Improvement of the Modulation Method for Single-Phase Transformerless Photovoltaic Conergy Inverter for Reactive Power Injection Capability

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***Abstract*—Several single-phase transformerless topologies have been proposed to mitigate the leakage problem in photovoltaic systems one of which is Conergy. It is an NPC derived structure which greatly reduces the leakage current and improves the total efficiency due to its fewer switches in comparison to other single-phase topologies. As the power capacity of photovoltaic systems is increasingly growing, many countries have revised their requirements for distributed solar generation units which enforces them to inject reactive power to support the grid voltage. In single-phase photovoltaic systems, this capability contributes to power quality of the grid. In this paper, the capability of the Conergy topology to inject reactive current into the grid is analyzed in detail. The conventional modulation method proposed in earlier works, is evaluated according to this capability, the leakage current issue, and efficiency of the topology. Moreover, two novel modulation methods are proposed enabling the reactive power generation. In addition, switches' stresses are reduced owing to the proposed modulation methods. The advantages of the proposed methods are validated using MATLAB/SIMULINK simulations.**

***Index Terms*—Conergy; EMI; leakage current; modulation methods; photovoltaics; reactive power generation; residential power system; single phase converter; smart grid; transformerless inverters.**

I. INTRODUCTION

Use of renewable energy systems is a prominent solution in order to alleviate CO2 emission problem and energy crisis [1]. Photovoltaic (PV) renewable energy systems as a kind of green energy, have become high penetration level in low-voltage and/or medium-voltage grids since the year of 2012 [2]. Actually, a large amount of solar energy is injected into the grid through grid-connected power converters [3, 4]. These power conditioners are basically divided into two groups. The first group has an isolation transformer which can be either high-frequency or low-frequency. On the contrary, the second group does not contain an isolation transformer [4]. In this case, improved size, cost, weight, and efficiency are the most important benefits of transformerless systems [5-7]. However, elimination of the isolation transformer would lead to some safety concerns such as the leakage current problem. This phenomenon appears through the leakage stray capacitor between the PV panel and ground [8-11]. In addition to the safety problem, more importantly, it would lead to lower conversion efficiency and power quality. Thus, solving this problem is of high importance in photovoltaic systems.

In order to fix this problem, new freewheeling paths should be provided to separate the PV side from the grid side during zero voltage states [8]. According to reference [8], several single-phase structures have been invented and studied to mitigate the leakage current issue and enhance the efficiency of the transformerless grid-connected PV inverters [12, 13]. The H5 topology was patented by SMA. It is an H-bridge inverter with an extra switch between the DC-link capacitor and the bridge. Highly efficient and reliable inverter concept (HERIC), Full-Bridge inverter with DC Bypass (FB-DCB), Conergy [12], and Neutral Point Clamped (NPC) are the other topologies used to reduce leakage current. Furthermore, as the power capacity of new PV systems is increasingly growing, their great impacts on power quality and voltage stability could not be neglected, so many countries have revised their requirements for large-scale PV inverter systems.

In this paper, the capability of Conergy topology for reactive power injection, its leakage current, and efficiency for the earlier modulation method are evaluated. The conventional modulation method will be modified to enable reactive power injection with less switching sequences. Accordingly, two novel modulation methods have been proposed to improve and balance switching losses, and reduce switches' stress. Finally, the advantages of the proposed methods over the conventional method are validated through simulation case studies in MATLAB/SIMULINK.

II. EARLIER MODULATION METHOD FOR CONERGY

Fig. 1 shows Conergy topology which is derived from classic NPC inverter with the output clamped to the neutral using a bidirectional switch realized with two series back-to-back IGBTs as patented by Conergy [12, 14]. This solution is applied to achieve zero voltage by 'clamping' the output to the grounded 'middle point' of the DC bus using S+ or S− depending on the sign of the current, reduce the leakage current of transformerless photovoltaic systems, and enhance the total efficiency by prevention of reactive power exchange between the line filter L and DC link capacitors C1 and C2 [14]. Similar to HERIC, H5, and FB-DCB topologies, Conergy is invented to mitigate the leakage current problem in transformerless photovoltaic inverters. The reactive power generation capability of this topology has been not investigated in the earlier works. In the following, the earlier modulation method of Conergy inverter topology in case of injecting reactive power is investigated in detail and two new modulation methods have been proposed to enable reactive power injection with lower output current THD.

A. *Conventional modulation method*

In this modulation method, during positive half cycles, S1 and S4 are switched at high frequency. In positive half cycles, when the reference voltage is greater than carrier waveform, S1 would be turned ON and otherwise S4 would be turned ON. During negative half cycles, S2 and S3 are switched at high frequency. In negative half cycles, when the reference voltage is greater than carrier waveform, S2 would be turned ON and otherwise S3 would be turned ON [12, 13]. Therefore, S1 and S4 are switched complementarily in positive half cycles, while S2 and S3 are switched complementarily in negative half cycles. The switching algorithm of this modulation method is shown in Fig. 2. For more clarification, the switching sequences of this modulation are depicted in TABLE I.

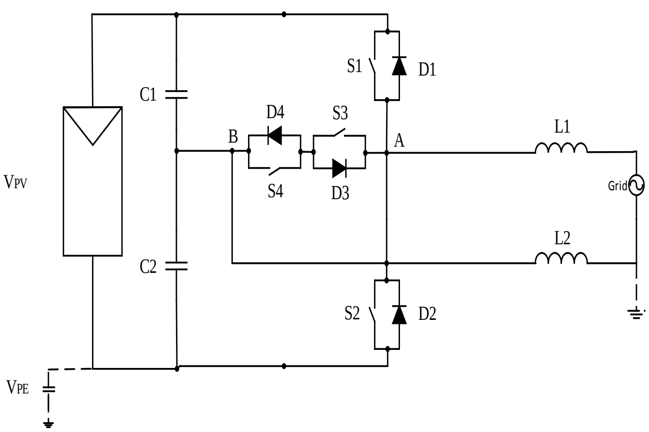

Fig. 1. Conergy topology

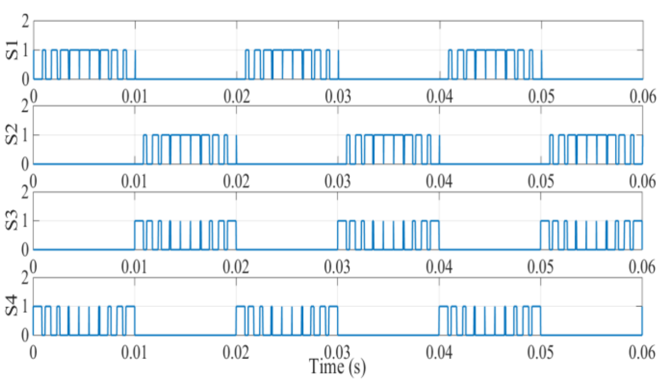

Fig. 2. Switching algorithm of the conventonal modulation method.

III. Proposed Modulation Methods

A. *First proposed modulation method*

In this modulation method, S1 is turned ON in positive half cycles. During positive half cycles, for modulating the reference voltage, when the reference voltage is greater than the carrier waveform, S1 would be turned ON and otherwise S3 and S4 would be turned ON. Thus, In contrast to the conventional method, during positive half cycles, S3 is also commutated at high frequency and complementarily to S1. On the other hand, during negative half cycles, S2 would be switched at high frequency. In negative half cycles, when the reference voltage is greater than the carrier waveform, S2 would be turned ON and otherwise S3 and S4 would be turned ON. Similar to the positive half cycles, both S3 and S4 are commutated at high frequency and complementarily to S2. Fig. 3 shows the switching algorithm for switches S1-S4. For more clarification, TABLE II illuminates the operation of switches in the second modulation method.

B. *Second Proposed modulation method*

This modulation method has been proposed in order to make this topology able to inject reactive power into the grid. This capability is analyzed in simulation results. In this modulation method, S1 is switched at high frequency and based on the comparison between the reference voltage and the carrier waveform. Also, S2 is commutated at high frequency in negative half cycles based on the PWM mentioned for positive half cycles. Therefore, S1 is turned OFF in negative half cycles and S2 is turned OFF during positive half cycles. In contrast to the conventional method and first proposed modulation method, S4 is always switched complementarily to S1. Thus, during negative half cycles, S4 is remained ON while in positive half cycles it is commutated at high frequency. On the other hand, S3 is always switched complementarily to S2. Thus, during positive half cycles, S3 is remained ON while in negative half cycles it is commutated at high frequency. The switching algorithm of the second novel modulation method is depicted in Fig. 4. To clarify, the switching sequences of the proposed method is illustrated in TABLE III.

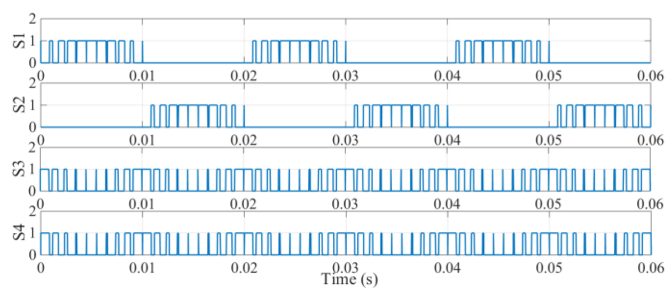

Fig. 3. Switching algorithm of first proposed modulation method.

TABLE I. SWITCHING SEQUENCES OF THE CONVENTIONAL MODULATION METHOD

Half Cycle	V_{AB}	S1	S2	S3	S4
Positive	$V_{PV}/2$	ON	OFF	OFF	OFF
	0	OFF	OFF	OFF	ON
	Commutation	20 kHz	0 Hz	0 Hz	20 kHz
Negative	$-V_{PV}/2$	OFF	ON	OFF	OFF
	0	OFF	OFF	ON	OFF
	Commutation	0 Hz	20 kHz	20 kHz	0 Hz

TABLE II. SWITCHING SEQUENCES OF THE FIRST PROPOSED MODULATION METHOD

Half Cycle	V_{AB}	S1	S2	S3	S4
Positive	$V_{PV}/2$	ON	OFF	OFF	OFF
	0	OFF	OFF	ON	ON
	Commutation	20 kHz	0 Hz	20 kHz	20 kHz
Negative	$-V_{PV}/2$	OFF	ON	OFF	OFF
	0	OFF	OFF	ON	ON
	Commutation	0 Hz	20 kHz	20 kHz	20 kHz

TABLE III. SWITCHING SEQUENCES OF THE SECOND PROPOSED MODULATION METHOD

Half Cycle	V_{AB}	S1	S2	S3	S4
Positive	$V_{PV}/2$	ON	OFF	ON	OFF
	0	OFF	OFF	ON	ON
	Commutation	20 kHz	0 Hz	0 Hz	20 kHz
Negative	$-V_{PV}/2$	OFF	ON	OFF	ON
	0	OFF	OFF	ON	ON
	Commutation	0 Hz	20 kHz	20 kHz	0 Hz

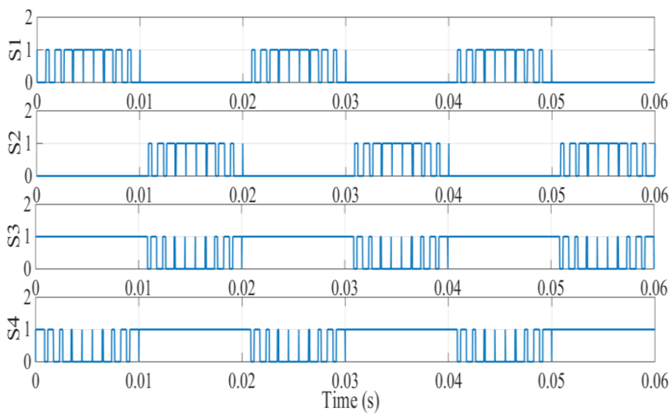

Fig. 4. Switching algorithm of the second proposed modulation method

IV. DESIGN CONSIDERATION

In this section, the design process of Conergy topology is presented. Nominal power for this study is assumed 2000 W and design parameters are based on it. DC link voltage is assumed 900 volt which is divided into two equal DC link in order to be able for injecting nominal power [3]. With the aim of reducing high order harmonics, this topology benefits from two discrete inductors with equal values as an L filter [3]. The simulation parameters are listed in Table IV. Modulation index, m_a, for this method is as follows:

$$m_a = \frac{V_{o(\max)}}{V_{PV}} \tag{1}$$

Where, $V_{o(\max)}$ is the amplitude of the grid voltage, and V_{PV} is the DC link voltage. The output filter inductance, with respect to an acceptable THD of the output current is achieved from (2) [6].

$$I'_{L_{ac(rms)}} = \frac{V_{dc}}{2 f_s L_{ac}} \frac{1}{2\sqrt{3}} \sqrt{\frac{1}{2} m_a^2 - \frac{8}{3\pi} m_a^3 + \frac{3}{8} m_a^4} \tag{2}$$

$$THD = \frac{I'_{L_{ac(rms)}}}{I_{L_{ac(1)}(rms)}} \times 100 \leq THD_{req} \tag{3}$$

Where, f_s is the switching frequency of the inverter, $I'_{L_{ac(rms)}}$ is the ripple of the output current and $I_{L_{ac(1)}(rms)}$ is the fundamental component of the output current.

The active and reactive power injected to the grid is controlled by a closed loop current controller. In this paper, the proportional resonant (PR) controller is adopted [3, 4]. The controller's block-diagram is depicted in Fig. 5.

I. SIMULATION STUDY

Reactive power in VAR is the product of the RMS voltage and current and depends on the phase shift between output voltage and current of the inverter [3]. The phase shift between voltage and current means that in a part of positive half cycle of the voltage, the current is negative [3]. Therefore the switching algorithm of the inverter has to make a path for passing the reverse current in order to generate reactive power with an acceptable THD. In this section, simulation results of the earlier modulation method is presented and analyzed in detail. Then, the advantages of the proposed modulation methods are validated according to simulation results. Afterward, the benefits of the second novel method is illustrated.

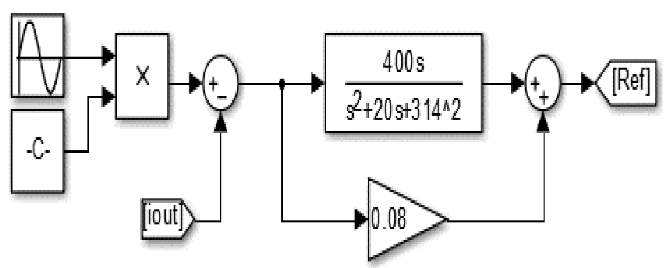

Fig. 5. The structure of the PR current controller.

TABLE IV. TECHNICAL SPECIFICATIONS OF THE TOPOLOGY

Nominal Power (VA)	2000
Grid Voltage (V)	230
Grid Frequency (Hz)	50
L Filter (mH)	5.4
Switching Frequency (kHz)	20
Parasitic Capacitor (nF)	20
DC Link Voltage (V)	900

In order to evaluate the capability of injecting reactive power for each modulation method, reactive and active power references are assumed 1414.2 VAR and 1414.2 W respectively. It means the phase shift between output voltage and current is $\pi/4$ radians. In the following, simulation results of the conventional modulation method is shown in Fig. 6. If reactive power is injected into the grid, the output current of the inverter would be greatly distorted, as illustrated in Fig. 6(a). Fig. 6(b) shows the grid voltage whose RMS value is 230 Volt. In this situation, when product of the instantaneous output voltage and current is negative, switching sequences would be changed in order to make a path for the reversing current. During this situation, the inverter would not produce the zero state voltage which leads to a highly distorted output current whose harmonic distortion spectrum is depicted in Fig. 7.

Fig. 8 shows the simulation results of the first novel modulation method. As depicted in Fig. 8(a), the inverter has the capability to generate reactive power without making the output current highly distorted. Harmonic distortion for this modulation is less than the conventional method which is shown in Fig. 9. This is because a possible path has been built for the reversing current to flow into the inverter. In this method, in each half cycle, three switches are commutated at switching frequency. In positive half cycle, S1 is commutated at high frequency and S3 and S4 are switched complementarily to S1. On the other hand, in negative half cycle, S2 is commutated at high frequency and S3 and S4 are switched complementarily to S2. Since in each half cycle of the proposed method, three switches are commutated at high frequency, switching losses is expected to be high. In the proposed method, these three switches are commutated at high frequency in each half cycle when the product of voltage and current is negative which leads to less power dissipation.

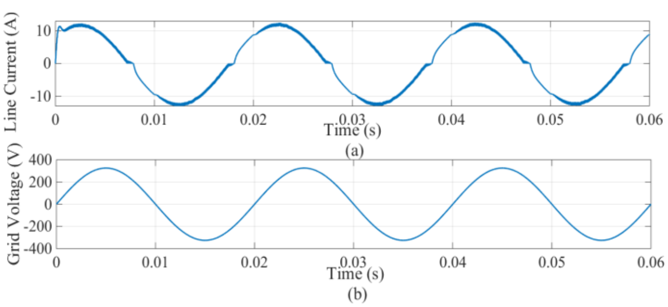

Fig. 6. Simulation results of the conventional method. (a) Line current. (b) Grid voltage.

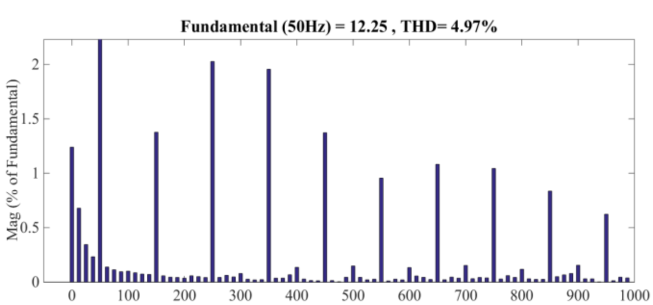

Fig. 7. Harmonic distortion spectrum of the output current in the conventional modulation method

Fig. 10(a) shows the output current of the power converter for the second novel modulation method. Since switching sequences are in a way that a freewheeling path is built for the reactive current, THD of the output current has the lowest value whose harmonic distortion spectrum is depicted in Fig. 11. It shows that amplitude of the high frequency components are much less than the conventional method. Accordingly, similar to the first proposed modulation method, the inverter has the capability of reactive power generation with an appropriate THD. However, in this modulation method, since only two switches are commutated at high frequency in each half cycle, switching losses are much less than the first proposed method. Thus, the second modulation method not only has the capability to generate reactive power with a lower THD, but also has the lowest power dissipation thanks to the optimized switching proposed. In addition, Fig. 12 is the leakage current for the all modulation methods. Since the voltage across the leakage capacitor is always equal to $V_{PV}/2$, the leakage current is near to zero which makes this topology really appropriate for photovoltaic grid-connected applications. Also, the voltage across the leakage capacitor is independent from the modulation method like NPC [12].

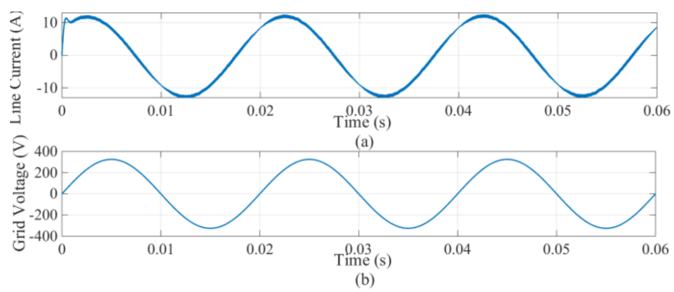

Fig. 8. Simulation results of the first proposed modulation method. (a) Line current. (b) Grid voltage.

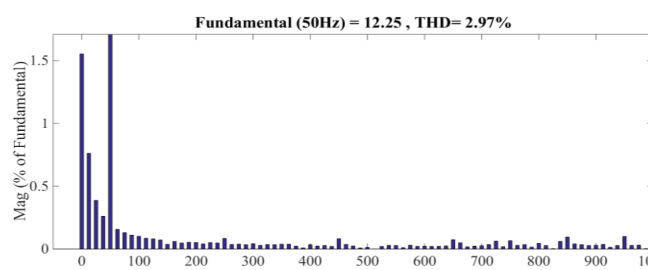

Fig. 9. Harmonic distortion spectrum of the output current in the first proposed modulation method

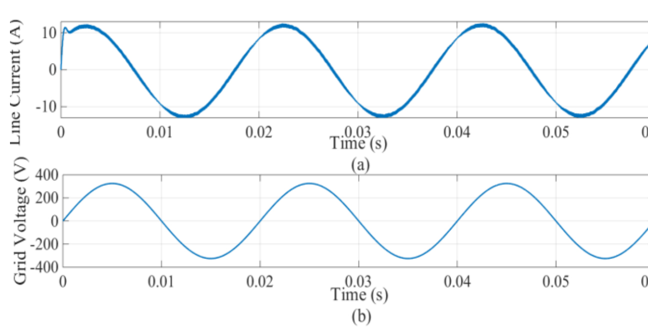

Fig. 10. Simulation results of the second proposed modulation method. (a) Line current. (b) Grid voltage.

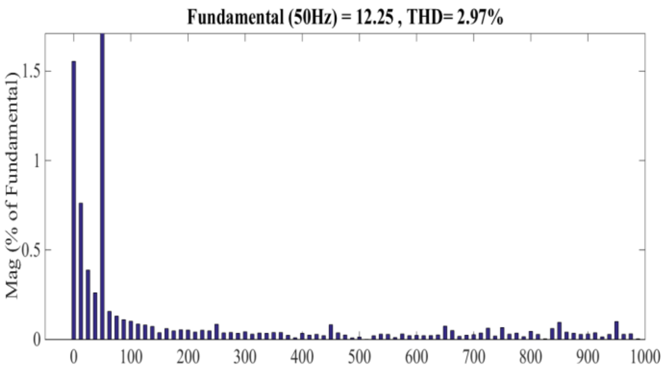

Fig. 11. Harmonic distortion spectrum of the output current in the second proposed modulation method.

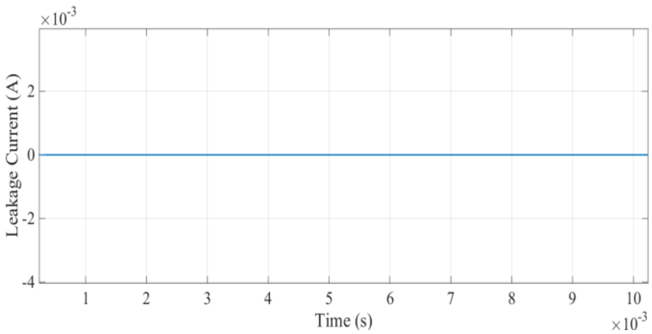

Fig. 12. Leakage current of the Conergy topology for all the modulation methods.

II. Conclusion

In this paper, the performance of the single-phase transformerless Conergy inverter for operating in power factors other than unity has been investigated. According to the simulation case studies, the conventional modulation method is not capable to inject reactive power. Thus, two novel modulation methods for this topology have been introduced in this paper. The two proposed modulation methods for this topology with closed loop control are comprehensively studied and simulated. The first conventional method is not capable to generate reactive power. Thus, output current THD would not be in an acceptable range in case of reactive power injection. In contrast, the first novel modulation method has the capability to generate reactive power. However, in this method, three switches are constantly commutated at high frequency which leads to higher switching losses. Then, a novel modulation method with the aim of enabling reactive power injection capability and reduction of switching losses is proposed to enhance the efficiency of the converter. This novel modulation method is able to inject reactive power, improve switching losses, and reduce switches' stresses. The simulation results confirmed the performance of the method. Finally, these modulation methods are compared as described in Table V. THD of the output current for two proposed method have the lowest value. The leakage current in these methods are similar to the conventional modulation methods although the reactive power generation, losses and switch stresses are improved.

TABLE V. Comparision of the three modulation methods

Methods	THD (%)	Reactive Power Injection	High Frequency Switching	Output Power (Per unit)
Conventional Method	4.97	No	Two Switches	0.971
First Novel Method	2.97	Yes	Three Switches	0.978
Second Novel Method	2.97	Yes	Two Switches	0.986

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