Performance analysis of high-power three-phase current source inverters in photovoltaic applications

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Abstract
In this study, a design of a medium-voltage current source inverter (CSI) and a conventional voltage source inverter (VSI) is presented for high-power (1 MW) photovoltaic (PV) applications. The characteristics of a new 1700 V/1600 A reverse-blocking insulated-gate bipolar transistor (IGBT) in the CSI are compared with the same generation of IGBT device in the VSI. The passive components design, including ac- and dc-side filters, are developed based on a given design procedure. Power loss analysis is demonstrated to compare the CSI efficiency with the VSIs in the specified power range. Simulation and experimental results for the operation and control of the CSI in grid-connected PV application in the central power range show the effectiveness of the proposed CSI and the possibility of applying it as a viable topological candidate.

1 | INTRODUCTION

Renewable energy sources such as wind and solar have experienced tremendous growth due to the increasing energy demand, depletion of fossil fuels, and concerns over the climate change [1]. Governments worldwide have also pushed for wide adoption of clean energy to comply with international agreements [2]. In 2018, the global capacity of solar energy was 505 GW, in which an increase of 103.2 GW was made over the previous year [3–5]. The booming utilization of photovoltaic (PV) systems is also attributed to the declining costs of components driven by continuous technological advancement. The global renewable energy source growth up to 2019, including PV and other forms, is shown in Figure 1.

PV applications are good options for helping with the transition of the global energy map towards renewables to meet the modern energy challenges that are unsolvable by traditional methods [6]. PV solar modules and their mounting systems, inverters, stepping-up transformers for grid connection are the main components in megawatt-scale grid-connected PV systems, where various environmental factors such as irradiance level and ambient temperature affect the conversion efficiency and energy yield [7–9]. PV inverters fall in several categories depending on their power ratings where they can be implemented as a big single unit at megawatt level (central inverters) or collections of smaller inverters (string inverters) attached to PV modules of different sizes and ratings. The design of the converter topology depends on several factors such as efficiency, compactness, cost, reliability, ripples on the dc and ac sides of the converter, and achievable power factor (PF) at the connection point to the grid. Both current-mode control and voltage-mode control are employed in practical applications. Most of the manufacturers of PV central inverters use conventional solutions such as megawatt voltage source inverters (VSIs) in series with possible dc–dc stages [10–12], where the dc–dc converters are adopted to increase the dc voltage produced by the PV array as the VSI can only work in the voltage-back mode.

On the contrary, current source inverters (CSIs) have inherent voltage-boost functionality and, therefore, do not require an additional conversion stage for voltage boosting (Table 1) [13]. The main advantages of VSIs include high efficiency and compactness with the highly mature power devices and packages, and continuously lowered cost levels. Its disadvantages include high dv/dt transients, which reduce the lifetime of equipment, and common-mode voltages that cause stresses on insulation and ground leakage current [14]. In contrast, high-power CSIs [15] have the general advantage of simple topology and reduced number of power semiconductors with the use of reverse-blocking (RB) devices.
inherent short-circuit protection, and high reliability, whereas they share disadvantages such as the relative lacking of commercially mature power devices at suitable power levels, volume and weight of the converter due to the need of a dc inductor, and possibility of resonances occurrence between the output capacitive filter and ac-/dc-side inductances [13–16].

The interest of this study is on the CSI topology, which has been developed for high-power drives [10–12,15]. In pulse-width-modulated (PWM) CSIs, power devices with reverse voltage blocking capability are required. In the low-voltage range, this needs the series connection of an insulated-gate bipolar transistor (IGBT) and a diode that results in extra conduction and switching power losses. However, with the recent developments of RB-IGBT devices, there is a good opportunity for the CSI to be proposed as a competitive candidate for low-voltage high-power PV systems. Figure 2 shows a CSI-based PV system, in which the CSI connects to the grid via three-phase CL filters, and on the other side, a decoupling inductor is used for interfacing with the PV array. The CSI offers advantages over a VSI in terms of its short-circuit protection capabilities and the direct output current controllability. Moreover, the main advantage for PV lies in the CSI’s inherent voltage-boosting capability, which makes it easier to match the level of the grid voltages without the need for an additional conversion stage, thus resulting in less complexity of the system and its control [17,18]. For high-power applications, system efficiency is one of the most important factors to consider. The PV inverter efficiency is calculated as the ratio of the ac power delivered by the inverter to the dc power from the PV array. Many studies in the literature have been carried out to improve the efficiency of motor drive systems [19,20].

In this work, the design of a 1-MW grid-connected PV system with a PWM CSI is presented. The passive components are designed based on the given design procedure and the control algorithm is also proposed. The effectiveness of the proposed control method is verified by both simulation and experimental results to show the operation of the proposed CSI in the central inverter power range. The efficiency analysis of the converter is carried out and results are compared with a conventional VSI case. The higher efficiency of the CSI solution with the use of the new RB-IGBT power semiconductor devices is demonstrated.

FIGURE 1 Global renewable power capacity growth [5]

TABLE 1 Central inverter specifications [2]

| Manufacturer | Model          | Rated power (kW) at 50°C | Max. (V<sub>DC</sub>) | Max. efficiency (%) | Inverter topology | Output filter | Weight (lbs.) |
|--------------|----------------|--------------------------|-----------------------|--------------------|------------------|---------------|---------------|
| ABB          | ULTRA          | 780, 1170, 1560          | 1000                  | 98.4               | 2,3-level        | N/A           | 3968–9000     |
| GE energy    | Prosolar       | 725, 800, 1000           | 1500                  | 98.4               | 3-level          | N/A           | N/A           |
| Huawei       | SUN 8000       | 500                      | 1000                  | 98.7               | 3-level          | LC            | 2700          |
| SMA          | Sunny central  | 800, 850, 900            | 1000                  | 98.6               | 2-level          | N/A           | 4123          |
| Bonfiglioli  | RPS            | 1000, 1200, 1400         | 1000                  | 98.6               | 2-level          | LC            | 4750–9020     |
| Schneider El.| Conext core XC | 540, 630, 680            | 1000                  | 98.6               | 2-level          | LC            | 3505          |
| Yaskawa      | SGI            | 500, 750                 | 1000                  | 98.3               | 2-level          | LC            | 3570          |
| Satcon       | Power gate plus| 1000                     | 900                   | 97                 | 2-level          | LC            | N/A           |
2 | SYSTEM CONFIGURATION AND CONTROL

2.1 | Operating principles of the PWM CSI

The three-phase grid-connected CSI with the proposed control algorithm is illustrated in Figure 3. The CSI is designed to use the new-generation RB-IGBT semiconductor device with voltage and current rating of 1700 V and 1600 A, respectively [23].

The grid is modelled as an ideal voltage source with \( L_g \) and \( R_g \) as a set of grid impedance. The PV array is modelled using the single exponential model of a solar cell in which a current source is paralleled with one diode and shunt and series resistances, respectively. The effect of temperature and irradiance is considered with the voltage computed from output dc current. The most commonly used maximum power point tracking (MPPT) algorithm, that is, the perturb & observe (P&C) method, is used in this work for PV operation, where proportional-integral (PI) dc voltage controller is adopted to control the PV voltage at selected reference point set by the MPPT algorithm. For simplicity of analysis of the control structure, the multilevel CSI control is designed based on the grid voltage-oriented synchronous reference frame. The three-phase currents are transformed onto a \( d-q \) synchronous frame, which is rotating at the grid angular speed \( \omega \) and is adjusted to be synchronized with the grid frequency by a phase-locked loop [24]. So, the \( d \)- and \( q \)-axis current components become time invariant in steady state, and thus, the controller design is greatly simplified. The ac-side \( d-q \)-reference frame PI controllers are utilized for current control, generating the reference current for the PWM switching of the CSI after the \( d-q/abc \) transformation. The PI controllers are easy to implement and can provide satisfactory performances. The reference current for the \( q \)-axis current controller is provided by the dc voltage controller and the reference current of the \( d \)-axis current controller is set to zero. After \( dq/abc \) transformation, the \( abc \) reference currents are used for gating signal calculations by the space vector PWM (SVPWM) method.

2.2 | ac-side filter design

Filter capacitors should be connected to the ac terminals of the CSI for attenuating PWM ripples and assisting with commutations of the switching devices. These capacitors along with the ac-side inductances form a \( L C \) filter and can diminish the unwanted high-frequency harmonics generated by PWM switching. The grid filter is designed in a way such that the grid ripple RMS value is kept within the range where it results in lower THD than the specified limit in the IEEE 519 standard, by which the grid current THD should be less than 5% of the fundamental current. The filter is designed as below to achieve a unity displacement PF at the modulation index \( (MI) = 1 \) [25,26]:

\[
(1) \quad \text{Select the corner frequency of the filter according to the first unwanted harmonic frequency.}
\]

\[
(2) \quad \text{Substitute the selected corner frequency into the following:}
\]

\[
f = \frac{1}{2\pi \sqrt{L C}}
\]

where \( L \) and \( C \) are the ac filter inductance and capacitance.

\[
(3) \quad \text{For unity PF operation, assign the displacement angle with zero.}
\]

\[
\theta = \tan^{-1} \frac{V_C}{IX_C} - \tan^{-1} \left[ \frac{V_L}{V_C(1 - X_L/X_C)} \right]
\]

Based on the assumption, the PWM current is synchronized to the capacitor voltage.

\[
(4) \quad \text{Solve the two equations to find values for } L \text{ and } C.
\]

2.3 | dc-side filter design

The value of the dc-link inductance \( (L_{dc}) \) is determined by its voltage-second balance as follows:

\[
V = L_{dc} \frac{di}{dt} \rightarrow L_{dc} = \frac{\Delta V \cdot \Delta t}{\Delta i}
\]

where \( \Delta V \) is the PV voltage difference with the voltage in the specified dwelling times by SVPWM, \( \Delta t \) is the calculated dwell time, and \( \Delta i \) is the maximum allowable current ripple in the switching period, which is decided as a percentage of the dc current [27]. In the case of constant dc inductor size, the maximum current ripple can be calculated based on MI, PF,
and the current angles in the specified dc inductor size by using the multi-variable extreme algorithm as follows:

\[
\Delta i = \frac{A}{L_{dc}} \left[ (V_{PV} - V_1) \times T_1 + (V_{PV} - V_2) \times T_2 \frac{B}{L_{dc}} \left[ (V_{PV} - V_3) \times T_3 \frac{C}{L_{dc}} \left[ (V_{PV} - \left( \frac{3V_M \cos(\theta)}{2} \right) + \left( \frac{\sqrt{3}V_M \sin(\theta)}{2} \right) \right] \times m_s T_s \sin \left( \frac{\pi}{6} - \theta + \phi \right) \right] \right] \times m_s T_s \sin \left( \frac{\pi}{6} + \theta - \phi \right) \right] \\
\]

where \( V_1, V_2, \) and \( V_3 \) are the amplitudes of the reference voltages in every switching vector, \( V_{PV} \) and \( V_M \) are the dc voltages of the connected PV source and the maximum voltage of each switching vector for dwell time calculation.

Figure 4 illustrates the current ripple graph based on the current angle \( \theta \) and the PF angle. The highest (H) and lowest (L) peaks in different parts of Equation (4) are illustrated in Figure 4a–c, and it is clear that part (c) has the highest impact on current ripple and thereby highest dc-inductor value since the ripple amplitude being the difference between the highest and lowest peaks is high.

After obtaining the dc-link inductor size in the assumed current ripple, the input capacitance can be calculated by solving the equation for input CL filter cut-off frequency in the dc side of the converter.

\[
f_{\text{Cut-off}} = \frac{1}{2\pi \sqrt{L_{dc} C_{dc}}} \quad (5)
\]

where \( C_{dc} \) is the dc-link capacitance.

The maximum allowable current ripple is calculated for different MI values in Figure 5, and it is clear that the current ripple size can be affected by MI, where the current ripple at unity MI is higher than that when MI equals to 0.1.

3 | SIMULATION RESULTS

The simulation is performed under the conditions listed in Tables 2 and 3 for the three-phase grid-connected CSI with a PV array and the designed filter parameters. The 1-MW power range is selected to compare the performance of the CSI-based system with the popular VSI topologies listed in Table 1. 1700 V/1600 A RB-IGBT devices are used in the CSI topology to have the same condition as compared with the VSI in terms of the selected switch voltage and current, which also helps with the converter performance comparison. In the similar conditions with the various VSI options from the listed manufacturers, by considering the dc voltage to be 1000 V, the input ac voltage of the CSI can be set to 816 Vrms. The PWM
regulating the dc voltage, which is determined by the P&O MPPT method. By applying the designed MPPT method and finding the reference dc voltage as 1000 V, the voltage control is done and the converter q-axis current reference is produced as an output of the dc voltage control. The q- and d-axis current controls are done by PI current controllers for CSI operation.

The performance of the grid-connected inverter is illustrated in Figure 6. It is seen that by utilizing the PI voltage controller, the dc-link voltage closely follows the reference issued by the MPPT algorithm under the specified irradiance and temperature. The maximum variation of dc voltage is up to 20 V in the average dc-link voltage of 1000 V even in big variation of output current from 1000 to 500 A. This shows the satisfactory dc-side control performance of the CSI. The output of the voltage controller produces the reference for the q-axis current controller. In this work, the q-axis current is assumed as an active component and to make the transient condition for verifying the controller operation performance, it is decreased by reducing the irradiance level to half while keeping the d-axis current to be zero to reach the unity PF. It is clear that the PI current controller operations in both current controllers are acceptable even under transient conditions in the q-axis current by decreasing irradiance.

Figure 7 shows simulation results for system operation in active power variation. The reactive power follows the d-axis current component and keeps zero since the d-axis current reference is set to zero and the active power variation by changing the active current component is illustrated. The three-phase voltage is shown, where the peak value of the three-phase grid voltages is about 1150 V for the designed dc voltage of 1000 V in the CSI. In the last part of Figure 7, the sinusoidal three-phase grid current is illustrated, which validates the filter design in the ac-side. The grid current THD is 2.86% and acceptable based on the IEEE 519 standard.

4 | POWER LOSS ANALYSIS

Power loss analysis for converters has been extensively reported in the literature [11,21–23,28,29]. The total power loss of switching devices is mainly divided into two parts: conduction losses and switching losses. A conduction loss is not affected by the switching frequency $f_s$, but depends on the MI and PF. The conduction losses occur while the power device is in the on-state and is conducting the current. Therefore, the power loss during conduction is computed by multiplying the voltage and the current in on-state [6]. The switching loss analysis of converters is calculated based on the turn-on and turn-off of IGBTs and diodes. In this study, the online power loss model is developed in Matlab/Simulink to calculate the loss of the CSI. The conduction and switching losses of each switch is calculated and averaged for a selected 1700 V/1600 A RB-IGBT device in the CSI and compared with the power loss results for 1700 V/1600 A IGBT from the same generation for the VSI (Figure 8). The $V_{GE}$ is determined based on the collector current and $V_{GE}$ for IGBT and RB-IGBT devices of

![Figure 5](image_url)  
**Figure 5** Maximum allowable ripple calculated. (a) MI = 1, (b) MI = 0.1; H, highest peak; L, lowest peak; MI, modulation index

| TABLE 2 | Pulse-width modulated inverter parameters |
|---|---|
| Parameters | Value |
| Power rating | 1 MW |
| Input ac voltage | 816 $V_{rm}/50$ Hz |
| dc-link voltage | 1000 V |
| Switching frequency | 3 kHz |

| TABLE 3 | Filter-designed parameters |
|---|---|
| Parameters | Value |
| Output ac filter | I. 0.057 p.u. |
| Input dc inductor | 0.38 p.u. |
| dc-link capacitance | 0.02 p.u. |

switching frequency is 3 kHz, which could meet the design requirements for the components. The output filter parameters have been designed based on the procedure in Section 2 for ac- and dc-side filters. The converter control is performed for
1700 V. To have a fair comparison, the online power loss model is also derived for the VSI in the same condition of CSI. The device characteristics of the 1700 V/1600 A RB-IGBT (MT5F3 1814) from Fuji Electric indicate that the RB-IGBT has 120% of $E_{\text{on}}$, 100% of $E_{\text{off}}$, and 115% of $E_{\text{th}}$ values versus the V-series 1700 V/1600 A IGBT module (IMB1600VC-170E). It should be noted that the inductors in the system are also significant sources of power loss; however, due to the high switching frequency enabled by the RB-IGBT devices, the size of the CSI filter inductors is much reduced, and as such, the power losses can be even lower than the filter inductors in a VSI [11,28,29].

It is worth mentioning that the power loss analysis is based on the same parameters that are considered in simulation (Tables 2 and 3). The results of power loss analysis are listed in Table 4, where the CSI efficiency is compared with that of the VSI under different grid voltages for various applications of CSI.

- Euro Efficiency = 0.03 × Eff 5% + 0.06 × Eff 10% + 0.13 × Eff 20% + 0.1 × Eff 30% + 0.48 × Eff 50% + 0.2 × Eff 100%
- CEC Efficiency = 0.04 × Eff 10% + 0.05 × Eff 20% + 0.12 × Eff 30% + 0.21 × Eff 50% + 0.53 × Eff 75% + 0.05 × Eff 100%

It is shown that the CSI has higher efficiency at the selected irradiance level. The maximum power loss is calculated based on the conduction and switching power loss formula in online condition for all IGBT and diodes, and since the power converters do not always operate at their maximum efficiency, the ‘European efficiency’ is adopted, which an averaged operating efficiency over a yearly power distribution is corresponding to Middle Europe climate. Also, for climates of higher insulations like US south-west regions, the California Energy Commission (CEC) has proposed another weighting. The calculated European efficiency and CEC is derived by using the proposed power loss model and the definition of Euro efficiency and CEC, which shows the effectiveness of the CSI in central inverters (Table 5).

5 | DISCUSSION AND EXPERIMENTAL RESULTS

To verify the performance of the proposed control method (Figure 5) in CSI, the experimental works have been carried out on a low-power CSI setup supplied by a PV simulator. The hardware setup consists of the following equipment: the CSI by RB-IGBT devices is connected to the grid through an LC filter with an inductance of 3 mH and a capacitance of 20 µF, the dc filter inductance is 0.2 mH.

A DSP controller (TI TMS320F28335) is utilized for running the control algorithms and producing the control signals for the CSI. It implements the P&O MPPT algorithm, the current and voltage controllers, and realizes the CSI PWM scheme with a switching frequency of 5 kHz.

The PV solar array simulator from Agilent (E4360 A) is used to generate the output characteristics of a PV array. The grid line-to-line voltage and grid nominal frequency are 220 V.
and 50 Hz, respectively. The experimental results for showing the control performance are illustrated in Figure 9. In part (a), the peak three-phase grid currents are shown to be about 11 A and the transient condition is made by reduction of currents for a while to 4 A to monitor the controller operation in transient condition. It is shown that the actual values of the $d$- and $q$-axis currents follow the reference well even in transient and the dc-link voltage keep the selected reference voltage at the detected point (250 V). The dc-link voltage is controlled at 250 V and the $d$-axis current is kept zero to achieve unity PF condition. The $q$-axis current control illustrates a good performance even in the condition of changing value from 11 to 14 A.

### Table 4 Power loss calculation results

| Irradiance level | Power loss [W] |
|------------------|----------------|
| S | VSI ($V_{L-L} = 480$-V) $V_{dc} = 1000$ | CSI ($V_{L-L} = 580$-V) $V_{dc} = 1000$ |
| 100% | 11,850 | 11,200 |
| 75% | 8500 | 7800 |
| 50% | 5290 | 4950 |
| 30% | 3060 | 2950 |

Abbreviations: CSI, current source inverter; VSI, voltage source inverter.
### TABLE 5  The calculated European efficiency and CEC

| Efficiency (%) | VSI ($V_{L-L} = 480\ V$) $V_{dc} = 1000$ | VSI ($V_{L-L} = 580\ V$) $V_{dc} = 1000$ | CSI ($V_{L-L} = 816\ V$) $V_{dc} = 1000$ |
|----------------|---------------------------------|---------------------------------|----------------------------------|
| Max. efficiency | 98.81%                          | 98.88%                          | 98.98%                           |
| European efficiency | 98.53%                          | 98.66%                          | 98.91%                           |
| CEC efficiency   | 98.47%                          | 98.60%                          | 98.88%                           |

Abbreviations: CEC, California Energy Commission; VSI, voltage source inverter.

### FIGURE 9  Experimental results for CSI operation and controller performance; CSI, current source inverter

6  CONCLUSION

In this study, the performance of a three-phase CSI as an interface between PV modules and the grid are evaluated in the central inverter power range. By using new RB-IGBT devices, the CSI offers comparable or even better performance as compared with conventional VSI solutions. The CSI topology features inherent voltage boost capability, which allows the elimination of a dc-dc converter stage often necessary in VSI configurations. It is shown that the CSI produces satisfactory dynamic performance under irradiance level changes and the actual dc-link voltage properly tracks its reference voltage generated by the MPPT method. Simulation and experimental results with the designed system parameters verified the performance of the presented solution.

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