This is an electronic reprint of the original article.

This reprint may differ from the original in pagination and typographic detail.

Eskandari, Bahman; Kyyrä, Jorma; Pournazarian, Bahram; Saeedian, Meysam; Pouresmaeil, Edris

Performance Evaluation of Three-Phase Boost-Inverter for Grid-Connected PV System

Published in:

Proceedings of the 11th IEEE International Symposium on Power Electronics for Distributed Generation Systems, PEDG 2020

DOI:

[10.1109/PEDG48541.2020.9244349](https://doi.org/10.1109/PEDG48541.2020.9244349)

Published: 01/01/2020

Document Version

Peer reviewed version

Please cite the original version:

Eskandari, B., Kyyrä, J., Pournazarian, B., Saeedian, M., & Pouresmaeil, E. (2020). Performance Evaluation of Three-Phase Boost-Inverter for Grid-Connected PV System. In *Proceedings of the 11th IEEE International Symposium on Power Electronics for Distributed Generation Systems, PEDG 2020* (pp. 459-462). [9244349] (IEEE International Symposium on Power Electronics for Distributed Generation Systems). IEEE.
<https://doi.org/10.1109/PEDG48541.2020.9244349>

This material is protected by copyright and other intellectual property rights, and duplication or sale of all or part of any of the repository collections is not permitted, except that material may be duplicated by you for your research use or educational purposes in electronic or print form. You must obtain permission for any other use. Electronic or print copies may not be offered, whether for sale or otherwise to anyone who is not an authorised user.

© 2020 IEEE. This is the author's version of an article that has been published by IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works.

Performance Evaluation of Three-Phase Boost-Inverter for Grid-Connected PV System

Bahman Eskandari
Electrical Engineering and
Automation Dep.
AALTO University
Espoo, Finland
bahman.eskandari@aalto.fi

Jorma Kyyra
Electrical Engineering and
Automation Dep.
AALTO University
Espoo, Finland
jorma.kyyra@aalto.fi

Bahram Pournazarian
Electrical Engineering and
Automation Dep.
AALTO University
Espoo, Finland
bahram.pournazarian@aalto.fi

Meysam Saeedian
Electrical Engineering and
Automation Dep.
AALTO University
Espoo, Finland
meysam.saeedian@aalto.fi

Edris Pouresmaeil
Electrical Engineering and
Automation Dep.
AALTO University
Espoo, Finland
edris.pouresmaeil@aalto.fi

Abstract—In this paper, a new efficient topology of three-phase boost type converter is developed based on 100kHz switching frequency. The nonlinear equations are extracted based on the averaging method and a controller for grid-connected PV system is developed via a nonlinear modulation technique.

Keywords— DC-DC converter, DC-AC converter, Nonlinear Modulation, power flow control, PV system

I. INTRODUCTION

The PV systems are divided into two categories, with and without DC-DC Regulator (DR). Almost low power applications equipped with the regulator while so many different topologies and controllers have been developed for that until now(1-8). Although, using the DR has own advantages to staying at Maximum Power Point Tracking (MPPT) and providing a regulated DC voltage for the converter part but it also has some drawbacks such as increasing the volume, weight and cost and reducing the efficiency and reliability because of extra switching device and actions. A single-stage structure of Three-Phase Boost-Inverter (TPBI) is introduced in [9] to supply a symmetrical stand-alone load. The principle idea is the implementation of three separate DC-DC boost converter in a differential form and producing three sinusoidal waveforms with equal DC biased and 120° phase shift respect to each other. The type of this converter is the boost and there is no need to extra DR. Therefore, structure of the converter is minimized while each one of boost converters consists of an input inductor and a couple of bidirectional switches and output capacitor. The problem is that the proposed modulation technique was based on the ideal steady-state equation of boost converter while in real case the output voltage of the boost converter is affected by even a small amount of input resistance and the steady-state equation is not valid for producing sinusoidal wave-form. In this research, the same structure is used except a more realistic nonlinear dynamic equation is extracted based on the averaging technique. To reduce the size of passive elements (L, C), 100kHz switching frequency is considered which could be implemented by

Galium-Nitride (GAN) devices easily. A combination of the PI controllers and nonlinear modulation technique is developed in the rotational reference frame to control the active power flow from PV array to the network.

II. ANALYTICAL STUDY OF STAND-ALONE THREE-PHASE BOOST-INVERTER (TPBI)

The structure of single-stage TPBI is shown in Fig.1 to supply a three-phase pure resistive load from a lower-level DC source. In this type of converter, Due to differential combination of three boost converter, increasing the voltage level and converting it to a sine wave takes place at the same time while it doesn't need to extra DR circuit. By increasing the switching frequency up to 100kHz and utilizing the GAN switches the actual size of passive elements could be reduced dramatically. Accordingly, it is expected to be an efficient and cost-effective converter.

Fig. 1. structure of the three-phase boost inverter with pure resistive delta load.

Due to the property of the boost converter, the minimum output voltage (respect to Negative pole) could be the same as the input DC voltage ($V_{xNmin}=V_{dc}$, $x=a,b,c$). Therefore, the desired sinusoidal output voltages for TPBI must have equal DC offsets which will be eliminated in differential mode at the line to line voltages (1). Generating the desired voltages of (1) is depends on to have a proper pattern of duty cycles ($D_{abc}(t)$) for each phase. Finding the proper $D_{abc}(t)$ needs to have an accurate dynamic equation which describes the performance of the system.

$$\begin{cases} v_{aN} = A \sin(\omega t + 0 + \delta) + A + V_{DC} \\ v_{bN} = A \sin(\omega t + 120^\circ + \delta) + A + V_{DC} \\ v_{cN} = A \sin(\omega t + 240^\circ + \delta) + A + V_{DC} \\ v_{aN} + v_{bN} + v_{cN} = 3(A + V_{DC}) \end{cases}$$

$$\Rightarrow \begin{cases} V_{ab} = v_{aN} - v_{bN} = \sqrt{3}A \sin(\omega t - 30^\circ) \\ V_{bc} = v_{bN} - v_{cN} = \sqrt{3}A \sin(\omega t + 90^\circ) \\ V_{ca} = v_{cN} - v_{aN} = \sqrt{3}A \sin(\omega t - 150^\circ) \end{cases} \quad (1)$$

To extract the dynamic equations, two switching states for each one of the boost converters are considered according to Fig.2.

Fig. 2. Two switching states of boost converter (a) first state, (b) second state.

At the first state, the inductor is in charging mode while the capacitor is discharging. Vice versa in the second state the inductor is discharged and the capacitor is charged. Two sets of equations could be written for inductor current and capacitor voltage in each state, (2) and (3).

$$f_{x1} = \begin{cases} L \frac{di_{x1}}{dt} = V_{DC} - ri_{x1} \\ C \frac{dv_{xN1}}{dt} = -\frac{v_{xN1} - v_{yN1}}{R} - \frac{v_{xN1} - v_{zN1}}{R} \\ x = a, b, c \quad y = b, c, a \\ z = c, a, b \end{cases} \quad (2)$$

$$f_{x2} = \begin{cases} L \frac{di_{x2}}{dt} = V_{DC} - ri_{x2} - v_{xN2} \\ C \frac{dv_{xN2}}{dt} = i_{x2} - \frac{v_{xN2} - v_{yN2}}{R} - \frac{v_{xN2} - v_{zN2}}{R} \\ x = a, b, c \quad y = b, c, a \\ z = c, a, b \end{cases} \quad (3)$$

After applying the averaging technique (4), the dynamic equation of the system is obtained in terms of the pulse width (5).

$$\begin{cases} f_{x\_mean} = D_x f_{x1} + D'_x f_{x2} \\ x = a, b, c \end{cases} \quad (4)$$

$$L \frac{di_x}{dt} = D_x [V_{DC} - ri_{x1}] + D'_x [V_{DC} - ri_{x2} - v_{xN2}] = V_{DC} - D'_x v_{xN} - ri_x$$

$$C \frac{dv_{xN}}{dt} = D_x \left[-\frac{2v_{xN1} - v_{yN1} - v_{zN1}}{R} \right] + D'_x \left[i_{x2} - \frac{2v_{xN2} - v_{yN2} - v_{zN2}}{R} \right]$$

$$= D'_x i_x - \frac{v_{xN} - A - V_{DC}}{R/3}$$

$$D_x + D'_x = 1 \quad x = a, b, c \quad y = b, c, a \quad z = c, a, b \quad (5)$$

In nonlinear differential equation (5), v_{xN} is specified from (1) and assumed as a certain reference value as well as its derivative. Therefore, to find the proper puls pattern, (5) must only be solved between i_x and D'_x . Hence $D'_x i_x$ is known and to find $D_{abc}(t)$ the equation (5) could be rewritten as (6) and solved through iterative technique. A practical example of solving the nonlinear modulation technique is presented in the next section. The accuracy of nonlinear modulation depends on the amount of load resistance (R) and it means for real implementation with load variations, the load resistance must be calculated beforehand. Moreover, considering only the resistive load type for TPBI could be another problem of the proposed nonlinear modulation technique in a standalone application because of the inductive feature of almost the loads.

$$\begin{cases} L \frac{di_x}{dt} + ri_x - V_{DC} = D'_x (-v_{xN}) \\ C \frac{dv_{xN}}{dt} + \frac{v_{xN} - A - V_{DC}}{R/3} = D'_x i_x \\ D_x + D'_x = 1 \\ x = a, b, c \end{cases} \quad (6)$$

III. GRID-CONNECTED BOOST-INVERTER FOR PV SYSTEM

Due to the compact structure of TPBI and its significant performance especially in high frequency, it seems a good idea to use this converter in the distributed solar generation as a new converter topology. Figure 3 illustrates the application of TPBI as a grid-connected converter in the PV system.

Fig. 3. Application of TPBI as a grid-connected converter in the PV system

A. Controller

The main object of the controller in the PV system is following the reference which is produced by MPPT to stay at maximum active power delivery to the gride while the reactive power must be zero. Due to this condition, the actual load of TPBI could be considered as a purely resistive load and the proposed nonlinear model (5) is valid here as well.

The controlling idea is based on the rotational reference frame (dq), Fig.4. A conventional MPPT unit produces V_{dc}^* from current and voltage of PV array and after that, a PI controller generates I_d^* from DC voltage error ($V_{dc}^* - V_{dc}$). Another PI controller produces ΔV_d from $I_d^* - I_d$ and finally, V_d is obtained from summation of the feedforward term E_d , which is extracted from PLL, and ΔV_d . Similarly, the voltage of quadratic axes V_q is obtained from summation of the feedforward term E_q and ΔV_q , which comes from a PI controller on ($I_q^* - I_q$).

Fig. 4. The proposed active power control algorithm for TPBI based on the rotational reference frame and feed-forward technique

Fig. 5. The proposed nonlinear modulator for TPBI

Fig. 6. Simulation results, (a) Irradiance power density and total DC power, (b) V_{dc} follows the MPPT output, (c) Three-phase actual current and dq components, (d) Calculated duty cycle pattern for three-phase

B. Nonlinear Modulator

After finding proper values for V_d and V_q through the control unit, according to (6) the nonlinear modulator is introduced in Fig.5. The first step is forming the three-phase voltages from (1) in the natural reference frame (v_{xN}). The important parameter in (6) is the load resistance which must be determined. The load resistor (R) is related to the symmetrical DELTA configuration. Therefore, the term of $R_{\Delta}/3$ in (6) could be assumed as a single-phase load in STAR configuration ($R_Y = R_{\Delta}/3$) and is equal to v_d/i_d^* . After generating $D'_x i_x$, the instantaneous value of D'_x could be extracted through a recursive loop by a single delay. Delay needs to prevent the algebraic-loop error. At the final stage, the calculated D_x for all the three converters is compared with 100kHz saw tooth carrier wave to produce the actual proper pulse width for each one of six switches.

C. Simulation Results

To evaluate the proposed control algorithm along with the nonlinear modulation for TPBI, a series of detailed simulation are performed in MATLAB environment. A 3kW PV array is considered as a DC source according to Fig.3. One step down

and another step up changes happen in irradiation power as shown in Fig.6(b). The output of the MPPT block (V_{dc}^*) and the actual DC voltage (V_{dc}) are compared in Fig.6(b). The success of the controller in tracking the reference value is clear. The actual currents along with dq component are depicted in Fig.6(c) which they are adapted to power changes. Calculated duty cycles by nonlinear modulator are shown in Fig.6(d).

IV. CONCLUSION

A new efficient and minimized topology of three-phase boost type converter is developed based on 100kHz switching frequency applicable for the PV system. The nonlinear equations are extracted based on the averaging method and a controller for a grid-connected PV system is developed in the rotational reference frame along with the nonlinear modulation technique. The good performance of the controller in tracking the reference value is validated due to performing a series of detailed simulation.

REFERENCES

- [1]. C. Tang, Y. Chen, Y. Chen, "PV Power System With Multi-Mode Operation and Low-Voltage Ride-Through Capability", IEEE Trans on Ind Electro, vol:62, no:12, pp:7524-33, 2015.
- [2]. E. Afshari, G. R. Moradi, Y. Yang, B. Farhangi, S. Farhangi, "A review on current reference calculation of three-phase grid-connected PV converters under grid faults", IEEE Power and Energy Conference (PECI), DOI: 10.1109/PECI.2017.7935761, 2017.
- [3]. H. Kim, B. Parkhideh, T. D. Bongers, H. Gao, "Reconfigurable Solar Converter: A Single-Stage Power Conversion PV-Battery System", IEEE Trans on Power Electron, vol:28, no: 8, pp:3788-97, 2013.
- [4]. I. C. Rath, A. Shukla, "Review of Three Phase Transformer-less PV Converters", IEEE International Conference on Sustainable Energy Technologies and Systems (ICSETS), DOI: 10.1109/ICSETS.2019.8745120 , 2019.
- [5]. L. B. G. Campanhol, S. A. O. da Silva, A. A. de Oliveira, V. D. Bacon, "Single-Stage Three-Phase Grid-Tied PV System With Universal Filtering Capability Applied to DG Systems and AC Microgrids", IEEE Trans on Power Electron, vol:32, no: 12, pp: 9131-42, 2017.
- [6]. M. Das, V. Agarwal, "Novel High-Performance Stand-Alone Solar PV System With High-Gain High-Efficiency DC-DC Converter Power Stages", IEEE Trans on Ind Applications, vol: 51, no: 6, pp: 4718-28, 2015.
- [7]. R. Mechouma, B. Azoui, M. Chaabane, "Three-phase grid connected inverter for photovoltaic systems, a review", First International Conference on Renewable Energies and Vehicular Technology, DOI: 10.1109/REVET.2012.6195245, 2012.
- [8]. S. Deshpande, N. R. Bhasme, "A review of topologies of inverter for grid connected PV systems", Innovations in Power and Advanced Computing Technologies (i-PACT), DOI: 10.1109/IPACT.2017.8245191, 2017.
- [9]. B. Eskandari, M. T. Bina, M. A. Golkar, "New concept on sinusoidal modulation for three-phase DC/AC converters: analysis and experiments", IET Power Electron, vol: 7, no: 2, pp: 357-65, 2014.