A Matrix-based Isolated Bidirectional AC-DC Converter with \( LCL \) type Input Filter for Energy Storage Applications

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An isolated three-phase AC-DC converter is proposed in this paper for integrating energy storage elements such as batteries to the utility grid. The proposed topology uses a matrix based AC-AC converter for three-phase to single-phase conversion, facilitates the use of high-frequency transformers for galvanic isolation, and provides the necessary turns ratio for matching the required voltages on both sides, and uses a full-bridge controlled rectifier section for AC-DC conversion. A Space Vector Modulation (SVM) based switching technique is implemented for the matrix-based converter to obtain superior input power quality and improved power conversion efficiency, and Sinusoidal Pulse Width Modulation (SPWM) is used for the full bridge controlled rectifier. A T-shaped \( LCL \) input filter is developed to provide low-pass filtering effect. Also, the filter realizes an inductance dominance, which provides current source characteristics hence, only a capacitive output filter is used. The simulation was carried out using Powersim (PSIM) simulation software. The variation of voltage gain for SVM and SPWM modulation indices is also presented. The converter is able to generate a charging voltage as well as three-phase sinusoidal voltage with a THD of 3%. A closed-loop control is developed for the matrix type AC-AC converter part. The control is capable of performing bidirectional operation of the system. The proposed converter topology and switching scheme are experimentally verified.

Keywords: matrix, bidirectional, SVM, AC-AC, AC-DC, isolation

1. Introduction

With increase in the distributed generation and renewable energy sources, use of energy storage devices has been increased. Integration of the storage elements with grid becomes mandatory. Siddhartha Singh, \textit{et al.}, describes the converters for renewable energy sources integration with the utility grid\(^(2)\). Various power electronic converter topologies can be applied. Isolated converters like full bridge DC-DC converter could also prove a better option having the advantages of high frequency transformer (turns ratio and galvanic isolation). Various modulation schemes for the converters like Sinusoidal Pulse Width Modulation (SPWM), Space Vector Modulation (SVM) etc. have been proposed and being used. Hence, it is important to apply the knowledge and formulate a topology based on certain application and parameters. A matrix based converter is multi-phase-to-multi-phase AC-AC converter with an array of switches. Patrick Wheeler, \textit{et al.}, have presented a review and analysis on matrix based converter topology along with modulation and control strategies\(^(2)\). Apart from modulation, the other point emphasized was of input filter. The filter is required to reduce the switching harmonics going into the system. The filter must be able to satisfy requirements such as having cutoff frequency lower than switching frequency (low pass), minimizing its reactive power to grid, minimizing size of capacitors and inductors and minimizing filter inductor voltage drop or impedance at rated current. Amit Kumar Singh, \textit{et al.}, presents a non-isolated matrix based buck-boost converter applicable for the aircraft systems\(^(3)\) and an isolated single-stage three-phase AC-DC converter\(^(4)\). Both applied the matrix topology to convert low frequency AC to high frequency AC. The proposed converter overcomes the limitations expressed for conventional converters and provides output DC voltage with reduced current distortion and improved power conversion efficiency. The proposed converter eliminates the DC link capacitor and combines the output filter inductors with inductors from other stages. As the proposed topology is operated at higher modulation index and lower duty cycle, it promises higher input power quality and lower semiconductor losses. The merits make the proposed converter suitable for aircraft system, telecommunication, micro-grid and energy storage. The SVM has been selected for modulation scheme. Manuel Ortega, \textit{et al.}, S. Mahdi, \textit{et al.}, presents the bidirectional capability of the matrix based converter\(^(5)-(8)\). Particularly, (5) and (7) developed matrix based topology for energy storage integration to utility grid. Sadao Ishii, \textit{et al.}, proves the step-up and step-down capability of the matrix based converter and its implication in bidirectional power flow mode\(^(9)\). Desheng Sha, \textit{et al.}, mentions the advantages of the proposed converter which are high voltage conversion gain, high power factor, high conversion efficiency and high power density. However, due to input LC filter, an output inductor filter is required\(^(7)\). Due to which for power flow towards the grid, a comprehensive modulation technique is required for matrix...
based converter to reduce Total Harmonic Distortion (THD). The main conclusion is the capability and smooth transition of power flow direction for matrix topology. From (9) to (12), it is clear that, using SVM, the advantages stated are lower input current THD, lower duty-cycle loss, maximum output inductor current ripple and minimum switching loss comparing to other PWM schemes when the MOSFET devices are employed. Keping You, et al., explains the use of the same SVM algorithm for bidirectional power flow and SVM is able to produce better output performance, particularly at low modulation indexes, in terms of output waveform harmonic content (10). Similar results were obtained similarly at low modulation indexes, in terms of output waveform harmonic content (10).

Thus, it can be concluded that bidirectional matrix based topology with galvanic isolation, lower THD values, higher power converter efficiency and power density using modulation schemes like SVM could form a competitive converter for integrating an energy storage element like batteries or super capacitors to utility grid. Hence, considering this, the block diagram of the proposed converter is as shown in Fig. 1.

The input three-phase voltages are first filtered using input LC filter (section a) followed by matrix (3x1) topology (section b). The matrix topology converts the three-phase line frequency AC voltages into an intermediate high frequency AC voltage. The high frequency AC voltage is then fed to a H-bridge (section c) through an isolating transformer (T) which in turn, rectifies it to output DC voltage. This H-bridge also inverts the DC power to high frequency AC which is converted to line frequency and voltage by the matrix based converter and fed back to the grid. Moreover, the high frequency AC voltage reduces the passive filter elements and transformer size and volume. The SVM based modulation scheme is proposed for the matrix based converter for improved input power quality. In summary, the novelty and contributions of the paper are as follows:

- Use of three-phase LCL (T-shaped) filter. This type of filter provides inductive dominance from either terminals, which is required for bidirectional operation of the converter.
- The proposed SVM based modulation scheme requires single control for each of the matrix switches and therefore, does not need switch body diode conduction and therefore, facilitates, reduced number of isolated gate drivers (six for six matrix switches) and no body diode loss (conduction loss and reverse recovery loss). Moreover, the switching sequence is arranged symmetrically to provide symmetrical bipolar high frequency AC voltage at the matrix output.
- Use of full bridge controlled rectifier to perform AC-DC as well as DC-AC operations. The load or energy storage device is connected to the H-bridge. Synchronous rectification can be carried out to provide lower conduction losses while a simple control technique like SPWM could be used for inversion operation.

The paper is organized as follows: Section II provides the details of the proposed topology and operation of the converter. In Section III, simulation of the converter is carried out. In Section IV, results of the simulation are described. Section V provides the conclusion.

2. Topology and Principle of Operation

The proposed converter is as shown in Fig. 2. Each matrix switch set (S_1 to S_6) contains two back-to-back connected switches.

2.1 Filters The LCL filter topology is as shown in Fig. 3.

Applying superposition theorem to Fig. 3, for \( v_2 = 0 \),

\[
i_2(s) = \frac{(L_2 C_1 s^2 + 1)}{(L_1 L_2 s^4 + (L_2^2 C_1) s^3 + (2 L_1 L_2 C_1) s^2 + (L_2 s + L_1)} \tag{1}
\]

Where, \( v_1 \) is an alternating source, \( i_2 \) is the current by another alternating source \( v_2 \), \( L_1 \) and \( L_2 \) are the filter inductors and \( C_1 \) is the filter capacitor.

For \( v_1 = 0 \),

\[
i_2(s) = \frac{1}{(L_1 L_2 s^2 + \frac{1}{C_1} (L_1 + L_2))} \tag{2}
\]

Where, \( v_2 \) is an alternating source. Similarly, for \( v_1 = 0 \),

\[
i_1(s) = \frac{(L_1 C_1 s^2 + 1)}{(L_1 L_2 C_1 s^4 + (L_1^2 C_1) s^3 + (2 L_1 L_2 C_1) s^2 + (L_1 s + L_2)} \tag{3}
\]

Where, \( i_1 \) is the current by source \( v_1 \). From the analysis, it is clear that, the LCL type of filter
provides rejection of higher frequency signals i.e. showing the low pass filtering effect. By comparing (1) and (3), it can be observed that, the filter topology is symmetric and depending on the values of all filter components, the LCL filter acts low pass or resonance filter for power flow in both directions. Further more, for $L_1 = L_2$, the filter is able to achieve same resonance at the required frequency in both directions with appropriate selection of component values. Hence, the resonance could be set near to the line frequency to obtain lower THD values. Also, due to dominance of inductance, this type of filter provides current source effect. To balance out, only capacitive output filter is required. This also provides the advantage of using devices with lower ratings. The RC snubber is used to reduce the voltage spikes generated due to inductances in the circuit. As no output inductor is required, reduction in snubber circuit as no LC filter oscillations will be involved in the output circuit.

2.2 Modulation For operation of the matrix based converter, the SVM is used. The reference voltages are sinusoidal with phase difference of 120°, frequency is of the required high frequency AC and with magnitude defined by modulation index.

The proposed converter operates in two regions, one is to supply power to energy storage device and other is to restore power to the grid back from the energy storage device. The two regions are described in Sections 2.3 and 2.4 respectively.

2.3 Charging of the Energy Storage using the Utility Grid Power flows from the utility grid to the energy storage device. The full bridge controlled rectifier acts as rectifier to convert the high frequency AC to DC. The rectification could be done by using either the body diodes of the semi conducting switches or by using synchronous rectification technique for MOSFET switches. The matrix based converter is switched using SVM. The reference sine wave for SVM is of frequency which is the desired high frequency AC signal.

2.4 Discharging of the Energy Storage to the Utility Grid The full bridge controlled rectifier acts as inverter to convert DC to high frequency AC. SVM is used for the matrix based converter while SPWM is used for the inverter. The reference sine wave for SPWM is of frequency which is of desired high frequency AC signal and compared with high frequency triangular wave. The reference sine wave for SVM will be the line frequency.

3. Simulation of the Proposed Converter

The simulation was carried out using PSIM (Version 10.0) software. A comprehensive simulation model was constructed with the parameters as mentioned. The parameters required for the simulation model is as expressed in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value (Rating)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load</td>
<td>Bat</td>
<td>300 V, 1000Ah</td>
</tr>
<tr>
<td>Input Filter</td>
<td>$L_1, L_2$</td>
<td>6 mH</td>
</tr>
<tr>
<td>(per phase)</td>
<td>$C_1$</td>
<td>600 μF</td>
</tr>
<tr>
<td>Output Filter</td>
<td>$C_2$</td>
<td>500 μF</td>
</tr>
<tr>
<td>Turns Ratio</td>
<td>$N \cdot M$</td>
<td>5 : 1</td>
</tr>
<tr>
<td>SVM Modulation</td>
<td>$m$</td>
<td>0.8</td>
</tr>
<tr>
<td>SVM carrier triangular signal</td>
<td></td>
<td>40 kHz</td>
</tr>
<tr>
<td>SVM sine reference signal (Section 2.3)</td>
<td></td>
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<tr>
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Fig. 4. Bode plot for LCL filter

Fig. 5. System schematic for closed loop calculations

margin implies the stability of the system.

3.1 Open Loop Operation The open loop operation involves direct power conversion without any feedback. As described in Sections 2.3 and 2.4, SVM and SPWM is used accordingly. The corresponding results are described in Section 4.1.

3.2 Closed Loop Operation The closed loop operation is based on current control method. In literature it is well established that for a boost type converter, the current control method (two loop control) is essential for safe operation as the open loop zeros lie on right half of complex s-plane. A closed loop scheme is developed considering the LCL filter as shown in Fig. 3. For energy storage operation to grid, the schematic is shown in Fig. 5.

The voltage difference is given by,

$$\Delta v = L \frac{d}{dt} i_1 + L \frac{d}{dt} i_2$$

Where, $L$ is the filter inductance, $i_1$ is input current to the filter and $i_2$ is output current from the filter.

Approximating, $i_1 = i_2$. 

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Matrix-based Isolated Bidirectional AC-DC Converter with LCL Input Filter

Prathamesh Pravin Deshpande et al.

Fig. 6. Closed loop topology

\[ \frac{d}{dt} i_{abc} = \frac{\Delta v_{abc}}{L} \]  
\hspace{1cm} (5)

Where, \( i_{abc} \) is current of either A or B or C phase, \( v_{abc} \) is the corresponding voltage of either phase.

Using \( abc \) to \( dq \) transformation,

\[ \frac{d}{dt} i_d = \frac{\Delta i_d}{L} + \omega i_q \]  
\hspace{1cm} (6)

\[ u_d = e_d + L \frac{d}{dt} i_d - \omega L i_q \]  
\hspace{1cm} (7)

Where, \( i_d, v_d, u_d \) and \( e_d \) are \( d \)-components of respective current \( i \) and voltage \( v \) and \( e \) and \( i_q \) is \( q \)-component of current, \( \omega = 2\pi f \), \( f \) is the line frequency,

\[ \Delta v_d = (u_d - e_d) \]

Similarly,

\[ u_q = e_q + \frac{d}{dt} i_q + \omega L i_d \]  
\hspace{1cm} (8)

Where, \( u_q \) and \( e_q \) are \( q \)-component of voltage \( u \) and \( e \) respectively.

Using equations 7 and 8,

\[ u_{dq} = L \frac{d}{dt} i_{dq} + jL\omega i_{dq} + e_{dq} \]  
\hspace{1cm} (9)

Taking Laplace transform and on simplification,

\[ G(s) = \frac{i_{dq}(s)}{(u_{dq}(s) - e_{dq}(s))} = \frac{1}{(s + j\omega)L} \]  
\hspace{1cm} (10)

Hence, by using the (9) for reference voltage as the grid voltage, the control loop is shown in Fig. 6. The corresponding results are described in Section 4.2.

4. Results and Discussions

The results obtained from simulation of the converter in the software has been described in this section. Simulation consist of two parts, power flow from grid to energy storage device and vice-versa. Along with waveforms for gating pulses, voltages and currents, variation of voltage ratio or gain is presented.

4.1 Open Loop Operation

4.1.1 Charging of the Energy Storage using the Utility Grid

Referring to Section 2.3, the purpose of this converter is for integration of energy storage element to the utility grid. Hence, the converter has to supply a charging voltage and current to the load. The simulation results are the gating signals for all 6 sets of back-to-back connected switches are as shown in Fig. 8, high frequency transformer high voltage side voltage and current are shown in Fig. 9 and DC output voltage and current as shown in Fig. 10.

Using simulation, the relation between SVM modulation index and voltage ratio or gain is determined and as shown in Fig. 11. The voltage ratio is defined as the ratio of output DC voltage or average value to peak value of input phase voltage.

From Fig. 11, the linear nature of the voltage ratio with respect to modulation index of SVM is observed. Appropriate modulation index can be selected to achieve desired output voltage. Also, buck nature of the converter for power flow from grid to energy storage device can be inferred.
4.1.2 Discharging of the Energy Storage to the Utility Grid

As described in Section 2.4, SPWM is used for the inversion. The main point is that no change of switching technique for the matrix based converter to act for bidirectional power flow. The only change is the frequency of reference signal provided to generate gating pulses. Also, the same carrier signal is used for both SVM (for matrix) and SPWM (for inverter). The matrix based converter is switched using the SVM signals shown in Fig. 12. The simulated transformer grid side or primary side voltage and current is as shown in Fig. 13. The three-phase AC voltage and current developed from the matrix based converter is shown in Fig. 14. Using simulation, the relation between SVM modulation index \(m\) and voltage ratio or gain was determined with respect to that of SPWM \(M\) and as shown in Fig. 15. The voltage ratio is defined as the ratio of output phase peak voltage to input DC voltage of energy storage.

Figure 13 shows the output voltage after the filter. The transformer voltage is formulated due to high frequency SPWM inverter. The SVM is operated with reference to line frequency. A discontinued current waveform is observed on zooming, as shown in Fig. 13. The SVM progression \((S_1, S_2\) and \(S_3\) in Fig. 13) is divided into 4 sections. The sections are repeatative. Section \((i)\) shows positive current waveform while section \((iii)\) shows negative waveform. Sections \((ii)\) and \((iv)\) shows the transition of the current waveforms. Also, the transformer current has line frequency component envelope. From Fig. 14, the three-phase voltages and currents are observed. The THD for voltage was calculated to be 3% while for current was 2%. Figure 15 shows the non-linear variation of the voltage ratio with respect to modulation index of respective SVM and SPWM. A steep change of voltage ratio can be observed. The voltage ratio goes beyond 1 for modulation index greater than 0.6 for both SVM and SPWM. This boosting nature due to current source type (by input LCL filter) is much required for Section 2.4 to achieve higher grid voltage from low voltage source. This reduces the number of transformer turns ratio. The same voltage ratio can be obtained by different combinations of modulation indices of SVM and SPWM. But for easier implementation, the
modulation obtained from Fig. 11 could be used to determine the other index for the operating point using Fig. 15.

### 4.2 Closed Loop Operation

The control loop as described in Section 3.2 is implemented using available library blocks in PSIM. The gains are adjusted corresponding to the carrier signal. The three phase output from DC-AC conversion is shown in Fig. 16.

For charging of the energy storage, the reference voltage is the DC output voltage and the measured voltage is the output DC voltage. For utilisation of the energy storage device, the reference is the AC output RMS voltage and the measured voltage is the output AC RMS voltage. As stated in Table 1, the reference sine frequency for SVM varies in both cases.

### 5. Experimental Verification

The laboratory hardware setup is as shown in Fig. 17. The Printed Circuit Board (PCB) is designed in-house, discrete components are ordered and soldering is done. Cree SiC MOSFET are chosen for switching devices and are mounted on bottom of the PCB while Cree SiC isolated gate driver is mounted on top of the PCB. The SVM modulation scheme is coded in a Digital Signal Processor (DSP) by Texas Instruments. Component specifications for test setup is given in Table 2. Litz wire is used as transformer winding. The parameters for the constructed transformer measured at 40 kHz is given in Table 3. As described, two back-to-back connected switches forms one matrix switch. Hence total 12 discrete devices are required to implement total 6 matrix switches to form three-phase grid frequency AC to single-phase high frequency AC. But only 6 gate drivers are required each for a matrix switch as same gate and source connection. No snubber circuit is populated on PCB.

The measurement is saved using the digital oscilloscope.

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### Table 2. Active and passive components selected for experimental hardware prototype

<table>
<thead>
<tr>
<th>Component</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOSFET</td>
<td>C3M0280090D</td>
</tr>
<tr>
<td>MOSFET Gate driver</td>
<td>CR001</td>
</tr>
<tr>
<td>High Frequency Transformer</td>
<td>Ferrite Core, ETDS9 core, 3C97 material</td>
</tr>
<tr>
<td>Controller board</td>
<td>TMS320F28335</td>
</tr>
</tbody>
</table>

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### Table 3. Transformer parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turns Ratio</td>
<td>4.5 : 1</td>
</tr>
<tr>
<td>Primary DC resistance</td>
<td>245 mΩ</td>
</tr>
<tr>
<td>Secondary DC resistance</td>
<td>20 mΩ</td>
</tr>
<tr>
<td>Primary leakage inductance</td>
<td>87 μH</td>
</tr>
<tr>
<td>Secondary leakage inductance</td>
<td>1.87 μH</td>
</tr>
</tbody>
</table>

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The voltage and current waveforms for input, output, primary voltage of high frequency transformer and gate-to-source voltages for AC to DC operation are shown in Figs. 18 and 19, while for DC to AC operation are shown in Figs. 20 to 22.

### 6. Conclusions

This paper presents a matrix based isolated three-phase AC-DC bidirectional converter suitable for energy storage...
by optimising the design and copper track layout of PCB and construction of the high frequency transformer.

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References

Amit Kumar Singh (Non-member) received B.Tech. degree in 2009 from the Indian Institute of Technology BHU, Varanasi, India. He has obtained his Ph.D. in electrical and computer engineering at National University of Singapore (NUS), Singapore. He worked for almost 4 years (2009–2013) as a Scientist with Defence Research and Development Organization (DRDO), Ministry of Defence, India. His main research interests include design, analysis and control of resonant DC-DC and matrix converter based three phase ACDC power converters for aircrafts and energy storage systems. He is a reviewer for IEEE Transactions on Power Electronics. Currently he is working as post doctorate in NUS.

Sanjib Kumar Panda (Non-member) received B.Eng. Degree from the South Gujarat University, India, in 1983, M.Tech. degree from the Indian Institute of Technology, Banaras Hindu University, Varanasi, India, in 1987, and the Ph.D. degree from the University of Cambridge, U.K., in 1991, all in electrical engineering. Since 1992, he has been holding a faculty position in the Department of Electrical and Computer Engineering, National University of Singapore and currently serving as an Associate Professor and Director of the Power and Energy Research Area. Dr. Panda has published more than 200 peer reviewed research papers, co-authored one book and contributed to several book chapters and six patents. His research interests include high-performance control of motor drives and power electronic converters, condition monitoring and condition based maintenance, building energy efficiency etc. He was the recipient of the Cambridge-Nehru Scholarship and M.T. Mayer Graduate Scholarship during his PhD study (1987–1991). He is serving as an Associate Editor of several IEEE Transactions and Editor of the Journal of Power Electronics, South Korea. He has served in various capacities for the two key conferences IEEE Power Electronics and Drive Systems (PEDS) Conference and IEEE International Conference on Sustainable Energy Technologies (ICSET) Conference series organized and managed by the IEEE Joint IAS/PELS Society Chapter, Singapore Section. Dr. Panda has received the IEEE Third Millennium Medal. He is serving as the IEEE R-10 AsiaPacific Liaison Officer for the IEEE PELS. He is also the recipient of the IEEE Singapore Section Outstanding Volunteer Award in 2010 and the IEEE Region-10 Outstanding Volunteer Award in 2014. He has served the IEEE Section Congress 2014 as a Member of the Program Committee.