More Efficient Power Inverters using Series Connected AC Capacitors for Large DC Voltage Variation Applications

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Abstract. *Conventional power inverters such as a voltage source inverter and a current source inverter may operate only with low efficiency when converting power from large DC voltage variation sources to constant AC voltage outputs. This is because large difference in voltage levels between the DC side and AC side of the inverters can occur and reduce voltage transfer capability of the inverters. Additional circuits such as a boost or a buck converter could be used to adjust DC voltage to the suitable levels for the inverters, but they add more cost, power loss and complexity to the inverter circuit. This paper proposed an alternative technique that allows the inverters to always operate with optimum voltage levels between the DC side and AC side. The proposed technique can achieve this by connecting an AC capacitor in series with each of output AC phase line of the inverters. Simulated results shows that the proposed technique provides improved efficiency and less voltage stress on inverter circuits compared to the conventional circuits.*

Keywords:

power inverter, series ac connected capacitors, large dc voltage variation

1. Introduction

A power inverter is always required when converting DC power into AC power. A voltage source inverter (VSI) and a current source inverter (CSI) are two most basic types of the power converters in the literature that could be used [1]. These inverters potentially provide high efficiency due to the capability of single-stage power conversion. However, these inverters operate only with low efficiency when required to convert power from large DC voltage variation sources (e.g. Solar cells or Fuel cells) to constant AC outputs (e.g. power grid) [2]-[3]. This is because large voltage difference between the DC side and AC side of the inverters can occur and degrade voltage transfer capability of the inverters as illustrated in Fig. 1.

In order to eliminate this problem, additional circuits such as a boost or a buck converter could be used to adjust DC voltage to the suitable levels for the inverter [4]. However, these added components add more cost, power losses and complexity to the inverters [5].

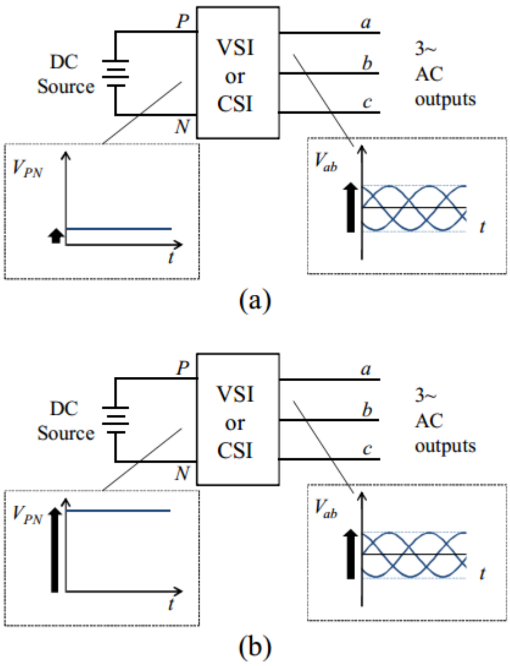


Fig. 1: Large voltage difference between the DC side and the AC side of the inverters: (a) during low DC voltage and (b) during high DC voltage

Impedance source inverters (also known as z-source inverters, ZSIs) are the inverter types that can both step-up and step-down DC voltage to constant AC voltage outputs levels with a wide DC voltage range [6]. These inverter types can provide these characteristics due to the use of an additional LC circuit with a diode in cooperation with special switching states (i.e. shoot-though switching states for the voltage fed ZSI and open-circuit switching states for the current fed ZSI). However, these special switching states can cause high voltage or current stress on circuit devices of the inverters. Moreover, the more the DC voltage are stepped up (or down), the less the voltage transfer ratio will be [7]-[8].

This paper proposes an alternative technique that could be used to always provide optimum voltage levels between the DC side and AC side of the inverters regardless of the DC voltage levels. The proposed technique can achieve this sophisticated characteristic by connecting an AC capacitor in series with each of AC phase line of the inverters. The presence of the series AC capacitor allows the voltage levels at the AC side of the inverters to be adjusted in response to low or high levels of input DC voltage whilst retaining constant AC voltage at the outputs. The connection of series AC capacitors for the inverters was first used in [9] to reduce voltage rating of semiconductor devices for an application of shunt active power filters based CSI configuration. This technique was introduced to improve efficiency of the CSI in [10] and [11]-[12].

In this paper, a more general procedure to implement this technique for all the inverter types is described. The paper begins with an introduction of circuit configuration of the proposed technique in Section 2. The principles of operation and control of this technique are presented in Section 3. Simulated results which are used to verify the performance of this technique are illustrated and discussed in Section 4; followed by the overall conclusions of the paper in Section 5.

2. Circuit Configuration

Fig. 2 shows circuit configuration of the proposed technique when using for three-phase AC system. An AC capacitor is connected in series with each of the AC phase line of the conventional inverter, which can be either a VSI or a CSI or a ZSI.

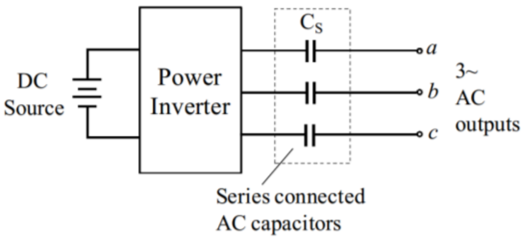


Fig. 2: Configuration of the proposed technique

As only three passive AC capacitors are added for the proposed technique, very little power losses are added. These power losses are much smaller than ones contributed from the semiconductor devices and thus can be ignored [13].

3. Operation and Control Principle

The proposed circuit in Fig. 2 can be represented as a per phase equivalent circuit operating in a rectification mode (for simplify the represented diagrams) as shown in Fig.3; where the parameters in the circuit are described in Table1. By applying electrical circuit theory and phasorial summation theorem for Fig. 3, the relationships among parameters in Fig. 3 can be derived as given in (1)-(2) and a corresponding phasor diagram as shown in Fig. 4.

$$\overline{V}_{inv} = \overline{V}_s + \overline{V}_c \tag{1}$$

$$\overline{V}_c = \overline{I}_s \cdot \left(\frac{1}{j\omega C_s}\right) = \frac{\overline{I}_s}{\omega C_s} e^{-\pi/2} \tag{2}$$

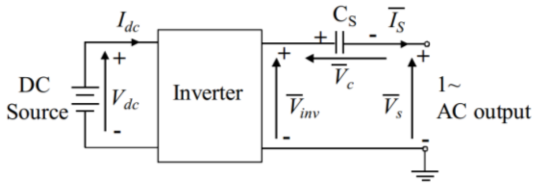


Fig. 3: Per-phase equivalent circuit of the power inverter with the proposed technique

Table 1: Circuit parameters according to Fig. 3

Parameter	Description
$\overline{V}_s$	output AC voltage phasor
$\overline{I}_s$	output AC current phasor
$\overline{V}_c$	AC voltage phasor across the series AC capacitor
$\overline{V}_{inv}$	AC voltage phasor seen at the terminals of the inverter
V_{dc}	DC voltage of the DC source
I_{dc}	DC current of the DC source

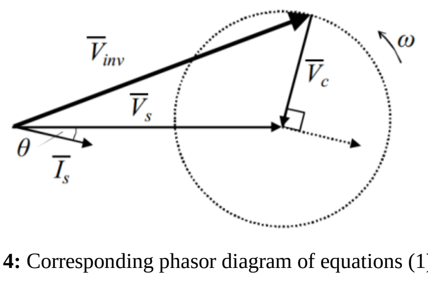


Fig. 4: Corresponding phasor diagram of equations (1)-(2)

The operation of the proposed technique can be described by the phasor diagram shown in Fig. 4. It can be seen that the vector V_{inv} is a summation result of V_s and V_c. If V_s is constant, the amplitude of V_{inv} will depend only on V_c. In addition, since V_c is a cross product of I_s and $1/j\omega C_S$, where ω is an AC line angular speed and if $1/\omega C_S$ is constant, the amplitude of V_c will depend only on the amplitude of I_s whilst the phase of V_c always lags I_s by 90 degrees. If the phase of I_s is varied by θ degrees, the phase of V_c will rotate ahead I_s by 90 degrees. This gives a change in the amplitude of V_{inv} to be high or low depended on the instantaneous value of θ by having the end point of the phasor on the circle.

In this way, the amplitude of V_{inv} can be adjusted by changing θ. This can produce low or high levels of AC voltage to match to low or high levels of the existing voltage at the DC side of the DC source. At the same time, the end AC voltage outputs can remain constant as shown in Fig. 5a-b. These are the results of the setting of as shown in Fig. 6a-b.

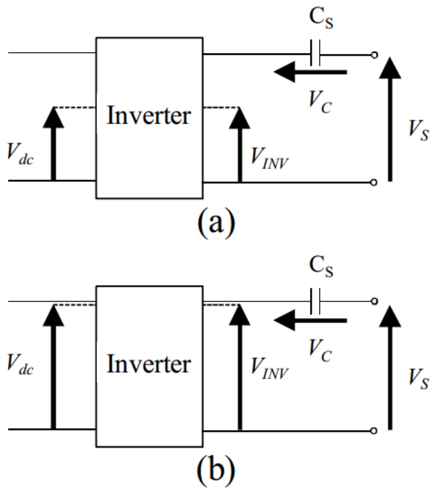


Fig. 5: DC-AC voltage matching using the proposed technique: (a) during low DC voltage and (b) during high DC voltage

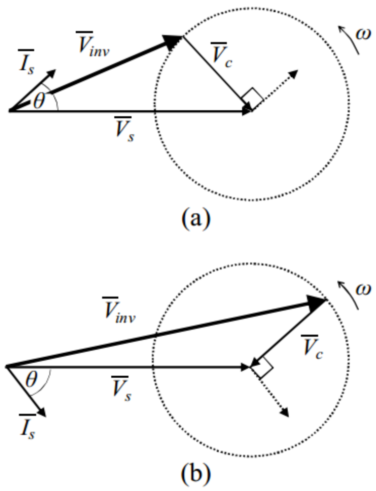


Fig. 6: Control of θ during the situations of (a) low DC voltage condition and (b) high DC voltage condition

4. Simulation Results

This section presents simulation results that are used to verify the performance of the proposed technique. Simulation models of the three-phase VSI (the most often used inverter for modern power electronic applications) with and without the proposed technique were tested. The parameters used in the models are the same except the series AC capacitors (C_S) were added for the proposed technique as shown in Fig.7 and Table 2; where values of the parameters can be determined using design procedures proposed in [11]. A standard space vector modulation (SVM) for the VSI [14]-[15] was used with the switching frequency (f_s) of 10 kHz.

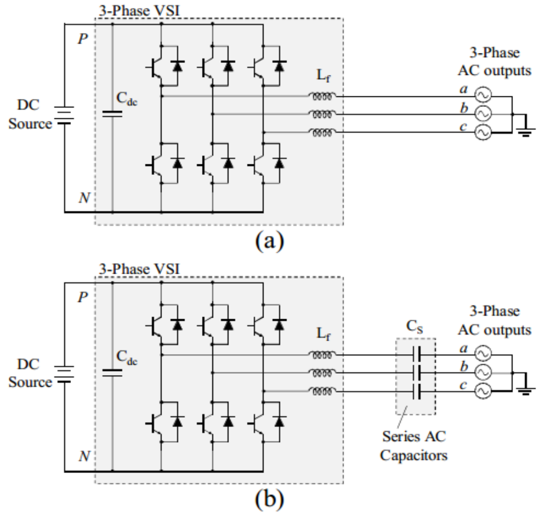


Fig.7: Simulation models: (a) conventional VSI and (b) VSI with the proposed technique

Table 2: Simulation Parameters

Parameter	Description
DC inputs	Voltage of 50% -150% of peak AC outputs with peak power level of 16.1kW
AC outputs	Voltage: Fixed at 3-phase, 380V, 50Hz
C_{dc}	30µF
L_f	1mH
C_S	30µF

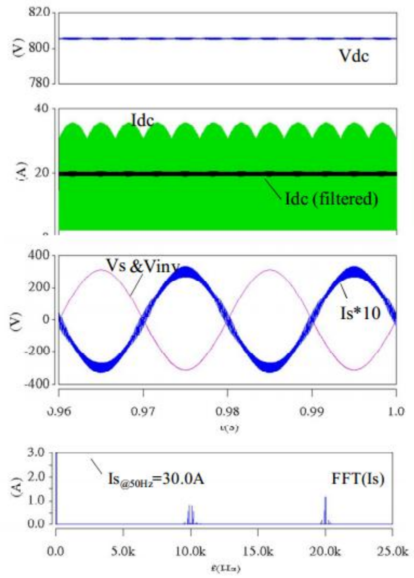
Fig. 8 shows simulation results of the VSI with and without the series connected AC capacitors when both inverters operate at high input DC voltage level (150% of peak AC voltage output with V_{dc}=805V and I_{dc}=20A whilst providing AC voltage and current outputs: V_s=310.3 V_{peak} and $I_{s@50Hz}$=30 A_{peak}. It can be seen that:

- The VSI with the proposed technique provides less value of peak DC current (I_{dc}) than the conventional VSI by 35.7%, reflected by lighter peak current on I_{dc} waveforms. This implies that the VSI with the proposed technique has less current stress on the inverter circuit when compared to the conventional VSI.
- The VSI with the proposed technique provides higher level of output AC voltage (V_{inv}=826$V_{pk\text{-}pk}$) than the conventional VSI ($620_{Vpk\text{-}pk}$), which would be better

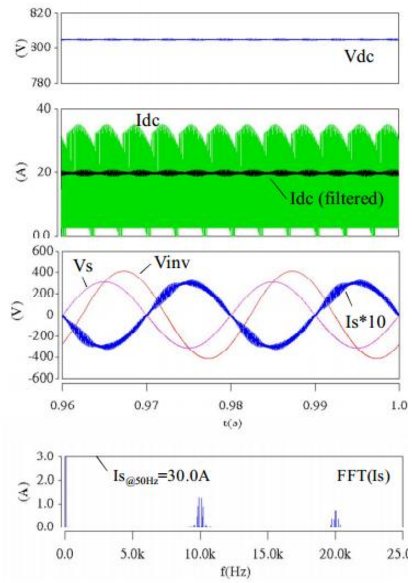
matching to the high level of DC voltage at the DC side (805V).

- The VSI with the proposed technique produces less peak-to-peak current waveform of the AC current output (I_s=65.2A_{pk-pk}) compared to (69.8A_{pk-pk}) of the conventional VSI, by mean of less current stress on the AC output circuit of the inverter.

Fig. 9 shows simulation results of the VSI with and without the series connected AC capacitors when both inverters operate at low input DC voltage level (50% of peak AC voltage output with Vdc=270V and Idc=60A whilst providing AC voltage and current outputs of Vs=310.3Vpeak and Is@50Hz=30Apeak.

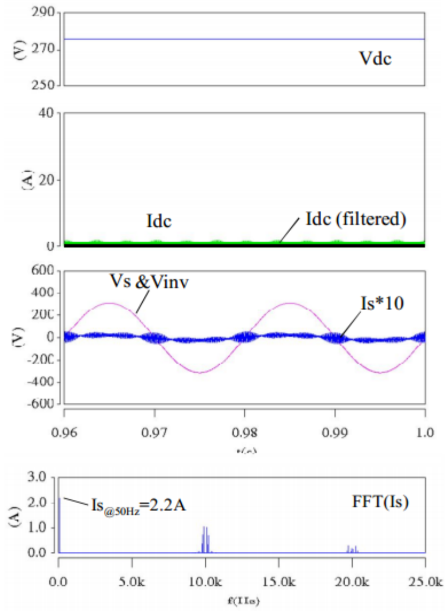


(a) Conventional VSI

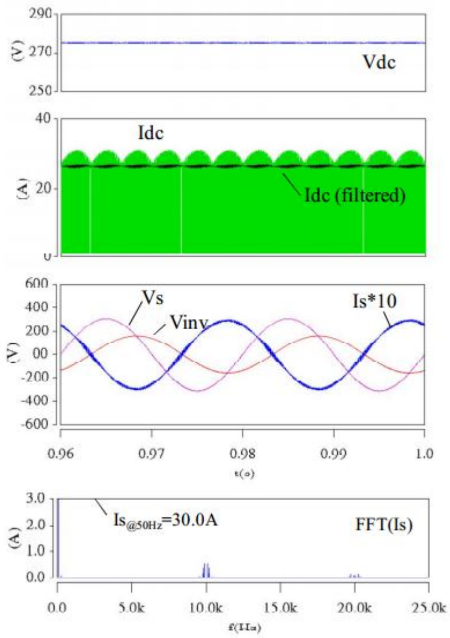


(b) VSI with the series AC capacitors

Fig.8: Simulation results during high input DC voltage level (150% of peak output AC voltage): (a) conventional VSI and (b) VSI with the proposed technique



(a) Conventional VSI



(b) VSI with the series AC capacitors

Fig.9: Simulation results during low input DC voltage level (50% of peak output AC voltage): (a) conventional VSI and (b) VSI with the proposed technique

It can be seen from Fig. 9 that:

- Conventional VSI cannot transfer power to the AC side due to its restriction that the DC voltage level must be always greater than peak output AC voltage (538V). This reflects by approximately zero DC current (I_{dc}) in Fig.9a.
- Indeed, The VSI with the proposed technique can transfer power from the DC side to the AC side, which reflects from the existence of current levels at

both the DC side (I_{dc}=27.6A) and the AC side ($I_{s@50Hz}$=30A$_{peak}$). Therefore, this technique can break through the voltage transfer limit of the conventional VSI. Moreover, the current ripple and peak current of DC current are also reduced as well as the output AC current are also improved (reflected by less harmonic amplitudes) compared to Fig.8b.

The successful results of the proposed technique shown in Fig.9b are a consequence of the adjustable AC voltage levels using series AC capacitors. As illustrated, the AC voltage level is significantly reduced to the suitable level for the VSI (V_{inv}= 280 V$_{pk\text{-}pk}$), which matches to the DC voltage level (275 V$_{peak}$) at the DC side. These characteristics cannot be achieved in the conventional VSI circuit.

5. Conclusions

This paper has proposed an alternative technique to provide optimum DC-AC voltage levels for three-phase power inverters when operating with large input DC voltage variation applications. The proposed technique can achieve a very simple structure and easy in control strategy by utilizing the use of series connected AC capacitors. The existence of series AC capacitor in the conventional inverter circuit allows the AC voltage of the inverters to be adjustable with a simple control of the phase displacement between AC output voltage and AC output current. Simulation results demonstrating for the VSI circuit show agreed results to the theoretical expectation. The results show that the proposed technique can significantly reduce current stress for the VSI as well as potential less switching power losses with less number of peak current on both input and output waveforms when compared to the conventional VSI circuit.

6. Acknowledgement

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Biography

Chonlatee Photong received his bachelor degree in Electrical Engineering from Khon Kaen University, Thailand. He received his master degree in Power Electronics and Drives and his PhD in Electrical and Electronic Engineering from the University of Nottingham, UK, in 2007 and 2013. He is currently a lecturer at the Faculty of Engineering and an Assistant to the President for Public Relations and International Affairs, Mahasarakham University, Thailand. His research interests include power electronics, power converters for renewable energy conversion, electrical machines and drives.

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