Sizing of dc-link capacitor for a grid connected solar photovoltaic inverter

Munwar Ayaz Memon\textsuperscript{1*}, Ghullam Mustafa Bhutto\textsuperscript{1}, Ehsan Ali Buriro\textsuperscript{2}

1 Department of Electrical Engineering, Quaid-e-Awam University of Engineering, Science and Technology, 67480, Pakistan. Tel.: +92-347-3634051
2 Department of Electronic Engineering, Quaid-e-Awam University of Engineering, Science and Technology, 67480, Pakistan

Abstract

Objective: To determine the optimum size of a dc-link capacitor for a grid connected photovoltaic inverter. Methods: Dc-link capacitors are considered as one of the sensitive parts of the grid connected photovoltaic systems and needs effort to design a reliable and optimal size capacitor as its reliability is concerned with the overall system reliability. The double line frequency power flows between the input and outside of a \( \Phi \) grid connected PV system which produces voltage ripples at the capacitor and dc link. This voltage ripple increases temperature of passive components and dc source which affects the MPP operation of the photovoltaic modules and the system life. Therefore, it is essential to limit the voltage ripples at the input side of the system. The easiest way to limit the double frequency ripple voltage is to connect a capacitor in parallel to the PV module and the inverter which buffers the double line frequency power and supply a constant power to the inverter. This study proposed a general method for sizing a dc-link capacitor for a \( \Phi \) grid connected voltage source inverter. It is seen that the capacitance is inversely proportional to the nominal dc and ripple voltage. Thus an increase in the nominal system voltage decreases the size of the capacitor and at the same time increases the voltage ripple. Therefore to limit voltage ripple within permissible limits and to ensure better system performance the dc-link capacitor must be appropriately sized. The simulations based on 3kW grid connected PV system are carried out in DgSILENT Power Factory software. Findings: A capacitor of \( 410 \mu F \) is needed to be connected in parallel with a 3kVA inverter having an nominal input voltage of 370V and maintaining a voltage ripple under 8.5\%. Novelty: After determining optimized dc-link capacitor size we will limit the voltage ripple under permissible limits and hence improves the system efficiency and life of the grid connected PV system.

Keywords: Voltage source inverter; voltage ripple; Dc-link capacitor sizing; distributed generation; grid connected PV system
1 Introduction

A constant increase in the energy demand and environmental challenges favors for the distributed generation (DG) sources such as photovoltaic (PV), wind, geothermal, biomass etc. as quality electrical power (1,2). Compared to the fossil fuel energy solar power generation has very low maintenance cost, noise free and without any moving part (3). DG sources are installed near the load centers at distribution level compared to the traditional non-conventional energy sources such as oil, coal, gas, nuclear etc. which are installed far away from the load centers which not only reduces the fuel cost but also reduces a major share of cost utilized on transmitting the generated power (4–6). Recently photovoltaic systems are actively researched as a sustainable power solution (7,8). The PV sources can be operated in standalone or grid connected mode (9,10). In order to inject the photovoltaic generated power to ac grid usually power electronic inverters are used with some standards and requirements (11,12).

A power electronic converter which converts dc power into ac power with controllable frequency and voltage is known as an inverter (13). Inverters are classified as under,

- Voltage Source Inverter
- Current Source Inverter → An inverter feed with constant voltage having a parallel capacitor in between PV and inverter is known as voltage source inverter. → An inverter feed with constant current having an inductor in series in between PV and inverter is known as current source inverter. (12,14)

Figure 1 (a & b) shows the single stage voltage source and current source inverter topology respectively, while a two stage voltage source inverter topology is shown in Figure 1 (c).

Figure 1. Inverter topologies

Distributed Generation (DG) sources such as photovoltaic (PV) systems, wind energy systems etc. produces power which is inherent intermittent and non-controllable as it depends on the weather conditions which may not
meet the demand of the user at standalone or grid connected operation\textsuperscript{(15,16)}. In PV applications, to assure the maximum power point operation (MPP) operation of the Photovoltaic modules, the voltage ripple at the input of the inverter must be lowered\textsuperscript{(17)}. In order to maintain the difference between input and output power, to decrease the double frequency voltage ripple from switching action to ensure effective dc-link and provide sufficient energy at the hold-up time, the capacitors are extensively used in pulse width modulation (PWM) inverters\textsuperscript{(18–21)}. The aim of this capacitor connection is to increase the life of the inverter compared to the PV panel operating life time. Typically more than 20 years life of commercial PV panels is provided by manufacturers while PV inverter's life is limited by life of individual components\textsuperscript{(17)}. It is seen that up to 30% of electronic system failures are due to the malfunction of capacitors. Thus in system performance a reliable dc-link capacitor plays a dynamic role\textsuperscript{(22,23)}. Therefore for improving the system performance and reducing the voltage ripple, the size of dc link capacitor must be determined.

Typically three types of capacitors such as Aluminum Electrolytic capacitor, Metalized Polypropylene Film capacitor and Multilayer Ceramic capacitor as shown in Figures 2, 3 and 4 respectively are available which can be utilized as dc-link capacitor\textsuperscript{(16,24)}, however their use depends on the type of applications such as UPS, drives, solar and wind etc\textsuperscript{(25)} but owing to high capacitance value and minimum cost aluminum electrolytic capacitors are extensively used. Each type of capacitor\textsuperscript{(18,26,27)} reveals their merits and demerits which are tabulated in Table 1.

| Table 1. Various types of capacitors with their merits and demerits |
|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|
| Aluminum electrolytic capacitor | Metalized polypropylene film capacitor | Multilayer ceramic capacitor |
| Greater capacitance per volume | Low capacitance per volume | Very low capacitance per volume |
| Low cost per joule | Higher cost per joule | Low cost per joule |
| High equivalent series resistance (ESR) | Low equivalent series resistance (ESR) | Low equivalent series resistance (ESR) |
| Low ripple current rating | High ripple current rating | High ripple current rating |
| Limited life time | Longer life time | Longer life time |
| Low operating temperature (85 to 105\textdegree{}C) | Up to 2000\textdegree{}C | Temperature ranges (-55 to 105\textdegree{}C) |
| Less Reliability | High Reliability | More Reliability |

---

\textbf{Fig 2.} Aluminum electrolytic capacitor
The single line diagram of the proposed research work with integration of solar panels is developed in DlgsILENT power factory software using real time data is shown in Figure 5\(^{(28)}\).

For this purpose the connected load of one of the class of Electrical Engineering Department is considered as shown in Table 2. In order to supply a 2.5kW load an inverter of 3kVA is chosen, whose specifications are shown in Table 3\(^{(29)}\).

The optimum size of the photovoltaic module is determined with respect to 3kVA inverter using the metrological data as irradiance and temperature of the site. PV panels are designed under standard test conditions but the site data are below the STC therefore the power generated by PV module is always below their rated capacity. Hence the power supplied to the inverter is intermittent which produces double frequency voltage ripple on the dc side of the inverter. An increased voltage ripple affects the MPP operation of the photovoltaic module and affects the system performance. Therefore, to balance the input instantaneous power to the inverter and limit the voltage ripple an energy storage device such as capacitor is placed in parallel to the photovoltaic module and inverter. Therefore, size of the dc-link capacitor must be calculated in terms of the maximum allowable voltage ripple for the considered system.
Fig 5. Model of distribution system with the integration of solar panels
Table 2. Typical load of final year class of electrical engineering department

| S.No | Load name with power rating       | Quantity | Total power |
|------|----------------------------------|----------|-------------|
| 1    | Electric Tube lights (40W)       | 16       | 640         |
| 2    | Electric fans (80W)              | 12       | 960         |
| 3    | Multimedia and speakers (900W)   | 01       | 900         |
|      | Total load of class              |          | 2500 Watt   |

Table 3. 3kVA inverter stipulations

| Type          | Hybrid |
|---------------|--------|
| Power Rating  | 3Kw    |
| Inverter Direct Current Input |
| Nominal Voltage | 360 V |
| Peak Voltage   | 500 V |
| Start-up Voltage | 116 V/150 V |
| Maximum Power Point Voltage | 250 V to 450 V |
| Peak Current   | 13 A   |
| Inverter AC Output |
| Minimum Voltage | 208, 220, 230, 240 V |
| Frequency Range | 47.5 to 50.2 Hz |
| Minimum Current | 13.6 A |
| Power Factor   | Greater than 0.99 |

2 Calculation of dc-link Capacitance

Figure 6 shows a grid connected power conversion system consisting of a PV generator, dc-link capacitor and a voltage source inverter supplying $V_g(t)$ and $I_g(t)$ respectively to the grid are given as (1) and (2) respectively,

\[ V_g(t) = V_{\text{peak}} \sin(\omega_g t) \]  \hspace{1cm} (1)

\[ I_g(t) = I_{\text{peak}} \sin(\omega_g t + \phi) \]  \hspace{1cm} (2)

![Fig 6. Grid connected power conversion system](https://www.indjst.org/)

https://www.indjst.org/
Where $V_{\text{peak}}$ and $I_{\text{peak}}$ peak or maximum voltage and current respectively, $\omega_g$ is the utility frequency which is equal to $2\pi f_g$ and angle of phase difference between current and voltage supplied to the grid is denoted by $\varphi$. The instantaneous output power is given as,

$$P_{\text{out}}(t) = V_g(t)I_g(t)$$

For unity power factor operation angle of phase difference will be zero, therefore (3) can be rewritten as,

$$P_{\text{out}}(t) = V_{\text{peak}}I_{\text{peak}}\sin(\omega_g t)\sin(\omega_g t + \varphi)$$

(3)

As $\sin^2(\omega_g t) = \frac{1}{2}(1 - \cos(2\omega_g t))$

Therefore, (4) can be rewritten as,

$$P_{\text{out}}(t) = \frac{V_{\text{peak}}I_{\text{peak}}}{2}(1 - \cos(2\omega_g t))$$

(4)

Equation (5) comprises of two parts, one is mean instantaneous ac power supplied to the grid given as,

$$P_{\text{avr}}(t) = \frac{V_{\text{peak}}I_{\text{peak}}}{2}$$

(6)

While the second part is the time varying oscillation of the alternating current power which is the cause of double frequency ripple given as,

$$P_{osc} = -\frac{V_{\text{peak}}I_{\text{peak}}}{2}\cos(2\omega_g t)$$

(7)

As seen from the Fig. 8 the PV generator has to supply the power to both the inverter and dc-link capacitor given as,

$$P_{pv} = P_{inv} + P_c$$

$$P_{inv} = P_{pv} - P_c$$

$$P_{inv} = P_{pv} - i_cV_{dc} \quad \text{as} \quad P_c = i_cV_{dc}$$

(8)

By ignoring the inverter losses and maintaining a constant power at the PV generator terminals, the PV generator power and inverter power output should be equal, and that is the average instantaneous ac output power given as,

$$P_{pv} = P_{inv} = P_{out} = P_{avr}(t) = \frac{V_{\text{peak}}I_{\text{peak}}}{2}$$

(9)

By inserting (9) in (8), we will have,

$$P_{inv} = \frac{V_{\text{peak}}I_{\text{peak}}}{2} - C_{dc}V_{dc}\frac{dV_{dc}}{dt}$$

(10)
Now by comparing the instantaneous ac output power in (5) and inverter output power as in (10), we will get,

$$\frac{dV_{dc}}{dt} = \frac{V_{peak}I_{peak}}{2C_{dc}V_{dc}} \cos(2\omega_g t)$$

(11)

As $S = \frac{V_{peak} \times I_{peak}}{\sqrt{2}} = V_{rms}I_{rms}$

Now by integrating (11) we will get,

$$C_{dc} = \frac{S}{2\omega_g V_{dc}} \sin(2\omega_g t)$$

(12)

Equation (12) reveals that the voltage reaches its maximum value at time $\omega_g t = \pi/4$, therefore (12) yield a dc-link capacitance size as,

$$C_{dc} = \frac{S}{2\omega_g V_{dc}}$$

(13)

Where $C_{dc}$ the capacitance of dc-link capacitor in farad, S is the rated power of the inverter, $V_{dc}$ is the dc input voltage and $V_{dc}$ is maximum permissible voltage ripple.

Equation (13) shows that the capacitance of dc-link capacitor is inversely proportional to the nominal bus voltage and voltage ripple. Hence a greater dc bus voltage yields a smaller capacitance capacitor however a smaller capacitance increases its voltage ripple. An increased voltage ripple affects the maximum power point operation of the PV generator if it is not properly controlled. Typically the value of voltage ripple should be kept below 8.5% to get maximum output from PV generator. Table 4 shows the size of dc-link capacitor at various ripple voltage i-e 3%, 5% and 8.5% respectively in terms of the rated KVA rating of the inverter and nominal input voltage.

Table 4. Dc-link capacitor size at various ripple voltages

| Power rating (kVA) | Inverter input voltage (V) | Ripple voltage (V) | Nominal frequency (Hz) | Dc-link capacitor size (µF) |
|--------------------|---------------------------|--------------------|------------------------|-----------------------------|
| 3                  | 370                       | 11.1 @ 3%          | 50                     | 1163                        |
| 3                  | 370                       | 18.5 @ 5%          | 50                     | 698                         |
| 3                  | 370                       | 31.45 @ 8.5%       | 50                     | 410                         |

Thus a capacitor of $410\mu F$ is needed to be connected in parallel with a 3kVA inverter having a dc input voltage of 370V and maintaining a voltage ripple under 8.5%.

3 Conclusion

The size of dc-link capacitor based on input dc voltage and maximum allowable voltage ripple is derived in this study. It is seen that the capacitance will decrease with the increase in dc input voltage which increases the voltage ripple. Therefore, a suitable dc-link capacitor size should be chosen to restrict the voltage ripple within a permissible limit and to ensure a better and reliable system performance and to achieve high power density of the system. Also a $410\mu F$ capacitor size is calculated for a grid connected inverter chosen in our research work. Also the types of capacitors used as dc-link are discussed in the study with their merits and demerits.

4 Acknowledgement

We are thankful to Quaid-e-Awam University of Engineering Science and Technology Nawabshah Sindh Pakistan for their financial support in conducting the research work.

https://www.indjst.org/
References

1) Hammami M, Ricco M, Ruderman A and Grandi G. Three-Phase Three-Level Flying Capacitor PV Generation System with an Embedded Ripple Feedback Control MPPT Algorithm. Electronics. 2019;8(2):118–118. Available from: https://dx.doi.org/10.3390/electronics8020118.

2) Eren S, Pahlevani M, Bakshai A and Jain P. An Adaptive Drop DC-Bus Voltage Controller for a Grid-Connected Voltage Source Inverter With LCL Filter. IEEE Transactions on Power Electronics. 2015;30(2):547–560. Available from: https://dx.doi.org/10.1109/tpele.2014.2308251.

3) Saidi AS, Slime MB and Khliifi MA. Transient stability of photovoltaic system with experimental shading effects. Engineering Technology and Applied Science Research. 2018;8(6):3592–3597. Available from: https://doi.org/10.5281/zenodo.2532664.

4) Ninand NA and Lopes LAC. A low power single phase utility interactive inverter for residential PV generation with small dc-link capacitor. In: and others, editor. 3rd Solar Building Research Network Conference . 2008,. p. 1–8.

5) Guerrero JM, Matas J, Vicuna LGDVD, Castilla M and Miret J. Wireless-Control Strategy for Parallel Operation of Distributed-Generation Inverters. IEEE Transactions on Industrial Electronics. 2006;53(5):1461–1470. Available from: https://dx.doi.org/10.1109/tie.2006.882015.

6) Kjaer SB, Pedersen JK and Blaabjerg F. A Review of Single-Phase Grid-Connected Inverters for Photovoltaic Modules. IEEE Transactions on Industry Applications. 2005;41(5):1292–1306. Available from: https://dx.doi.org/10.1109/tia.2005.853371.

7) Alsafasfeh Q, Saraereh OA, Khan I and Kim S. Solar PV grid power flow analysis. Sustainability. 2019;11(6):1–25. Available from: https://doi.org/10.3390/su11061744.

8) Watanabe H, Sakuraba T, Furukawa K, Kusaka K and ichi Itoh J. Development of DC to Single-Phase AC Voltage Source Inverter With Active Power Decoupling Based on Flying Capacitor DC/DC Converter. IEEE Transactions on Power Electronics. 2018;33(6):4992–5004. Available from: https://dx.doi.org/10.1109/tpele.2017.2727063.

9) Mohamed SR, Jeyanthy PA, Devaraj D, Shwedi MH and Alldalbahi A. DC-Link Voltage Control of a Grid-Connected Solar Photovoltaic System for Fault-Ride Through Capability Enhancement. Applied Sciences. 2019;9(5):952–952. Available from: https://dx.doi.org/10.3390/app9050952.

10) Latreche AS, Essalam M and Khemliche. Implementation of MPPT algorithm and supervision of shading on photovoltaic module. Engineering Technology and Applied Science Research. 2018;8(6):3541–3544. Available from: https://dx.doi.org/10.5281/ZENODO.2532638.

11) Soreng B, Behera P and Pradhan R. Design of A Grid Integrated PV System with MPPT Control and Voltage Oriented Controller using MATLAB/PLECES. IOP Conference Series: Materials Science and Engineering. 2017;225:012249–012249. Available from: https://dx.doi.org/10.1088/1757-899x/225/1/012249.

12) Ertasgin G, Whaley DM, Ertugrul N and Soong WL. Analysis of DC Link Energy Storage for Single-Phase Grid-Connected PV Inverters. Electronics. 2019;8(6):601–601. Available from: https://dx.doi.org/10.3390/elecronics8060601.

13) SHAYESTEGAN M. Overview of grid-connected two-stage transformer-less inverter design. Journal of Modern Power Systems and Clean Energy. 2018;6(4):642–655. Available from: https://dx.doi.org/10.1007/s40565-017-0367-z.

14) Jana J, Saha H and Bhattacharya KD. A review of inverter topologies for single-phase grid-connected photovoltaic systems. Renewable and Sustainable Energy Reviews. 2017;72:1256–1270. Available from: https://dx.doi.org/10.1016/j.rser.2016.10.049.

15) Marcos VMM, Martinez MAG, Gonzalez FB and Montero MIM. A grid-connected photovoltaic inverter with battery-supercapacitor hybrid energy storage. Sensors. 2017;17(8):1–18. Available from: https://dx.doi.org/10.3390/s17081856.

16) Liang W, Liu Y, Ge B, Abu-Rub H, Balog RS and Xue Y. Double-Line-Frequency Ripple Model, Analysis, and Impedance Design for Energy-Storage Single-Phase Quasi-Z-Source Photovoltaic System. IEEE Transactions on Industrial Electronics. 2018;65(4):3198–3209. Available from: https://dx.doi.org/10.1109/tie.2017.2750630.

17) Karanayil B, Agelidis VG and Pou J. Evaluation of dc-link decoupling using electrolytic or polypropylene film capacitor in three-phase grid-connected photovoltaic inverters. In: 39th Annual Conference of the IEEE Industrial Electronics Society . 2013,. p. 6980–6986.

18) Wang H and Blaabjerg F. Reliability of Capacitors for DC-Link Applications in Power Electronic Converters—An Overview. IEEE Transactions on Industry Applications. 2014;50(5):3569–3578. Available from: https://dx.doi.org/10.1109/tia.2014.2308357.

19) Hu H, Harb S, Kutkut N, Batarseh I and Shen ZJ. A Review of Power Decoupling Techniques for Microinverters With Three Different Decoupling Capacitor Locations in PV Systems. IEEE Transactions on Power Electronics. 2013;28(6):2711–2726. Available from: https://dx.doi.org/10.1109/tpele.2012.2221482.

20) Yao F, Geng L, Janabi A and Wang B. Impact of modulation schemes on dc-link capacitor of VSI in HEV applications. In: IEEE International Electric Machines and Drives Conference . 2017,. p. 1–7.

21) Wang B, Hinkel P and Song Y. Single phase VSI with reduced-size dc-link capacitor. 4th International Conference on Power Engineering, Energy and Electrical Drives. 2013sp. 1427–1430.

22) Lalitha A, Subramanyam M, Shobhha M and Narendra B. Series voltage compensator modeling and design for reduction of grid-tie solar inverter dc-link capacitance. International Research Journal of Engineering and Technology. 2017;4(12):1091–1095.

23) In HC, Kim SM and Lee KB. Design and control of small dc-link capacitor-based three level inverter with neutral-point voltage balancing. Energies. 2018;11(6):1–18. Available from: https://dx.doi.org/10.3390/en11061435.

24) Types of capacitor images . 2019,. Available from: https://www.google.com/search?q=types+of+c...
25) Mnati MJ, Abed JK, Bozalakov DV and A. Van den Bossche. Analytical and calculation DC-link capacitor of a three-phase grid-tied photovoltaic inverter. In: IEEE 12th International Conference on Compatibility. Power Electronics and Power Engineering. 2018., p. 1–6.

26) Yan W, Meek L, Navabi SMH and Abshar M. A Study of dc-link capacitor selection for 250kW battery energy storage system. In: IEEE Australian Universities Power Engineering Conference. 2014., p. 1–5.

27) Witting B, Franke WT and Fuchs FW. Design and analysis of a dc/dc/ac three phase solar converter with minimized dc link capacitance. In: IEEE 13th European Conference on Power Electronics and Applications. 2009., p. 1–9.

28) Memon MA and Bhutto GM. Effect of optimum sized solar pv inverter on energy injected to ac grid and energy loss in Pakistan. *Indian Journal of Science and Technology*. 2020;13(8):954–965.

29) Inverter specifications . . Available from: http://solar.elant.cz/navody/InfiniSolar%203kW-manual%20EN.pdf. Date accessed: 5/08/2019.

30) Shi Y, Liu L, Li H and Xue Y. A single-phase grid-connected PV converter with minimal dc link capacitor and low frequency ripple-free maximum power point tracking. *IEEE Conference on Energy Conversion Congress and Exposition*. 2013;p. 1–5. Available from: https://doi.org/10.1109/ECCE.2013.6647006.2385-2390.