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Multi-Stage Converter Based on Two Voltage Sources Sub-Multilevel Converter in Output Stage Suitable for Distribution Generation Systems

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ABSTRACT

This paper presents a novel multi-stage converter for distributed generation systems based on sub-multilevel converter in output stage. In proposed topology each sub-multilevel converter includes two voltage sources. In comparison with conventional multi-stage converters, the stages of voltage transform are reduced. The proposed multi-stage converter consists of two power electronic converters and one high frequency transformers. In addition, there is not any DC-link in the proposed converter. The proposed converter can be a suitable solution for power conditioning in distributed generation systems, especially for the medium to high-power applications. The operation and performance of the suggested converter has been verified by the simulation results using SIMULINK /MATLAB.

Key Words: *Power conditioning, multi-stage converters, Two voltage sources sub-multilevel converter*

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1. INTRODUCTION

The distributed generation (DG) concepts emerged as a way to integrate different power plants, increasing the DG owner's reliability, reducing emissions and providing additional power quality benefits. The energy sources used in DG systems usually have different output characteristics and for this reason power electronic converters are usually employed to connect these energy sources to the grid [1]. Many of the newer forms of DG cannot be connected directly to the AC grid. Fuel cells and solar cells, for example, generate at DC. A fuel cell is a device that directly converts the chemical energy of fuel to electric energy. Different common strategies for connecting a fuel cell to the grid are used in the DG systems. These converters are called multi-stage converters [2-5]. In the first strategy the fuel cell supplies energy to the DC bus via a DC/DC converter. A voltage-source inverter provides the connection between the DC bus and the AC grid. A line-frequency transformer may be added to this strategy for boosting and isolation. Since fuel cell sources operate in low voltage range and load/grid voltage is relatively high, a step-up transformer is required to generate the desired voltage level. It also provides the isolation between power supply and load. In the second strategy the galvanic insulation and voltage transformation are obtained with a high frequency (HF) transformer. This type of multi-stage converters consists of three power electronic converters and one HF transformer. The DC voltage from the input source is fed to single phase inverter, modulated into a high frequency square wave, coupled to the secondary of the high frequency transformer and rectified to form three DC link voltages by using one rectifier. The output stage consists of inverter that converts the DC voltage into balance AC sinusoidal voltage [6-9]. Multilevel converters are one of the power electronic converters that have been used in multi-stage power conditioners. In recent years, there has been great interest in multilevel converters for high-voltage and high-power applications. One of them uses cascade converters with isolated DC sources. The full-bridge topology with four switches is used to synthesize a three-level square-wave output voltage waveform [10-13].

Figure 2 shows multi-stage converter based on H-bridge multilevel converter. In this circuit H-bridge multilevel converter is used as inverter. The main disadvantages of the isolated type DC/AC multi-stage converter based on H-bridge multilevel converter are the use of a larger number of semiconductor switches and a complex control circuitry and needing the equilibrate of the voltage at the boundaries of capacitors.

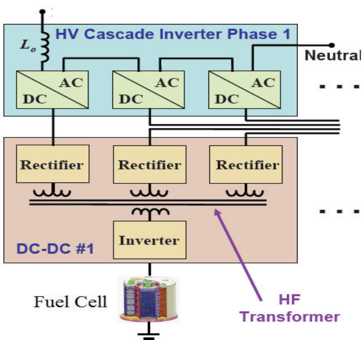


Figure 1. Multi-stage isolated type DC/AC converter based on cascade multilevel converter.

The multi-stage converters need either too many AC/DC and DC/AC links, large bulky magnetic components or DC-link electrolytic capacitors. Thus they result in increasing of losses, installation area and converter cost.

This paper investigates the multi-stage converter that includes three parts: voltage source converter (VSC), HF transformer and novel AC/AC converter. The proposed AC/AC converter can generate staircase output voltage from square input voltage. The main purpose of this paper is reduction of the stage and components of the multi-stage converters. Simulations results carried out by MATLAB/SIMULINK, verify the operation of suggested topology.

2. PROPOSED MULTI-STAGE DC/AC CONVERTER

The main purpose of proposed converter is reduction of the components and power delivery stage (AC/DC and DC/AC links) in multi-stage DC/AC converter. The reliability of a system is indirectly proportional to the number of its components. Semiconductor switches and transformers are main components in multi-stage DC/AC converters. Power frequency transformers (50 and 60Hz) are heavy and bulky items in power conversion. Transformer size is inversely proportional to the frequency of operation and saturation flux density. Hence a reduction in volume and weight can be obtained by high frequency operation of the magnetic core [1-4]. The proposed converter utilizes power electronic converters along with a HF transformer to obtain overall size and cost advantages over a conventional transformer. Voltage transformation and isolation between source and load is obtained by HF transformer. In comparison with multi-stage isolated type converter based on H-bridge multilevel converter, in proposed converter power delivery stages and power electronic converters have been reduced and AC/AC converter is replaced by two multilevel converters (rectifier and inverter). The novel AC/AC converter consists of n voltage sources and 3n bidirectional switches.

The block diagram of the proposed multi-stage converter is shown in Figure 2. As can be seen from the Figure 2, this is a three-stage design that includes an input stage, an isolation stage and an output stage. The input DC voltage is first converted into a high frequency voltage by the primary side of VSC, and then, magnetically coupled to the secondary. In the secondary side, the high frequency voltage is revealed as a power-frequency voltage. Figure 3 shows circuit diagram of proposed multi-stage converter. The architecture proposed in this paper includes a VSC, the high (or medium) frequency transformer and output m-level novel AC/AC converter.

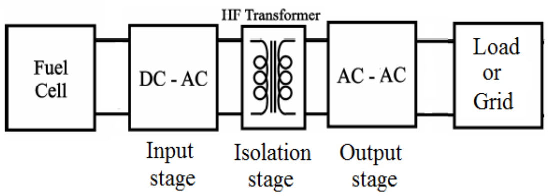


Figure 2. Block diagram of the proposed converter.

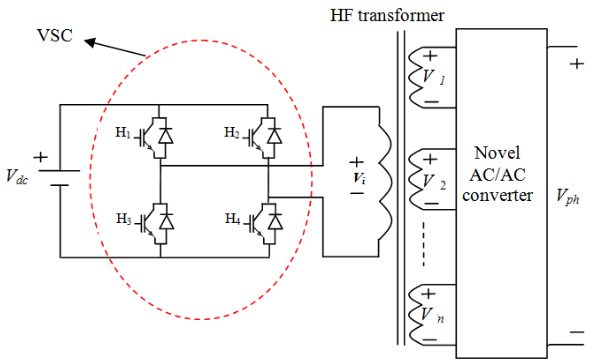


Figure 3. Circuit diagram of proposed multi-stage DC/AC converter.

In the input stage, there is a single-phase high frequency VSC, which converts the input DC voltage to AC square voltage with high (or medium) frequency. Circuit diagram of VSC is the same as H-bridge cell. The principle of modulation is based on a comparison of a sinusoidal reference waveform with zero carrier waveform. The principle of switching H-bridge is described with conditions bellow:

Condition 1: if sin wave ≥ 0, then H_1 and H_4 are turned on.

Condition 2: if sin wave < 0, then H_2 and H_3 are turned on.

If sine reference wave has a frequency f_r and an amplitude A_r then output voltage of VSC has a frequency f_r.

The main functions of the isolation stage are such as: voltage transformation and isolation between source and load. Isolation stage is provided by multi winding HF transformer. By neglecting the losses of HF transformer, the isolation stage can be treated as a proportional amplifier. The simplified model of the isolation stage is presented as:

$$V_k = \frac{N_k}{N_i} V_i \qquad k = 1,2,\ldots,n \tag{1}$$

V_i, V_k are the primary and secondary voltage in HF transformer respectively and N points to turn ratio. Various square voltage sources can be generated using multi winding HF transformer. These voltage sources can be used in output stage.

Figure 4 shows a one unit of novel topology for square to sinusoidal voltage converter with two square voltage sources per phase. The common emitter anti-parallel IGBT with diode pair arrangement has been used in this topology. This bidirectional switch arrangement consists of two diodes and two IGBTs and has capability of blocking voltage and conducting current in both directions. The basic unit shown in Figure 4 can be cascaded as shown in Figure 5.The proposed converter generates desired output voltage with suitable shape and frequency. Operation of proposed converter is the same as multilevel inverter but here voltage sources have two polarities. Multilevel AC/AC converter can be considered as voltage synthesizers, in which the output voltage is synthesized from many discrete smaller voltage levels.

In comparison with the multi-stage converter that uses of cascaded H-bridge multilevel converters, the proposed converter needs a few numbers of components. The cascaded H-bridge multilevel inverter in traditional multi-stage converter needs some independent DC-link voltage. The DC-links are provided by the cascaded H-bridge multilevel or separate rectifier and complex control circuit is needed to regulate voltage of DC-links. There are not DC-links in the proposed converter and converter dose not need complex control circuit. In other hands, converters control is simple.

The proposed converter needs fewer switches and components for realizing m voltage level for output voltage. Each switch in the converters requires an isolated driver circuit. The isolation can be provided using either pulse transformers or opto-isolators. Reduction of switches reduces number of gate drive circuit. Finally reduction of components reduces the installation area and cost of the recommended converter.

The proposed converter can operate in symmetric and asymmetric states.

If all square voltage sources in Figure 3 are the same (V_1= V_2=... =V_n=V_{ref}), then the converter is known as symmetric multilevel converter.

The maximum number of levels of phase voltage is given by:

$$m = 2n + 1 \tag{2}$$

n, m are the number of AC voltage source and the maximum number of levels of phase voltage, respectively.

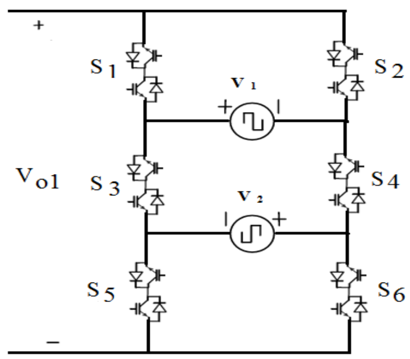


Figure 4. Proposed basic unit of multilevel AC/AC converter.

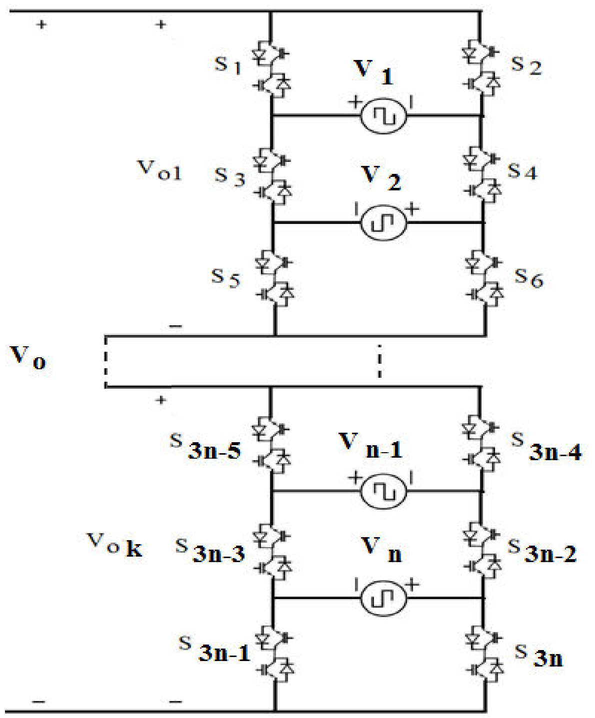


Figure 5. Proposed multilevel AC/AC converter.

Since the square voltage sources are different, this multilevel inverter can be known as an asymmetric multilevel converter. To obtain uniform step in the asymmetric state, the voltage sources in the proposed multilevel AC/AC converter are chosen according to the following equations:

$$V_1 = V_{ref} \;\&\; V_2 = 2V_{ref} \quad (3)$$

$$V_j = 2V_{(j-2)} \quad \text{for } j=3,4,....,n \quad (4)$$

The number of maximum output voltage levels can be determined by the following equation:

$$m = 7^{n/2} \qquad n \text{ is even} \quad (5)$$

3. SIMULATION RESULTS

A detailed system as shown in Figure 6 has been modeled by MATLAB/SIMULINK to study the operation of suggested multi-stage converter. Figure 6 shows 7-level multi-stage with two square voltage sources. The system parameters are listed in Table 1.

Table 1. The system parameters.

Parameter	Value
DC Source voltage	700V
Nominal frequency	50Hz
Transformer frequency	1000Hz
Load power	200 kW+j150 kVar

In this paper, switching algorithm is multi-carrier PWM. At each instant, sin wave is compared with carriers signal then 7 pulses are produced. Look-up table of switching is created then using the look-up table, switching pulses are used to toggling switches. The main point of switching is this point that with changing of polarity in input sources, on switches are turned off and other switches in arms are turned on. For example in zero state in positive polarity, switches with odd number are turned on and in negative polarity switches with even number are turned on.

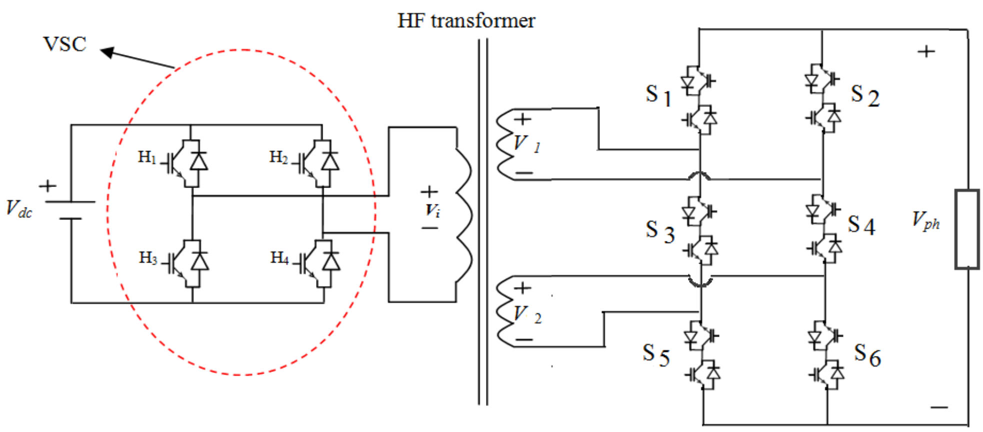
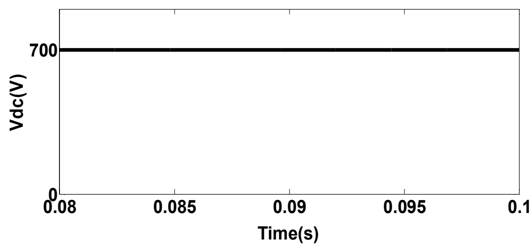


Figure 6. Proposed 7-level multi-stage converter.

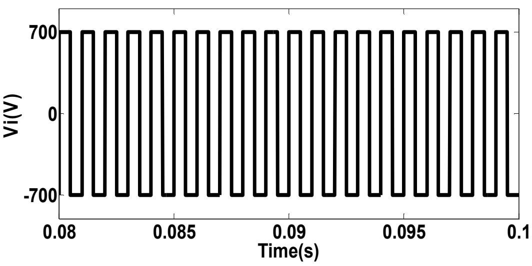
In the first, it is assumed that AC/AC converter is asymmetric. The turn ratio of HF transformer is 1:2 and 1:4. The magnitude of voltage sources is considered as 1400 V and 2800 V. Table 3 shows the ON switches look-up table of the proposed AC/AC converter. In the Table 2, V_i is the primary side voltage in HF transformer and state 1 indicates the switch is on and state 0 indicates it is off. The results of the most important simulations in asymmetric state are described in Figure 7. As it can be seen in Figure 7(a), the output DC voltage (the output fuel cell) is 700 V. Figure 7(b) depicts the output voltage of VSC that transforms input DC voltage to high frequency AC voltage as the transformer primary voltage. The level of high frequency AC voltage in secondary side is changed by HF transformer in Figure 7(c). In the output stage, the high frequency voltage is revealed into a 50 HZ waveform by AC/AC converter as shown in Figure 7(d). Output voltage waveform is shown in Figure 7(d) that is a typical staircase seven level waveform. Figure 7(e) shows FFT analysis output phase voltage, total harmonic distortion (THD) is 12.23%.

Table 2. Look-up table of a single-phase 7-level converter.

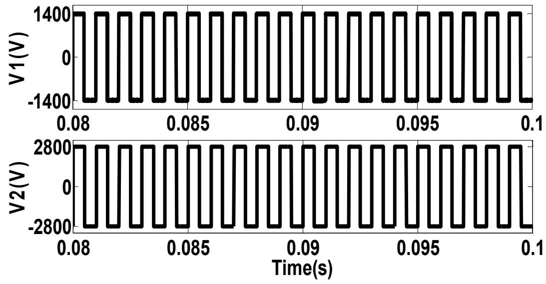
Switches												
	$V_i \geq 0$						$V_i < 0$					
Output voltage(V)	S_1	S_2	S_3	S_4	S_5	S_6	S_1	S_2	S_3	S_4	S_5	S_6
4200	1	0	0	1	1	0	0	1	1	0	0	1
2800	0	1	0	1	1	0	1	0	1	0	0	1
1400	1	0	0	1	0	1	0	1	1	0	1	0
0	1	0	1	0	1	0	0	1	0	1	0	1
- 1400	0	1	1	0	1	0	1	0	0	1	0	1
-2800	1	0	1	0	0	1	0	1	0	1	1	0
-4200	0	1	1	0	0	1	1	0	0	1	1	0



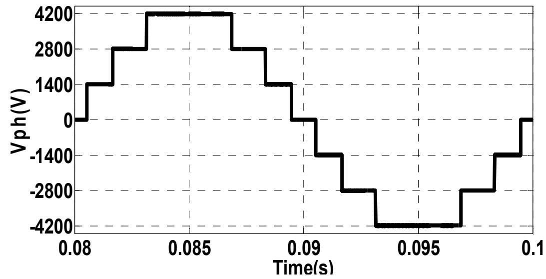
(a)



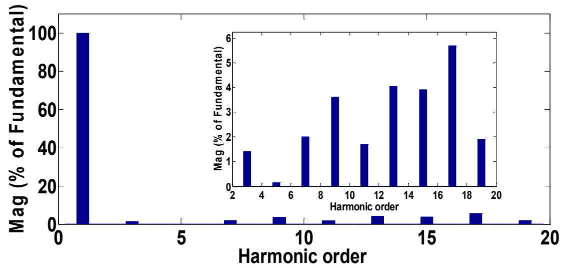
(b)



(c)



(d)



(e)

Figure 7. (a) DC supply voltage, (b) the HF transformer primary voltage (c) the HF transformer secondary voltage (d) output phase voltage and (e) Output phase voltage FFT analysis.

CONCLUSION

A multi-stage converter based on high frequency transformer and novel AC/AC converter has been proposed in this paper. The proposed circuit configuration can be used as a DC/AC converter in DG system. Electrical galvanic isolation and voltage transform have been obtained by HF transformer. Novel multilevel AC/AC converter produces desired output voltage. The stages have been reduced in the proposed converter and there is not any DC-link in the proposed converter. These lead to reduction of installation area and cost and have simplicity of control system.

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