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A THREE-PHASE CURRENT SOURCE INVERTER WITH HIGH POWER FACTOR FOR GRID-CONNECTED RENEWABLE POWER SOURCES

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Abstract: *This paper presents a new type of current-source inverters suitable for application in grid-connected renewable power sources. It is based on three-phase six-pulse inverter topology with unidirectional switches using line-synchronous control to achieve unity displacement factor and an additional power circuit which implements the third-harmonic current injection in order to improve the total harmonic distortion. Experimental results on a 1.5 kW prototype with the optimal third harmonic current injection are shown; they confirm predictions of total harmonic distortion and power factor improvement.*

Key Words: ***Renewable power sources, distributed power generation, six-pulse inverter, third-harmonic injection principle, optimized third-harmonic injection.***

1. INTRODUCTION

For the last 25 years, there has been an increasing demand for renewable power sources, from low to very high power [1]. This complies with different global energy and environmental policies which actively propagate the idea of lowering emission of greenhouse gases and preventing the energy collapse due to the exhaust of fossil fuels. Main source of renewable energy is wind-power, and according to projections it will stay at that position for the next 20 to 30 years. Conversion of the solar energy into electrical is a viable option, but the technology is not mature and commercially acceptable yet, and it is projected to become a significant source not before the next 30 to 40 years.

Lately, the number of installed small- and medium-size power generation utilities grows rapidly, increasing the demand for power electronics used as a grid interface. Old fashioned technology, which operates without power electronics, does not meet requirements, despite its simplicity. Main drawback of these solutions is a lack of support for wide operating range of the generator, which leads to poor utilization of the facility. Using power electronics systems to interface to the grid significantly improves controllability and, consequently, improves efficiency in a great extent. One of the new and very stringent requirements for grid-interfacing devices is to keep the line current undistorted or with minimum distortion level, generally below few percent according to standards. Many new topologies were proposed since the old ones could not satisfy the requests, and making the right choice has become everything but simple [2-5].

The interface converters must provide service regardless the generator operating conditions (high or low wind speed, insolation, etc.). This request is a limiting factor when choosing a suitable power converter topology. A widely used option is to apply a diode bridge rectifier over electrical generator to provide a DC source of energy, which is then transferred to the grid through a single- or two-step power converter. This converter is usually implemented with PWM control, influencing efficiency and reliability of the system.

This paper presents a new type of grid-connected inverter which is realized as three-phase current source inverter supplemented with the third harmonic current injection system [6, 7]. It is an extending application of the third-harmonic current-injection principle which is by now implemented only in rectifiers [6, 7]. It will be shown that the same principle can be used for the inverting mode of operation, and that it is suitable for application in renewable energy sources.

2. THE THIRD HARMONIC CURRENT INJECTION PRINCIPLE

It is reported in literature that using the third harmonic current injection technique in rectifier circuits can significantly improve their input current harmonic distortion [6-8]. Also, most of the work is done in defining all of the necessary circuits to upgrade the standard rectifiers without changing the already installed structure. However, it was oriented to power consumption only, leaving the field of power generation (inverter mode of operation) neglected.

Modification of the original circuit is basically made in order to enable reversing the direction of the energy flow. The original current-sink which modeled the load was transformed into a current source. The same applies for all current sources and current directions in the original circuit [7, 8]. In that way, the inverter oriented version of the original circuit is achieved, and it is presented in Fig. 1.

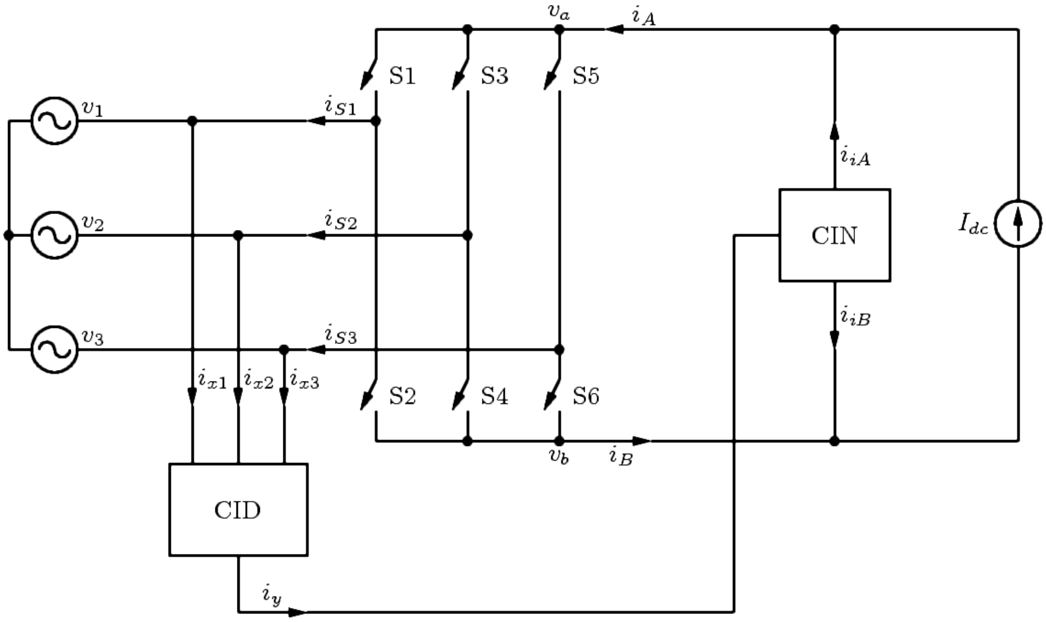

Fig 1: Basic circuit for inverter with third-harmonic injection

Segment	$d_1(\omega_0 t)$	$d_2(\omega_0 t)$	$d_3(\omega_0 t)$	$d_4(\omega_0 t)$	$d_5(\omega_0 t)$	$d_6(\omega_0 t)$
$0 < \omega_0 t < 60°$	1	0	0	0	0	1
$60° < \omega_0 t < 120°$	0	0	1	0	0	1
$120° < \omega_0 t < 180°$	0	1	1	0	0	0
$180° < \omega_0 t < 240°$	0	1	0	0	1	0
$240° < \omega_0 t < 300°$	0	0	0	1	1	0
$300° < \omega_0 t < 360°$	1	0	0	1	0	0

Table 1: switching functions for main inverter switches

In Fig.1, there are four different subcircuits: current source I_{dc} represents the energy source which is basically some type of converter connected to the generator at the input, supplied with the output current control. Current injection network (CIN) generates programmable currents i_{iA} and i_{iB}, while current injection device (CID) provides the exact splitting of the current i_y into three identical parts - currents i_{x1}, i_{x2} and i_{x3}. The last subcircuit is the main inverter (grid-interface converter) which is composed of six unidirectional controlled switches S_1-S_6. According to the third harmonic current injection principle [6, 7], it is necessary to provide a synchronized control between the main inverter and the injection network to achieve the exact superposition of circulating third harmonic currents and useful portion of phase currents.

In order to control the main inverter, switching functions must be derived. The phase voltages are assumed as

$$\begin{aligned} v_1 &= V_m \cos(\omega_o t) \\ v_2 &= V_m \cos\left(\omega_o t - \frac{2\pi}{3}\right) \\ v_3 &= V_m \cos\left(\omega_o t + \frac{2\pi}{3}\right). \end{aligned} \tag{1}$$

Since the basic idea is to force the interface converter to operate in recuperation mode with maximal utilization, the same switching function as in the case of the diode rectifier should be used. These functions are given in Table 1, and they coincide with the diode-bridge rectifier switching functions. In such a way, unity displacement power factor can be achieved, which is important if generation of reactive power is not a demand. Thus, to satisfy the power factor requirements the only thing left to do is to control harmonic distortion of the line currents. As shown in [4, 5], by properly driven controlled current sources in the injection network it is possible to lower the distortion level significantly. To achieve this, the current sources should be controlled to implement

$$i_{iA}(\omega_o t) = i_{iB}(\omega_o t) = I_{mi}\cos(3\omega_o t) \tag{2}$$

The line currents can be expressed as

$$\begin{aligned} i_1(\omega_o t) &= d_1(\omega_o t) i_A(\omega_o t) - d_2(\omega_o t) i_B(\omega_o t) - i_{x1}(\omega_o t) \\ i_2(\omega_o t) &= d_3(\omega_o t) i_A(\omega_o t) - d_4(\omega_o t) i_B(\omega_o t) - i_{x2}(\omega_o t) \\ i_3(\omega_o t) &= d_5(\omega_o t) i_A(\omega_o t) - d_6(\omega_o t) i_B(\omega_o t) - i_{x3}(\omega_o t) \end{aligned} \tag{3}$$

and using inherent feature of the current injection device to split neutral point current i_y into three equal phase currents

$$i_{x1}(\omega_o t) = i_{x2}(\omega_o t) = i_{x3}(\omega_o t) = i_x(\omega_o t) = \frac{1}{3} i_y(\omega_o t) \tag{4}$$

the complete set of equations which describes the circuit is

$$\begin{aligned} i_A(\omega_o t) &= I_{dc} + i_{iA}(\omega_o t) \\ i_B(\omega_o t) &= I_{dc} - i_{iA}(\omega_o t) \\ i_{x1}(\omega_o t) &= i_{x2}(\omega_o t) = i3(\omega_o t) = i_x(\omega_o t) = \frac{2}{3} i_{iA}(\omega_o t) \\ i_{iA}(\omega_o t) &= i_{iB}(\omega_o t) = I_{mi}\cos(3\omega_o t) \end{aligned} \tag{5}$$

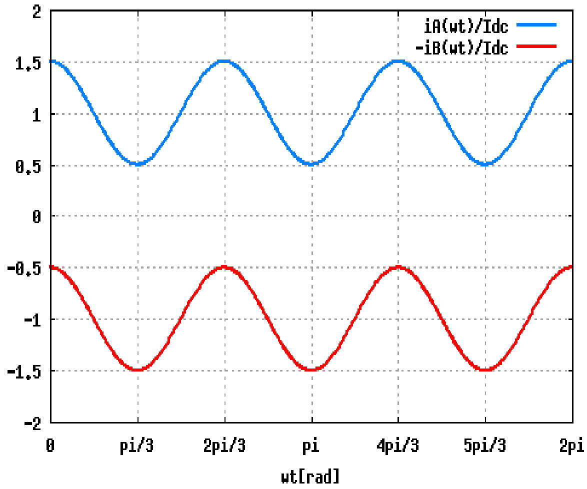

Fig 2: waveform diagrams of DC link currents: upper trace – i_A, lower trace - i_B

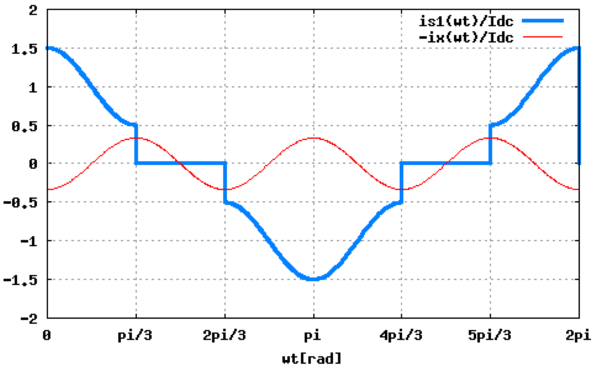

Fig 3: waveform diagrams of inverter terminal current i_{s1} (thick blue trace) and inversed corresponding CID current i_x (thin red trace)

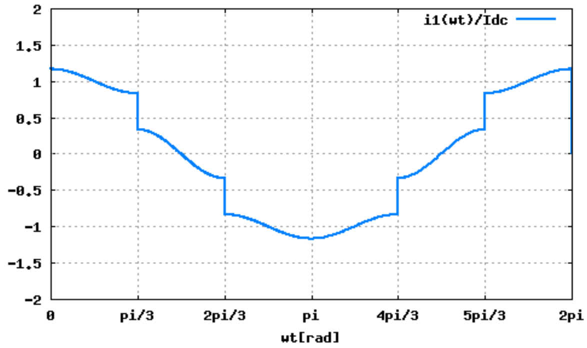

Fig 4: waveform diagram of line current i_1

In order to illustrate the principle, an example of typical currents is shown in Figs 2, 3, and 4. As it can be seen, the input current waveform is improved regarding the harmonic content compared to the case without the compensation.

3. OPTIMIZATION

After the system structure is chosen, a goal is to optimize the injected current amplitude I_{mi} for a given input current I_{dc} to minimize the output current THD. The output current RMS value is obtained as

$$I_{RMS}(I_{dc},I_{mi}) = \frac{\sqrt{6I_{dc}^2+I_{mi}^2}}{3} \tag{6}$$

while its fundamental harmonic amplitude is

$$I_{1,RMS}(I_{dc},I_{mi}) = \frac{2}{\pi}\sqrt{\frac{3}{2}}I_{dc} + \frac{1}{4\pi}\sqrt{\frac{3}{2}}I_{mi} \tag{7}$$

Using the standard definition for the THD, it is minimized for

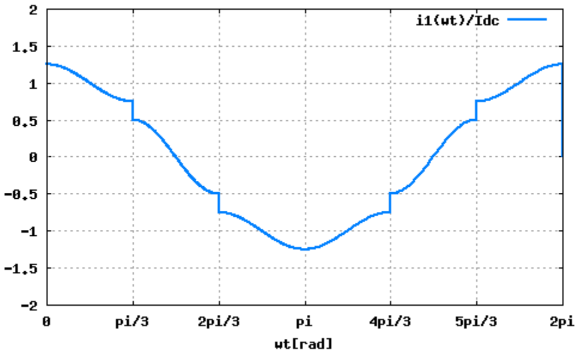

Fig 5: Line current waveform for optimal third-harmonic

$$I_{mi,opt} = \frac{3}{4}I_{dc} \tag{8}$$

resulting in $THD_{i,min}$=5,125%. In that case, the line current waveform is shown in Fig. 5.

4. EXPERIMENTAL RESULTS

In order to verify the new type of current inverter, an experimental circuit is built and tested. The circuit is shown in Fig. 6. The DC power source V_{dc} of 400 V is an intermediate DC link and it supplies all of the equipment. The buck converter that follows acts as a current source I_{dc} which is achieved by controlling the current of L_1. Current mode control is achieved using a hysteretic current controller.

Two modifications of the original topology are implemented:

- current injection network (CIN) is modified in such a way that instead of using two different current sources i_{iA} and i_{iB}, there is just one current source i_y and the current sharing device T_{CIN} which provides equal currents i_{iA} and i_{iB}
- current source i_y is built using current controlled half-bridge inverter, which is supplied by the intermediate DC link; it is the current of the inductor L_2 that is controlled; the transformer T_{HB} acts as a current transformer resulting in the waveshape of i_y that is controlled.

It is important to compare the line currents with and without the third harmonic injection. Fig. 7 shows the line voltage and current waveforms and RMS values at phase 1 in the case the current injection is inactive.

In Fig. 8, three phase currents are shown when the current injection circuit is active. Harmonic distortions are also shown, and it is obvious that there is a significant improvement in the current harmonic content, since the THD is decreased to about 7%. There is a small discrepancy between the theoretical and the experimental results, and there are two reasons for that: the reference value for current i_y is not a pure sinewave (it is slightly distorted with THD=3.5%); also, the currents i_y and I_{dc} have high switching ripple which passes through, into the line conductor. Therefore, slightly higher THD is obtained. These effects can be seen in Figs. 7-9. In Fig. 7, only a portion of I_{dc} current is presented, and it can be seen that the high frequency ripple is small. However, in Figs. 8 and 9, the line currents are rich with

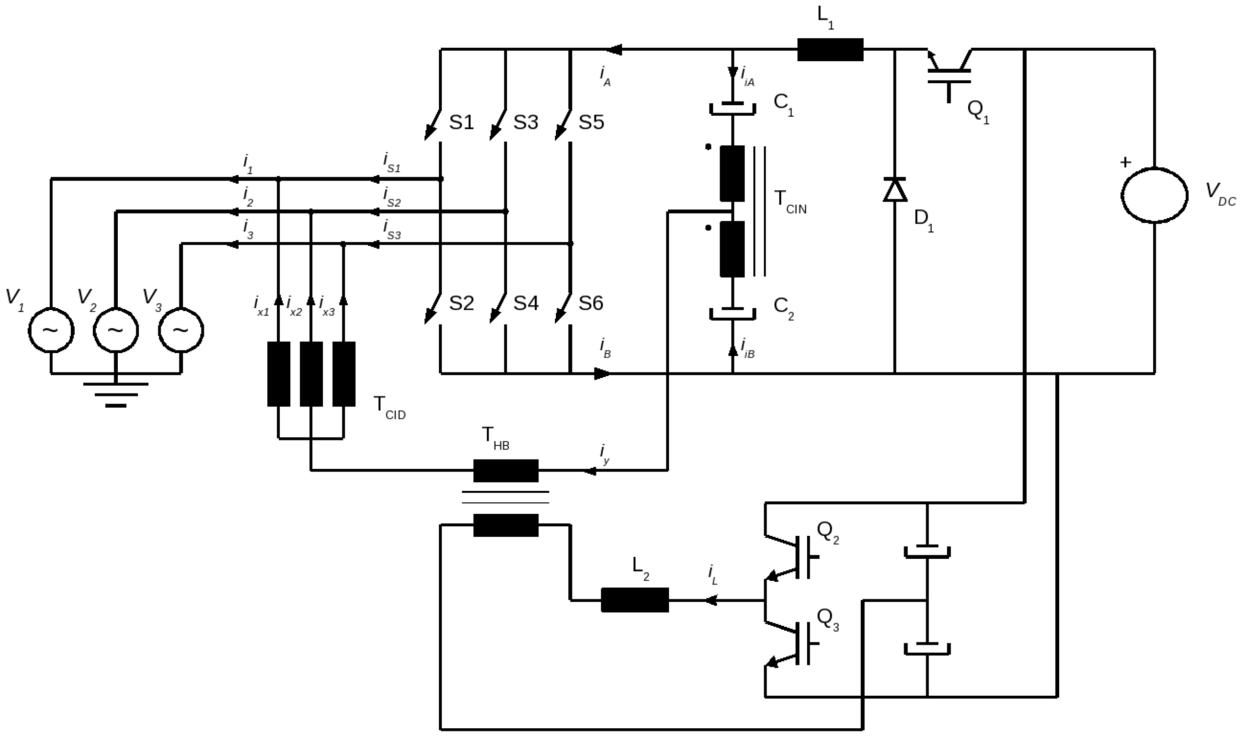

Fig 6: complete experimental circuit

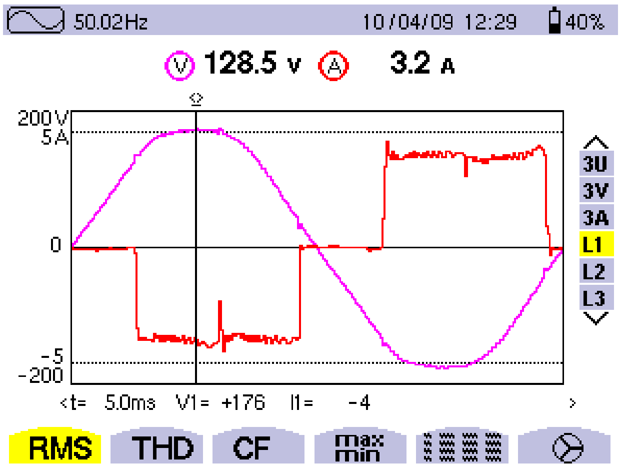

Fig 7. Phase a voltage and current waveforms and THD factors while injection network is disabled

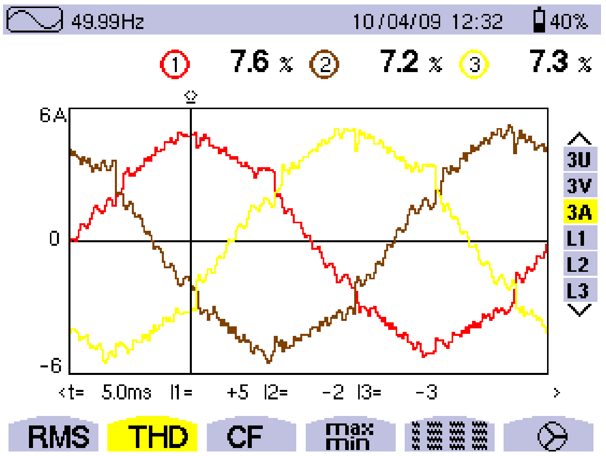

Fig 8: Line currents waveforms and THD factors when the injection network is active

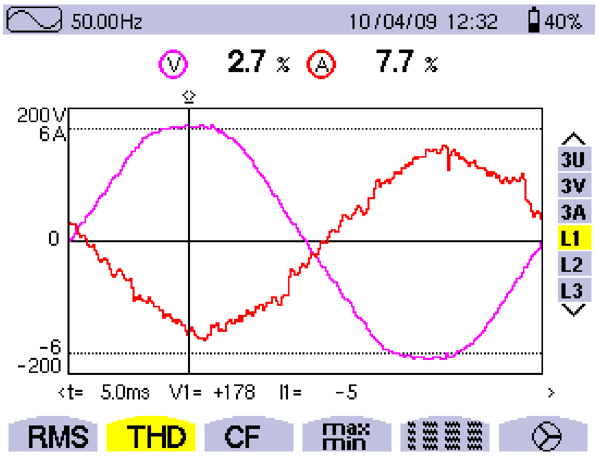

Fig 9. Phase a voltage and current waveforms and THD factors while injection network is active

the high frequency ripple, due to the poor filtering. It is possible to filter out the high frequency content using additional filtering elements in the buck and the half-bridge converters, but this requires more complex power and control circuitry. Nevertheless, despite somewhat higher THD, the principle is verified in practice

5. POWER BALANCE

Another topic of interest is to track the power as it flows from the source to the line, in order to analyze the converter efficiency. It is possible to separate two paths: the power delivered to the line can go through the main inverter and through the current injection device. Similarly, the power taken from the source can be transferred by the buck converter or by the half bridge inverter.

Since the currents through the current injection device contain only the third harmonic, there is no power transfer to the line, because the line voltage does not contain significant harmonic components except the fundamental component. Thus, all the power is transferred through the main inverter.

Regarding the power generation, the current source I_{dc} represents one path of the power transfer from the source. The power transfered here is

$$P_{DC} = V_{OUT,AVG} \cdot I_{dc} = \frac{3\sqrt{3}}{\pi} V_m I_{dc} \tag{9}$$

The second source of power, the current injection network, provides power from the DC link

$$P_{HB} = V_{THB,SEK(3h)} \cdot I_y = \frac{9\sqrt{3}}{32\pi} V_m I_{dc} \tag{10}$$

where $V_{THB,SEK(3h)}$ is RMS value of 3rd harmonic voltage component at secondary terminals of T_{HB} and $I_{THB,SEK}$ is the RMS value of i_y.

Finally, the power taken from the voltage source is

$$P_g = P_{out} = \frac{3\sqrt{3}}{\pi}(1 + \frac{3}{32}) V_m I_{dc} \tag{11}$$

which means that the buck converter transfers 91.43% and that the half-bridge inverter processes 8.57% of total power.

It is interesting to compare the theoretical results to the experiment. In the case the injection circuit is not active (Fig. 7), it can be concluded that the amplitude of the phase voltage V_m is equal to 181 V and that the I_{dc} value is approximately 4 A. Thus, calculation using (9) shows that the buck converter output power is 1197 W. Measurement shows that DC voltage at the input terminals of the main inverter is equal to 298 V, meaning that the power transferred from buck is equal to 1192 W.

Measurement of output active power transferred to the line has shown the amount of 1163 W, meaning that losses in the main inverter are 29 W, which corresponds to 3.6 V voltage drop on the series connection of the IGBT transistor and the diode forming each switch. At the same time, the power taken from the DC source and given to the buck converter is 1260 W, having 68 W of losses in the buck converter, corresponding to 94.6% efficiency of the buck converter. Total efficiency at 1260 W of the input power and 1163 W of the output power is 92.3%.

In the case the injection system is active, increase in power is 112 W, meaning that expected output power is 1275 W. Measurement shows that the output power is now equal to 1274 W. The buck converter provides 91.3% of the power while the injection circuit brings another 8.7% of the output power. These numbers are very close to theoretical values of 91.43% and 8.57%. The power taken from the DC source is 1511 W. Since the raise in the input power is directed only to the half-bridge inverter, the increase of the input power of 251 W and the output power of 113 W results in the injection circuit efficiency of only 45%. Thorough analysis has shown that resistive losses in the injection circuit are 23 W and that dissipation in the switching circuit is about 115 W. This is caused by the high switching frequency of 20 kHz applied to reduce the current ripple. In the case the switching losses are decreased, it would be possible to increase the overall efficiency of the system to about 88.5%.

6. CONCLUSION

This paper presented a new inverter suitable for application in renewable power sources. It is built using six unidirectional switches and the third harmonic injection circuit. It is shown that it is possible to improve the harmonic content of line currents and to achieve very low total harmonic distortion. Experiments have shown that it is easy to reach THD of 7%, possibly reduced to the theoretical minimum of 5,125%. High level of agreement between theory and experiments is obtained.

It is also shown that all of the power is transferred to the line through the main inverter. Large part of the power is supplied by the buck converter, while only 9% of the power is provided by the half-bridge inverter.

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