switching period. As shown in Figure 4-a and b, the dc-dc boost converter has two modes of operation [22] depending on switch states.



(a) (b)

Figure 4. Equivalent circuits for switch closed (a) and for switch open (b).

If the switch S is closed, the diode D reverse biased and becomes off. The current in the inductor increases linearly. The capacitor feeds the load at this mode. In the second mode the switch is become off and the stored inductor current discharges through the diode and the load. Thus in this mode both inductor current and capacitor voltage feeds the load.

Waveforms of the steady state operation of the converter during one period of the switching is shown in Figure 4.

From Figure 4, the voltage across the inductor L during a switching period T is,

$$V_L(t) = \begin{cases} E & during \quad DT \\ E - V & during \quad (1-D)T \end{cases} \tag{1}$$

Due to the volt-second balance, the average voltage across the inductor in one switching period must be zero then,

$$E.DT + (E - V)(1 - D)T = 0 \quad (2)$$

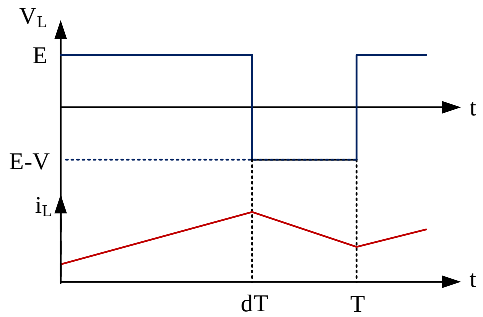


Figure 5. Boost converter waveforms for inductor voltage and current.

rewriting,

$$\frac{V}{E} = \frac{1}{1-D} \quad (3)$$

and the output voltage of the boost converter related to input voltage and duty cycle is

$$V = \frac{E}{1-D} \quad (4)$$

Equation 4 says that if switch is always open then D is zero, then the output voltage is equal to the input voltage. If duty ratio D is increased the denominator of Equation 4 will be smaller producing large output voltage. Thus, dc-dc boost converter produces an output voltage which is greater than or equal to the input voltage.

4. Model of Boost Cascade Connected Converter-Inverter

In this study, a cascade connected DC-DC power converter, an H-bridge inverter and a DC motor, as depicted in Figure 6, is considered.

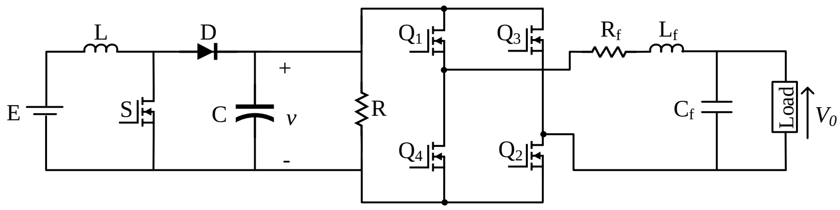


Figure 6. Single phase boost converter-inverter.

The DC-DC power converter is a boost type converter, consists of a DC power supply (E), a switching transistor (S) which regulates the converter output voltage (v), a diode (D), resistor (R), inductor (L) and capacitor (C). This converter is used to adjust the motor voltage which, in this case, is the dc link voltage of the inverter.

The inverter is an H-Bridge inverter i.e. two leg inverter with four switching transistors Q1-Q4. Transistors Q1 and Q2 are given with the same gate signal. The complement of this signal is applied to the other two transistors Q3 and Q4. That is, if Q1-Q2 both are on then Q3-Q4 both are off at the same time.

The load is an ac load.

The overall system, as listed in Table 1, have four modes of operation depending on the state of the switches S and Q1-Q4. Therefore, this system constitutes a variable structure system.

Table 1. Modes of operation.

Modes	S	Q1-Q2	Q3-Q4
1	ON	ON	OFF
2	ON	OFF	ON
3	OFF	ON	OFF
4	OFF	OFF	ON

5. Dc Bus Voltage Controller

The overall boost converter inverter system with control scheme is shown in Figure 7. The input voltage of the boost converter is provided by a photovoltaic array. The PV module generates a dc voltage output depending on the irradiation and temperature conditions. The dc link voltage of the inverter which is the output of the boost converter is measured and compared with the reference voltage. The error between the measured voltage and reference voltage is applied to a PI controller. In the PWM block, the output of the PI controller is compared with a triangular carrier wave to produce a PWM signal for the switch S of the boost converter. Depending on the error between measured and reference voltage a PWM signal is produced for the switch S to increase the output voltage of the boost converter if the error is positive and to decrease the output voltage if the error is negative. Thus regulating the output voltage of the boost converter which is also the dc bus voltage of the inverter. The parameters of the PI controller here is determined by trial and error method.

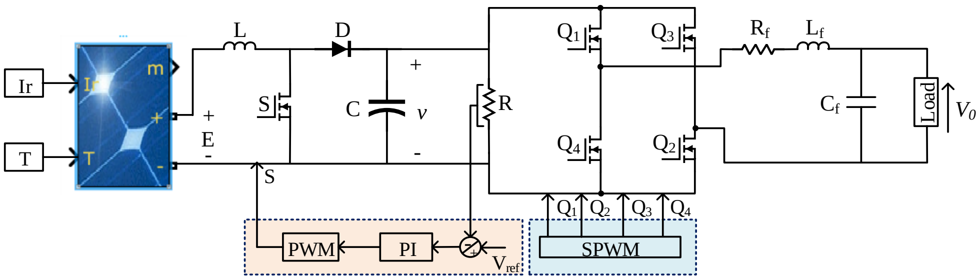


Figure 7. Block diagram of the converter-inverter system with control scheme.

6. Simulations

The Simulink program block of the boost converter-inverter system is shown in Figure 8. In this study Trina Solar TSM-250PA05.08 PV module is used. This PV module is 250 W, 31 V and 8.55 A at 1000 W/m^2 at maximum power point. The PV array contains 8 series connected modules produceing 240 V, 2000 W under 25 °C temperature and 1000 W/m^2 irradiation which is the standard test conditions (STC) as shown in Figure 8.

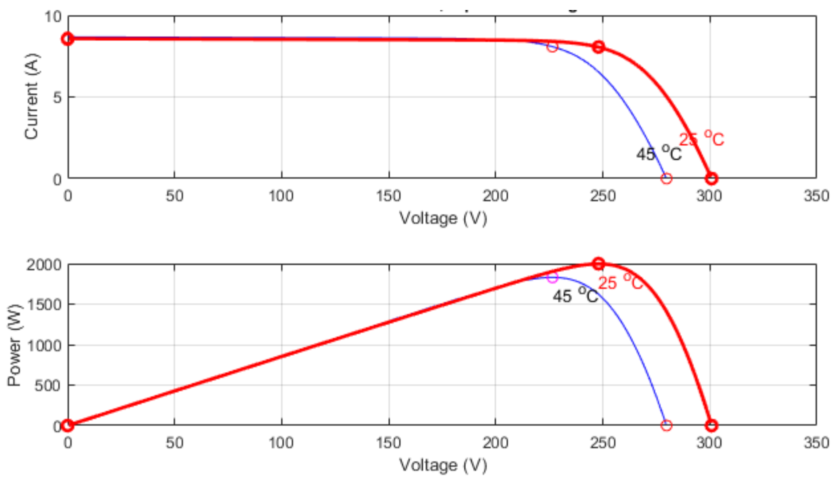


Figure 8. I-V and P-V characteristic curve of the PV module.

The boost converter has the parameters of L = 3 mH, C = 1 μF. The inverter is a full bridge single phase inverter. The PWM signals are produced using sinusoidal pwm technique within the PWM Pulse Generator block.

PWM technique comprises a compare of the high frequency triangular carrier signal with a low frequency sinusoidal reference signal. The controller is a PI type controller having proportional constant P= 0.0001 and integral constant Ki = 1. These parameters are obtained by trial and error. The load is a RL type load with R = 400 W and L = 1 mH.

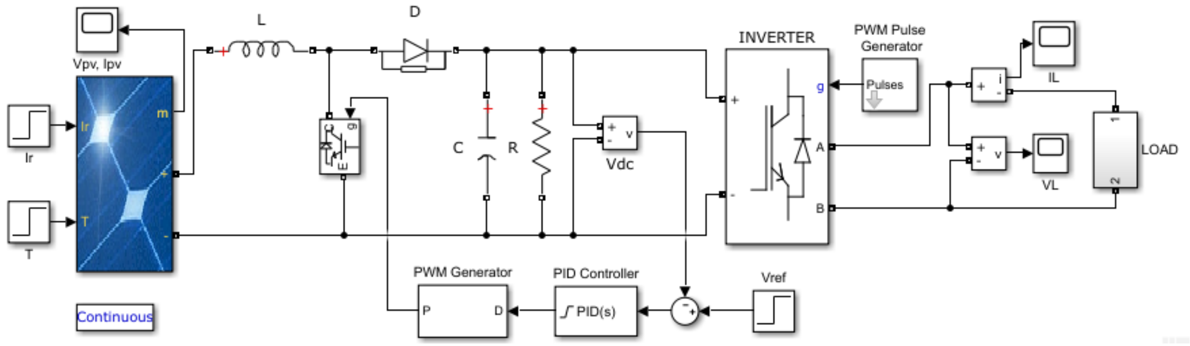


Figure 9. Simulink block of the converter-inverter system.

The system given in Figure 9 is simulated and results are presented. The voltage obtained from PV module vary with the environmental changes such as temperature and illumination or partial shading. To see the effect of input voltage variations on dc link voltage, only the results with abrupt changes in input voltage is presented here. The input voltage variation is shown in Figure 10. The Figure 10 shows the dc link voltage which is the output voltage of the boost converter when a step change in input voltage from 240 V to 280 V and then 280 V to 200 V occur.

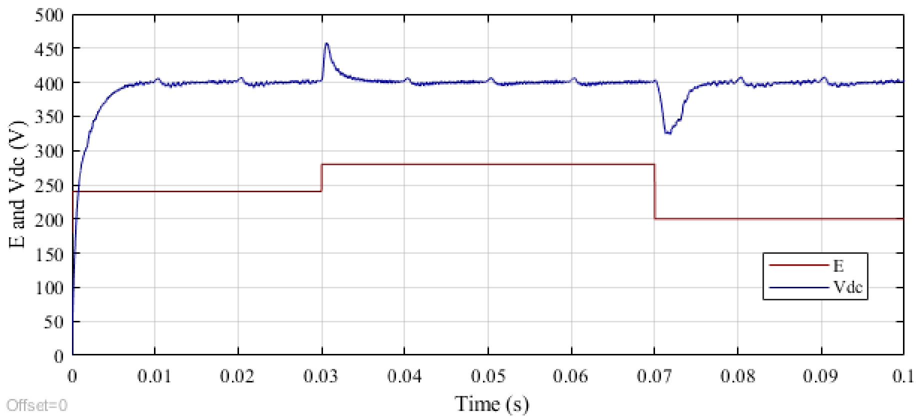


Figure 10. Dc link voltage of the inverter when changes in input voltage of boost converter occur.

The reference voltage command is 400V. It can be seen in Figure 10 that the output voltage of the boost converter reaches and follows the reference voltage even in input voltage change which occurs at t = 0.03 s and t=0.07 s. The Load voltage and current waveforms are presented in Figure 11 and Figure 12 respectively.

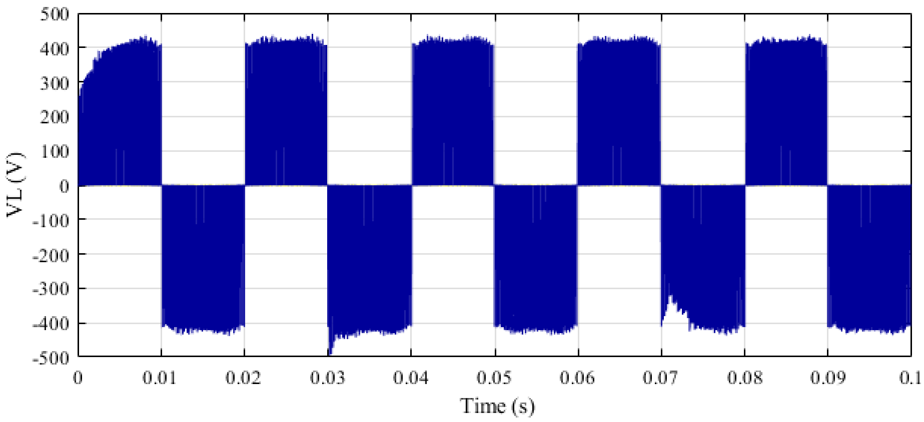


Figure 11. Inverter output voltage waveform.

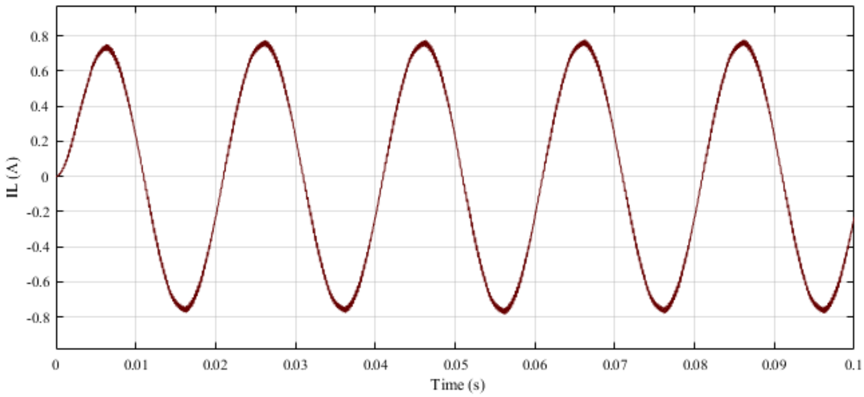


Figure 12. Load current waveform.

Figure 13 shows the dc link voltage waveform. The figure is obtained while the system is running with 350 V reference dc link voltage, this reference voltage is changed to 400 V at time t = 0.005 s. The input voltage of the boost converter maintained constant at 200 V. As it is clearly seen in the figure the dc link voltage follows the reference voltage command.

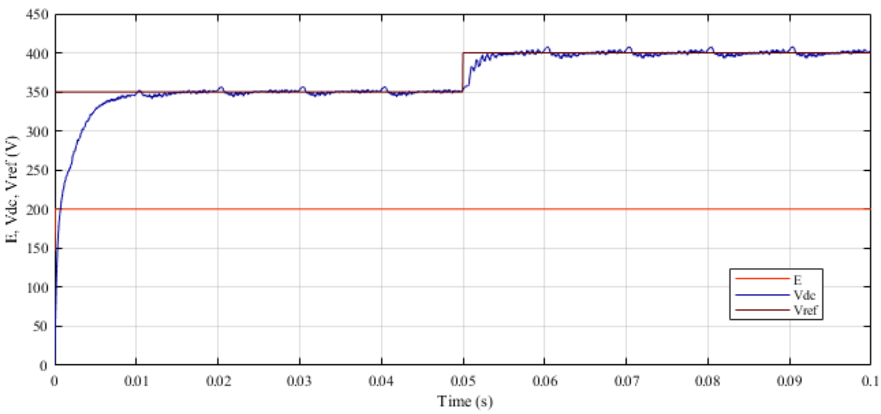


Figure 13. Dc link voltage of the inverter when refernce voltage is changed from 350 V to 400 V at t = 0.05 s.

7. Conclusion

In this study, dc link voltage control of an inverter is presented. The inverter dc link voltage is obtained from a boost converter which is powered by a photovoltaic solar module. A conventional PI controller is used to control the dc link voltage of the inverter which is actually the output voltage of the boost converter. As the voltage obtained from solar PV module is dependent the climatic conditions such as temperature and irradiation, the system is simulated to obtain the output voltage with input voltage variations. The reference voltage command change is also provided to see the reference tracking performance of the system. The system is simulated using Simulink. Some of the obtained results are presented which show the effectiveness of the dc link voltage control of a boost-converter inverter system presented in this study. In the presented scheme, output voltage of boost converter follows the reference command voltage very closely even with input voltage and reference voltage changes. The system is insensitive to input voltage variations due to climatic environmental conditions and produces a constant dc link voltage for the load. Thus, this system can be used with off-grid applications requiring constant voltage.

References

[1] Sheila JH, Alicen K. Renewable Energy Applications for Existing Buildings. Oak Ridge, TN, USA: US Department of Energy, 2011.
[2] Taibi E, Gielen D, Bazilian M. The potential for renewable energy in industrial applications. Renewable Sustainable Energy Rev 2012; 16(1): 735-744.
[3] Chel A, Kaushik G. Renewable energy for sustainable agriculture. Agron. Sustainable Dev 2011; 31(1): 91-118.
[4] Singh GK. Solar power generation by PV (photovoltaic) technology: a review. Energy 2013; 53: 1-13.
[5] Van Campen B, Guidi D, Best G. Solar Photovoltaics for Sustainable Agriculture and Rural Development. Rome: FAO Publication, 2000.
[6] Duranay ZB, Guldemir H. Modelling and simulation of a single phase standalone PV system. In: ECAI 2019 International Conference, 11th Edition Electronics, Computers; 27-29 June 2019; Pitesti, Romania.
[7] Akikur RK, Saidur R, Ping HW, Ullah KR. Comparative study of stand-alone and hybrid solar energy systems suitable for off-grid rural electrification: a review. Renewable Sustainable Energy Rev 2013; 27: 738-752.
[8] Ghafoor A, Munir A. Design and economics analysis of an off-grid PV system for household electrification. Renewable Sustainable Energy Rev 2015; 42: 496-502.
[9] Sukamongkol Y, Chungpaibulpatana S, Ongsakul W. A simulation model for predicting the performance of a solar photovoltaic system with alternating current loads. Renewable energy 2002; 27(2): 237-258.
[10] Guldemir H. Sliding mode control of DC-DC boost converter. Journal of Applied Sciences 2005; 5(3): 588-592.
[11] Habetler TG, Naik R, Nondahl TA. Design and implementation of an inverter output LC filter used for dv/dt reduction. IEEE Trans Power Electron 2002; 17(3): 327-331.
[12] Kim SJ, Sul SK. A novel filter design for suppression of high voltage gradient in voltage-fed PWM inverter. In: IEEE Appl Power Electron Conf; 27 February 1997; Atlanta, GA, USA. pp. 122–127
[13] Von Jouanne A, Rendusara D, Enjeti P, Gray W. Filtering techniques to minimize the effect of long motor leads on PWM inverter-fed AC motor drives. In: IEEE/IAS Ann Meeting Conf; 8-12 October 1995; Orlando, FL, USA. pp. 37–44.
[14] Steinke J, Stulz C, Pohjalainen P. Use of a LC filter to achieve a motor friendly performance of the PWM voltage source inverter. In: 1997 Int. Electric Mach. Drives Conf., 2001.
[15] Renzhong X, Lie X, Junjun Z, Lie D. Design and research on the LCL filter in three-phase PV grid-connected inverters. International Journal of Computer and Electrical Engineering 2013; 5(3): 322-325.
[16] Liserre M, Blaabjerg F, Hansen S. Design and control of an LCL-filter-based three-phase active rectifier. IEEE Trans Ind Appl 2005; 41(5); 1281-1291.
[17] Ahmad AA, Abrishamifar A, Farzi M. A new design procedure for output LC filter of single phase inverters. In: 3rd International Conference on Power Electronics and Intelligent Transportation System; January 2010; China. pp. 86-91.
[18] Pavkovic D, Kristovic P, Hrgetic M,Komljenovic A, Uzarevic V. Single phase AC inverter current PR control with auxiliary PI controller for DC current suppression. In: IEEE EUROCON 2017-17th International Conference on Smart Technologies; 6-8 July 2017; Ohrid, Macedonia. pp. 324-329.
[19] Terzic B, Majic G, Slutej A. Stability analysis of three-phase PWM converter with LCL filter by means of nonlinear model. Automatika 2010; 51(3): 221-232.
[20] Reznik A, Simoes MG, Al-Durra A, Muyeen SM. LCL filter design and performance analysis for grid-interconnected systems. IEEE Trans Ind Appl 2014; 50(2): 1225-1232.
[21] Casadei D, Grandi G, Rossi C. Single-phase single-stage photovoltaic generation system based on a ripple correlation control maximum power point tracking. IEEE Trans Energy Convers 2006; 21(2): 562-568.
[22] Duranay ZB, Guldemir H, Tuncer S. Fuzzy sliding mode control of DC-DC boost converter. Engineering, Technology and Applied Science Research 2018; 8(3): 3054-3059.