Comparison of single-phase matrix converter and H-bridge converter for radio frequency induction heating

N. Nguyen-Quang, D.A. Stone, C.M. Bingham, M.P. Foster
SHEFFIELD UNIVERSITY
Department of Electronic and Electrical Engineering
Mappin Street, Sheffield S1 3JD, England
E-Mail: n.nguyen-quang@sheffield.ac.uk, d.a.stone@sheffield.ac.uk,
c.bingham@sheffield.ac.uk, m.p.foster@sheffield.ac.uk

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«High frequency power converter», «Matrix converter», «Induction heating», «Resonant converter».

Abstract

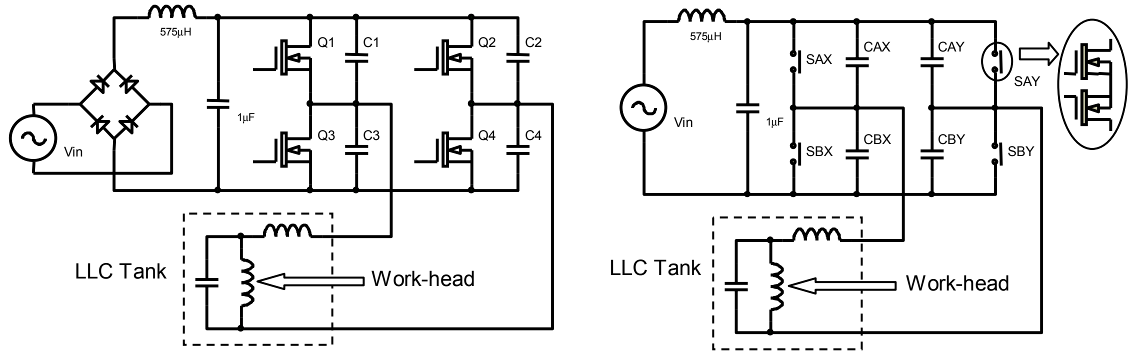
This paper compares the newly developed single-phase matrix converter and the more conventional H-bridge converter for radio frequency induction heating. Both the converters exhibit unity power factor, very low total harmonic distortion at the utility supply interface, good controllability under soft switching condition for a wide range of power, and high efficiencies, whilst still having simple structures. A novel switching control pattern has been proposed for the matrix converter in order to maintain the comparable performance to the H-bridge converter. Simulation and experimental results for both converters are presented. Comparisons between two converters have confirmed the excellent performance of the proposed matrix converter.

Introduction

Radio frequency (R.F.) induction heating requires a high frequency AC power supply, typically 100-200 kHz. However, the conventional AC-DC-AC converter topology makes use of large energy storage components, and requires complicated control algorithms to provide a unity power factor sinusoidal input current [1], [2]. Other systems [3]-[6] usually assume that a DC power supply is available, requiring power quality improvements for interfacing to the utility supply, as reviewed in [7], [8]. There have been attempts in improving the power factor and input current waveform of the AC-AC converter for induction heating, as reported in [9]-[11], where the voltage drop across the switch at turn off may be much higher than the input voltage, which in turn, may limit the system to low frequency applications due to the difficulty of making high-speed, high-voltage devices. In addition, frequency modulation used for power control may cause some EMC problems at high operating frequencies. The single-phase H-bridge converter developed in [11], however, has successfully operated at unity power factor and with a nearly sinusoidal input current. Recently, an alternative for that single-phase H-bridge, in the form of a single-phase matrix converter, has been introduced [12], claiming to have the same features as those of the H-bridge.

This paper compares the H-bridge converter and the single-phase matrix converter (Fig. 1), in order to verify the performance of the novel matrix converter. Both the converters use the method of pulse-width modulation to control the output power, however, a new switching control pattern is required for the matrix converter, due to the absence of a DC link. The new switching algorithm and the operating principle of the matrix converter will therefore be explained in the following section, before comparing the performance of the two converters.

In the next sections, comparisons in topology, input current harmonics, power factor, and controllability are presented, together with test data from prototype converters. Lastly, practical efficiencies of both the converters will be presented.

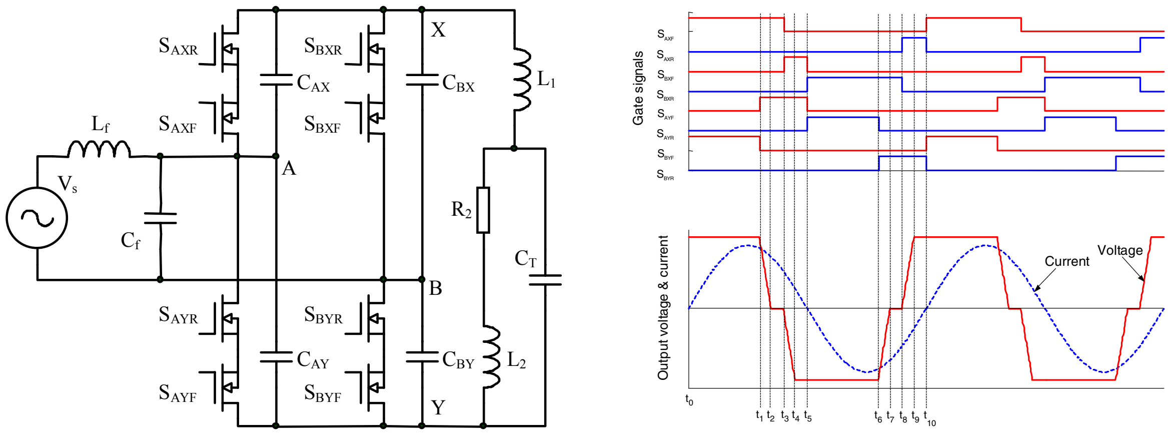


H-bridge converter induction heating system　　Matrix converter induction heating system

Fig. 1: High power factor single-phase converters for induction heating

Proposed matrix converter and principle of operation

With the help of a more detailed schematic and key operation waveforms, Fig. 2, the operation of the proposed single-phase matrix converter can now be described. Because the system operates closely to the resonant frequency of the load, the load can be considered as a current sink, simplifying the explanation of the operating principle.



Single-phase matrix converter　　Operation waveforms

Fig. 2: Proposed single-phase matrix converter and its key operation waveforms

The AC input is fed to the converter through a small line filter, comprising of inductor L_f and capacitor C_f. The converter is a 2x2 matrix converter, in which each bidirectional switch is implemented using two MOSFETs connected in common source configuration, utilising the built-in diode of the device. Across each bidirectional switch is a commutating capacitor. Capacitors C_{AX} and C_{BX} have the same value and are associated with the load-commutated (LC) row. Similarly, C_{AY} and C_{BY} belong to the pulse-width-modulation (PWM) row. The load is an LLC resonant circuit, where L_1 is the series inductor for matching the parallel resonant tank, consisting of work-head inductance L_2, reflected load resistance R_2 and tank capacitor C_T, with the high frequency voltage source.

Because of the presence of the series inductor L_1, a simple explanation of the operating principle can be made by assuming that the load acts as a sinusoidal current sink, and that the devices are ideal. Starting with the load current (output current of the matrix converter) crossing zero and entering its positive half-cycle, the converter will go through the following modes of operation in the positive half-cycle of the input voltage ($V_{AB} > 0$), Fig. 3. The number in a circle on each schematic represents the corresponding operating mode of the converter, and mode 1 is repeated after mode 10 for the sake of convenience.

Mode 1 [t_0, t_1]: Before this mode, $t < t_0$, switches S_{AXR} and S_{BYR} are on, creating a path for the load current in its negative half-cycle, and making zero voltage drop on C_{AX} and C_{BY}. The voltage on C_{AY} and C_{BX} will be the instantaneous input voltage V_{AB}. At $t = t_0$, both S_{AXR} and S_{BYR} are turned off, and switches S_{AXF} and S_{BYF} are turned on under zero-current and zero-voltage condition. As the current is flowing in the diodes associated with devices, the output voltage equals the input voltage V_{AB}.

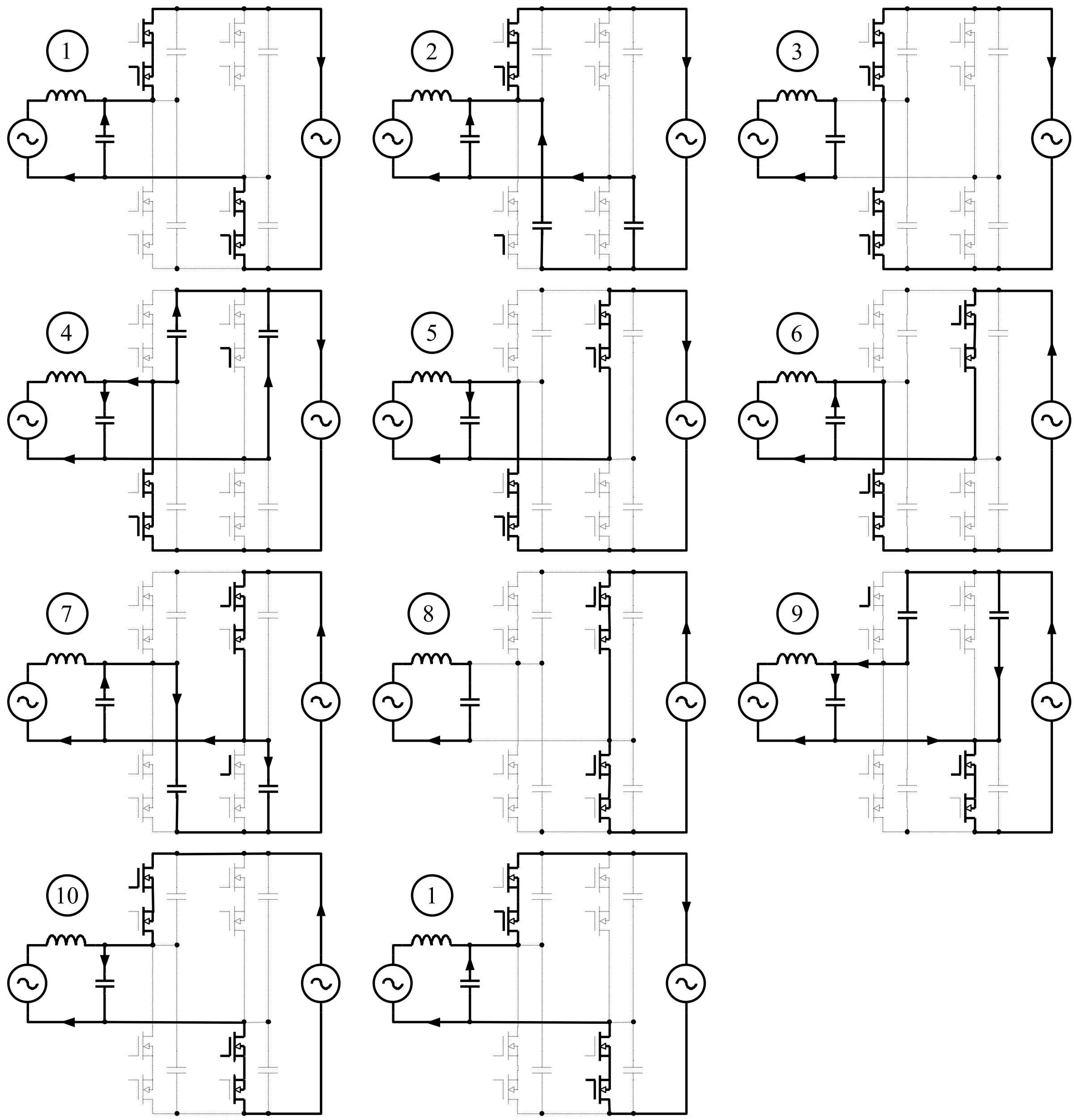


Fig. 3: Operation modes of the proposed single-phase matrix converter

Mode 2 [t_1, t_2]: At some time through the switching cycle, S_{BYF} is switched off, and its counterpart in the opposite phase leg, S_{AYF}, is turned on under zero-current condition, because the built-in diode of S_{AYR} has been reversed-biased by the positive voltage drop on C_{AY}. The load current will therefore charge up C_{BY} and discharge C_{AY}, making the output voltage decrease to zero at $t = t_2$.

Mode 3 [t_2, t_3]: When C_{AY} is fully discharged, the built-in diode of S_{AYR} is forward-biased, and the load current will circulate through S_{AXF} and S_{AYF}, making zero output voltage. This condition remains until the load current has almost reached zero, when S_{AXF} is turned off at $t = t_3$.

Mode 4 [t_3, t_4]: Similarly, S_{BXF} will be turned on at zero current when S_{AXF} is switched off, causing C_{AX} to charge up and C_{BX} to discharge. This will cause the output voltage to further decrease, giving a negative output voltage.

Mode 5 [t_4, t_5]: At $t = t_4$, when C_{BX} is fully discharged, the built-in diode of S_{BXR} is forward-biased, and the output current will circulate through S_{AYF} and S_{BXF}, making the output voltage clamped at $-V_{AB}$. Just before the current reverses, S_{AYF} and S_{BXF} are switched off.

Mode 6 [t_5, t_6]: At the same time S_{AYF} and S_{BXF} are turned off, at $t = t_5$, S_{AYR} and S_{BXR} are switched on under zero-voltage and zero-current condition. The output voltage equals $-V_{AB}$ and the current will circulate through S_{AYR} and S_{BXR}, starting the negative half-cycle.

Mode 7 [t_6, t_7]: Part way through the cycle, S_{AYR} is turned off and S_{BYR} is switched on, at $t = t_6$. The load current will then be carried by C_{AY} and C_{BY}, causing the output voltage to increase until it reaches zero, at which time the built-in diode of S_{BYF} becomes forward-biased.

Mode 8 [t_7, t_8]: This mode is similar to mode 3, when the load current circulates through S_{BXR} and S_{BYR}, giving zero output voltage. This condition remains until the output current is almost zero, when S_{BXR} switches off, at $t = t_8$.

Mode 9 [t_8, t_9]: At the same time S_{BXR} is turned off, S_{AXR} will be switched on under zero-current condition, causing C_{AX} to discharge and C_{BX} to charge up. This will cause the output voltage to further increase, giving a positive output voltage.

Mode 10 [t_9, t_{10}]: At $t = t_9$, when C_{AX} is fully discharged, the built-in diode of S_{AXR} is forward-biased, and the output current will circulate through S_{AXR} and S_{BYR}, making the output voltage clamp at V_{AB}. Just before the current reverses, S_{AXR} and S_{BYR} are switched off, and S_{AXF} and S_{BYF} are turned on under a zero-current and zero-voltage condition, starting a new output cycle.

For the negative half-cycle of input voltage, switches S_{AXF} and S_{BXF}, S_{AYF} and S_{BYF}, S_{AXR} and S_{BXR}, and S_{AYR} and S_{BYR} exchange their role, respectively.

As may be seen, in addition to zero-current switching on or zero-voltage zero-current switching on, all the switches are switched off under zero-voltage condition, with the support of commutating capacitors rapidly removing the current from the switches.

In line with conventional matrix converters, there are two basic commutation strategies, namely "voltage commutation", which requires the knowledge of the sign of input voltage, and "current commutation", which needs the knowledge of the sign of output current [13], [14]. These strategies can be made in four-steps or two-steps, requiring little dead time between the steps. The commutation strategy used in the proposed converter falls in the category of voltage commutation, using the sign of the input voltage to select an appropriate switching pattern. The commutation, however, does not need to ensure a path for the inductive load current, owing to the support of the commutating capacitors, and the single-step switching pattern is therefore proposed, as may be seen in Fig. 2.

The proposed voltage commutation strategy is very simple and can be implemented at no extra cost for additional snubbing components. It is also possible to find an optimal switching angle for the LC row that enables the power control over a wide range, under soft switching condition. The power is controlled by varying the switching angle of the PWM row with a fixed switching angle on the LC row, instead of varying the switching frequency. This helps reduce the EMC problems associated with the power control method of frequency modulation.

Topology comparison

As the structure is concerned, the matrix converter has a similar but somewhat simpler structure than that of the H-bridge, without the rectifier between the line filter and the utility power supply. A summary of component counts is given in Table I.

Table I: Component comparison among H-bridge converters and matrix converter

	Traditional H-bridge	Modified H-bridge [12]	Matrix converter
Switches	4 + various number	4	8
Diodes	4 (built-in) + various number	4 (1 bridge) + 4 (built-in)	8 (built-in)
Inductors	Various number	1 (small)	1 (small)
Capacitors	4 (small) + various number	5 (small)	5 (small)

In the modified H-bridge an unsmoothed DC link is accepted with a small LC filter after the rectifier, allowing a practically unity power factor sinusoidal current to be drawn from the supply. In the matrix converter, the rectifying action is done with a proper switching control pattern, which means the matrix converter and the modified H-bridge should appear very similar to the utility supply, due to the same line filter they utilise for interfacing to the supply. The traditional H-bridge, however, must use an active rectifier, which is also a switching system, in order to improve the power quality at the utility supply interface. Considering only unidirectional active rectifiers, up to two switches, two diodes and one inductor are required in addition to the bridge rectifier and the large DC-link LC filter network in some boost converter arrangements [7]. Other topologies, such as buck, buck-boost, or multilevel converters, can also be used [7], with up to two switches, two diodes and one capacitor are required as additional components in certain variations of multilevel converter. The traditional H-bridge would therefore require a more complicated algorithm for the two switching circuits within a complex structure, when comparing to the matrix converter and the modified H-bridge. Furthermore, the additional components would introduce some extra cost and power losses in the traditional H-bridge, hence lowering the efficiency of the system.

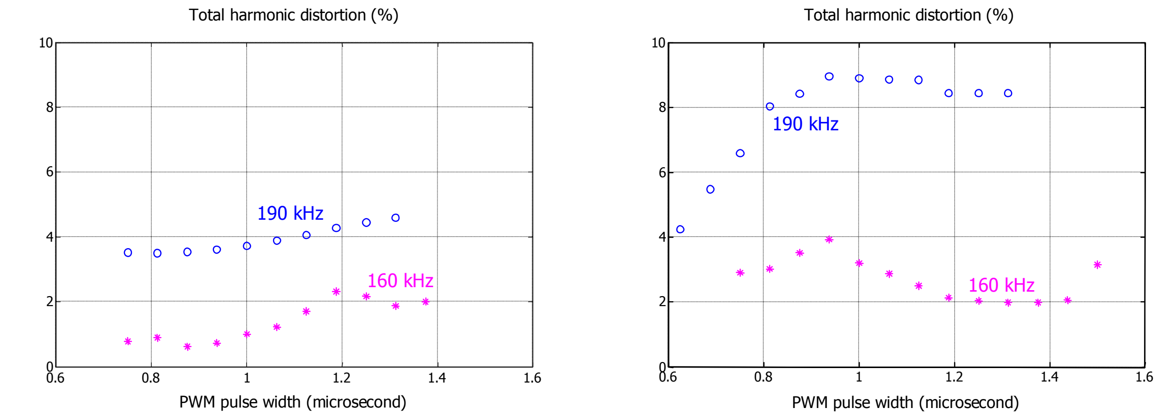
The modified H-bridge converter [12] features soft switching over a wide range of power control, which is done by varying the pulse width of one leg of the H-bridge, whilst fixing the pulse width of the other leg. The matrix converter can maintain that soft switching feature, but with a novel switching control pattern, as described in the previous section.

In steady-state intervals of an output cycle, namely power transferring, zero output voltage, and back power transferring (to the input capacitor), the matrix converter always needs two built-in diodes and two active switches carrying the current. On the other hand, the H-bridge only needs one built-in diode and one active switch to carry the current in the back power transferring phase, or two active switches in the zero output voltage phase. Therefore, the overall voltage loss in the H-bridge should be less than that of the matrix converter, despite the voltage loss on two diodes in the rectifier and two active switches in the power transferring phase.

The situation, however, can be improved for the matrix converter if devices with full reverse blocking capability are used, in which the matrix converter would only need two switches to carry the current for any steady-state interval.

Input current harmonics and power factor comparison

A water-cooled load, with a quality factor of 7 (the ratio between reactive power and active power of a loaded work-head), was used with both the converters, together with a power analyser (NORMA D6100), and a power supply (California Instruments 4500iL) for maintaining the same input voltage, when conducting the experiments.



H-bridge converter Matrix converter

Fig. 4: Total harmonic distortion of input current

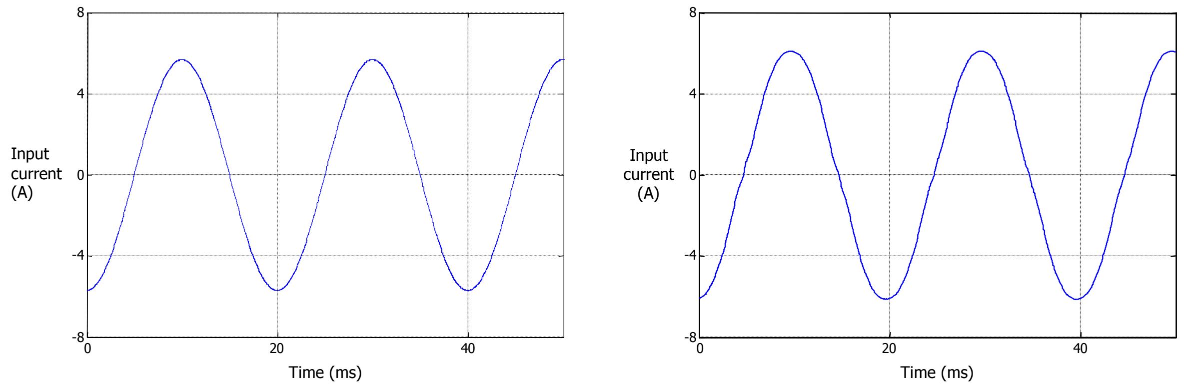
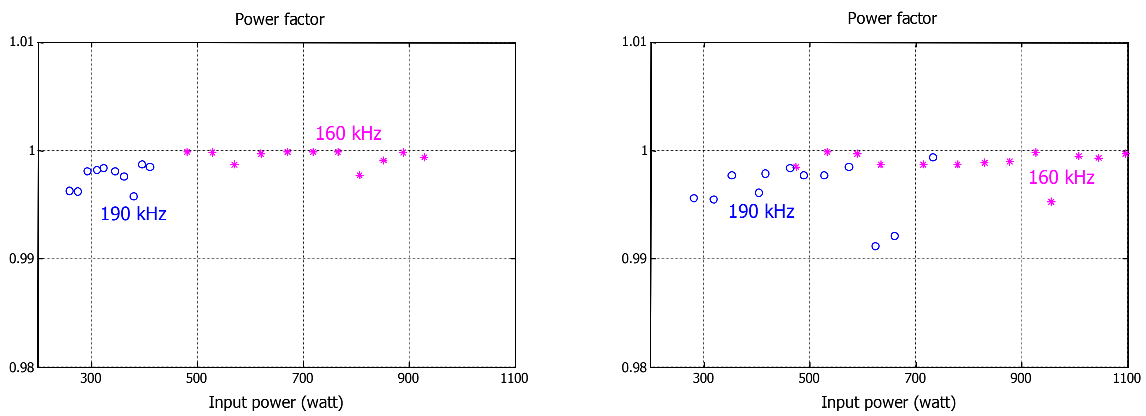


Fig. 5: Simulated (left) and experimental (right) input current of the matrix converter at the input power of 1 kW



H-bridge converter Matrix converter

Fig. 6: Power factor of the converters

Both the converters are introducing very low total harmonic distortion (THD) to the power supply, as may be seen in Fig. 4. As long as the converters operate close to the resonant frequency (about 167 kHz) of the LLC tank, the maximum THD value of 4% for the matrix converter over the full range of power control can be achieved. The very low THD value suggests a practically sinusoidal input current waveform, as showed in Fig. 5.

Also, both the converters have a very high (practically unity) power factor for a wide range of input power, as depicted in Fig. 6, especially when operating at frequencies close to the resonant frequency of the load.

Controllability comparison

The power controllability of both the converters can be seen from the graphs of input current against PWM pulse width in Fig. 7, with a slightly higher ratio between maximum and minimum power for the matrix converter. The matrix converter also features high power transfer compared to the H-bridge converter at the same frequency.

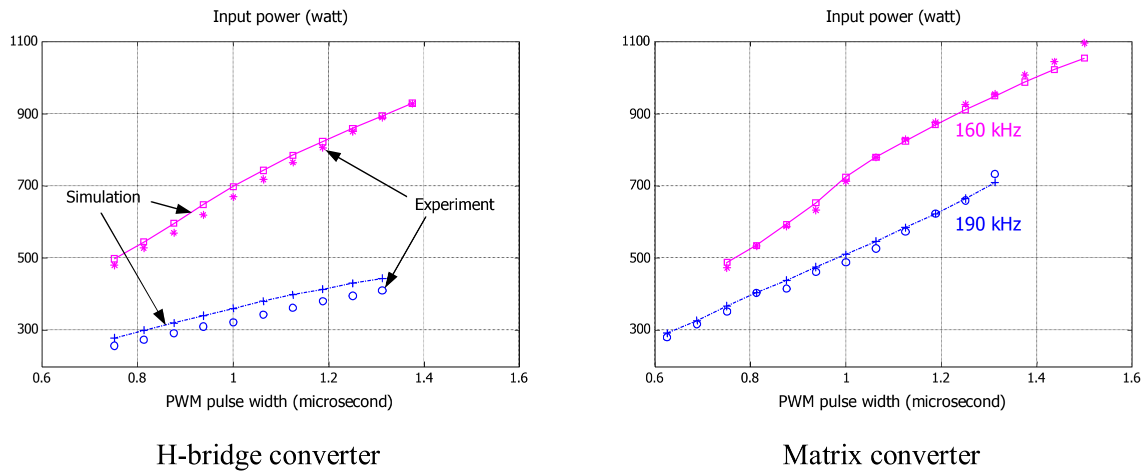


Fig. 7: Power control capability of the converters

By combining the power control range of different but very close frequencies, one can obtain a wide range of power control. It should be noted that the power control range can be expanded for real loads, which have higher Q-factor than that of the water-cooled load, because the higher selectivity of the load can create faster power drop when moving away from the resonant frequency.

As may be seen in Fig. 7, the input power varies almost linearly with the PWM pulse width in both the converters, which means a computationally effective model can be used for the controller to implement modern control methods, such as predictive or observer-based control.

Efficiency comparison

In Fig. 8, the efficiencies of the converters are presented, showing that the matrix converter has a high efficiency over the full power control range, although not as good as that of the H-bridge.

There are two factors contributing to the lower efficiency of the matrix converter when comparing to the H-bridge converter. The first factor is the higher voltage loss in the matrix converter, as described previously, hence higher conduction losses in steady-state intervals. The second factor is the number of devices being turned on and off in one output cycle of the matrix converter is eight, which is as twice as that of the H-bridge. Assuming that the same devices are to be used for both the converters, the switching loss of the matrix converter should be two times higher than the switching loss of the H-bridge, for the same output current.

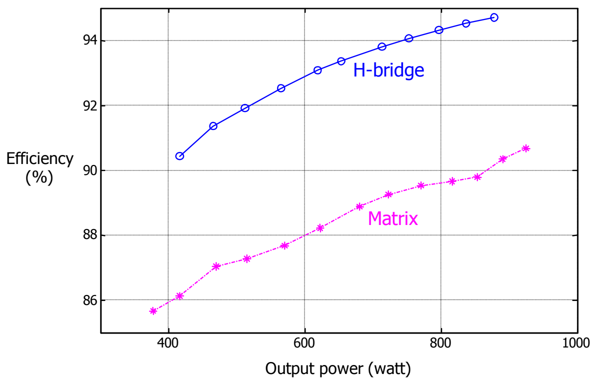


Fig. 8: Efficiencies of the converters

As mentioned in the topology comparison part, the use of the high-speed, full reverse blocking switching devices can reduce the conduction loss in the matrix converter. Furthermore, the switching loss can also be decreased owing to the reduction of devices being turned on and off in one output cycle as in the H-bridge. The single-phase matrix converter can then become a strong contender to the H-bridge converter as a high efficiency induction heater.

Conclusion

This paper has compared the novel single-phase matrix converter and the more conventional H-bridge for R.F. induction heating. The matrix converter has showed excellent performance in terms of power factor and total harmonic distortion at the utility supply interface, and good controllability under soft switching condition for a wide range of power, whilst still having a simple structure. Comparisons between the proposed matrix converter and the reference system have confirmed the performance of the proposed system. The efficiency of the matrix converter is quite high, although not as high as the H-bridge converter. However, the matrix converter could achieve a higher efficiency if the high-speed, full reverse blocking devices are used, should they become available.

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