AC Drive Solution with Integrated Matrix Converter

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Abstract

This paper presents an overview of research on a novel AC drive with fully integrated matrix power converter that implements bus bar structure for overvoltage minimization during power switch commutation. This overview includes mathematical description of matrix converter, main features of power IGBT gate driving, principles of bus-bars, as well as active gate driver for power IGBT overvoltage and overcurrent protection.

Keyword
Matrix Converter, Integrated Drives, IGBT gate drivers

Introduction

The initial problem is stated as the high complexity of drive systems that implement AC machines, frequency inverter module, filters and wiring. Such solution is convenient in application when frequency regulation must be added to already existing drive system. However in many cases when a new drive system is developed it is more convenient to have all components concentrated in one unit hence saving up on space. Such solution can be implemented in electric vehicle, aerospace or other applications where space saving is one of the key features. As a perspective solution – a matrix converter is considered in combination with low inductance bus-bar system in power module and active power IGBT gate drive technique is proposed for overvoltage minimization and device protection.

1. Matrix converter technology

1.1. Matrix converter

Matrix converter is a direct frequency converter (Fig. 1.) that consists of nine bi-directional switches that allow connection of any input phase to any of the output phases. Main advantages of matrix converter over a conventional voltage-source inverter are: sinusoidal input current and output voltage with minimal harmonic distortions, full range input power factor control, inherent bi-directional power flow capability and there is no requirement for reactive energy storage elements that makes matrix converter a compact device.

There are also several disadvantages: it requires more power switching devices than conventional AC-DC-AC inverters, in most cases the input voltage transfer ratio is limited to 0.866 and matrix converter is sensitive to the input voltage disturbances due to the lack of the energy storage elements.

1.2. Bi-directional switch

One of the main problems of the matrix converter is related to bi-directional switch realization. The key feature of a bi-directional switch is its capability of conducting current and blocking voltage in both directions. Because a real bi-directional switch is still unavailable on the market conventional unidirectional devices are combined as a solution.

Simple solution for bi-directional switch implementation is a two anti-parallel IGBT connection (Fig. 2.a.). It is possible in case semiconductor devices are with high reverse voltage blocking capability. This arrangement yields a compact design and possibility in efficiency improvement. However this configuration is not commonly used due to its poor reverse recovery characteristics that increase commutation losses.

Another simple configuration implements only one switching device and a diode bridge. Collector of power IGBT is connected to anodes of the bridge, and emitter is connected to cathodes of the diode bridge (Fig. 2.b.). One active switching element of this configuration makes this a very attractive solution from point of view of costs and complexity of gate drive circuits. However there are two considerable disadvantages related to this circuit: it is impossible to control the direction of the current flow (this is considered as disadvantage since some
commutation strategies are based on independent current control in each direction) and relatively high conduction losses due the series connection of three semiconductor devices in each conduction path.

This problem can be solved by implementation of two series connected IGBTs with anti parallel diodes (Fig. 2.c.) that ensure higher reverse blocking capability of IGBTs. Main advantage can be considered that only six isolated power supplies are needed for gate drive circuits. [1]. It is ideal in case of implementation of matrix converter modules where all switching devices are integrated in one package, but with increasing power the individual stray inductance of single switch still becomes considerable.

Similar configuration to the previous is common collector connection (Fig. 2.d.). This configuration requires isolated power supply for each bi-directional switch, which is total nine for a 3x3 matrix converter. Conduction losses in this arrangement are the same as in the previous case.

![Fig. 2. Bi-directional switch realization](image)

**3. Insulated Gate Bipolar Transistor**

- **a)** schematic symbol; **b)** IGBT with extracted capacitances

### 2. Power IGBT commutation

#### 2.1. Power IGBT

Insulated gate bipolar transistors (IGBT) are characterised by their high off-state and low on-state voltage properties inherent to bipolar junction transistors (BJT) combined with high input impedance of metal-oxide-field-effect-transistor (MOSFET) (fig. 3.a.) IGBTs are voltage controlled semiconductor devices that conduction is determined by gate voltage according to emitter. It conducts electrical current (turn-on) when the positive voltage, usually 15V, is applied to the gate, and stop conducting (turn-off) when 0V or negative, usually -15V, is applied to the IGBT gate according emitter.

Since IGBTs gate is electrically insulated from its emitter by a dielectric layer of silicon dioxide, theoretically no current flows when a DC voltage is applied to its gate. In practice, gate current is required to charge devices capacitances (Fig.3.b.) and a small leakage current of the order of nano-amps does flow in order to maintain the gate voltage.

#### 2.2. Gate Drive Circuits of Power IGBTs

Since the IGBT switching speeds and hence commutation losses are determined by that speed at which the gate voltage can reach a level above the gate-emitter threshold voltage at turn-on and below the threshold voltage at turn-off, the gate capacitance charge and discharge current is essential.

In order to make the commutation of power IGBT efficient and reduce commutation losses, the gate
current must reach highest possible value. To amplify the logic signal a gate drive circuit (GDC) is required.

GDC are viewed in context of integrated drive concept – that is devices must be small and at the same time system must ensure maximum efficiency and reliability. Several GDC circuits are proposed in [1], [6] – [9].

The most attractive solutions for integrated drive system with matrix converter are described, simulated and experimentally tested.

Simple circuits such as TTL or CMOS logic gates that employ minimum auxiliary components and are often used for simplicity of the GDC system are not discussed here because of their inefficiency of gate current for power electronic applications.

2.2.1. Optoelectronic driver

A high speed optoelectronic (optocoupler) can be used to drive a power IGBT (Fig. 4.). These devices implement an infrared-emitting-diode (IRED) on primary side that can be driven directly from a microprocessor unit. Secondary side consists of photo-diode, receiving IC and BiCMOS output cascade that allows large output current up to 5A [13]. Some devices include Under-Voltage Lock Out function that protects both optoelectronic and power device when input signal level drops or any dangerous conditions appear. Optoelectronic driver (OED) ICs are compact and provide high isolation voltage level between primary – low voltage and secondary – high voltage/power sides. However, these devices have limited maximum switching time – upper limit reaching up to 500ns. In case of matrix converter optoelectronic driver can be used with separate isolated power supplies for each bidirectional switch.

2.2.2. Half-bridge topology

This is amplification BJT follower for CMOS gates (Fig. 5.a.). Fed with uni-polar voltage $V_{cc}$ up to +18V DC, it implements two bipolar-junction-transistors – npn and pnp. Operation of this circuit is based on the inverted properties of BJT totem-pole.

![Fig. 4. Optoelectronic power IGBT driver](image)

Form PSpice simulation maximum gate current of 0.87A at turn-on and -0.97A at turn-off can be reached. Experimental results approve that this circuit is not capable of delivering gate current more than 0.82 A at turn-on and -1.16 A at turn-off.

2.2.3. Full-bridge topology

More gate current could be drawn from GDC if larger voltage difference is applied to the power IGBT gate. In case of uni-polar voltage supply of 15V this problem can be solved by implementation of full-bridge topology (Fig. 5.b.). This requires additional totem-pole BJT transistor pair VT4 and VT5 that are controlled with inverted $V_{in}$. Main drawback is high number of components: two more transistors, optocoupler and an inverting element are required.

From simulation maximum gate current of 1.7A at turn-on and -1.9A at turn-off can be reached. Experimental results approve that no more than 1.72A at turn-on and -1.65A at turn-off can be drawn from this circuit.

2.2.4. Double-fed Half-Bridge topology

This circuit implements two voltage levels according to common node: $+V_{cc}$ and $-V_{cc}$ (Fig. 7.a.). The operating principle is similar as in case of half-bridge topology, but yields higher $\Delta V_{GE}$ as in case of full-bridge topology. This configuration requires minimum additional components: voltage dividing capacitors C1 and C2 and a balancing resistor Rb (usually of 10 kΩ order.)
2.3. Active gate drive circuit

Here a overvoltage protection method by means of gate driver circuit is presented. This method does not require any additional power elements for overvoltage minimization during power switch commutation.

The previously chosen half bridge double feed principle is the most compromising solution from the point of view of switching dynamics and space.

A 300 V 10 A 20 kHz power setup was simulated with several gate drive control techniques.

2.3.1. Voltage controlled turn-off

Passive gate voltage control produces overvoltage of 155V across collector-emitter of power device (Fig. 8.a). Here controlling voltage is applied to gate of the power transistor directly through a gate resistor. This fixes gate current of the actual turn-off (voltage rising stage) at the certain level. Smaller gate voltage or higher value of gate resistance will produce just slightly smaller overvoltage of 145V (Fig. 8.b) but at the cost of much slower switching process and, hence much bigger commutation losses.

2.3.2. Two-level voltage controlled turn-off

Solution – reduction of applied turn-off gate voltage till a positive value by means of special circuit only during the most active phase of the switching that takes place at rising collector voltage and falling collector current (Fig. 8.c). Reduced gate voltage command (voltage applied to the gate resistor) is activated when the voltage rises above the defined level and removed when collector current reaches 0. The command is slightly smaller than the gate voltage corresponding to the load current. This approach produces 55V overvoltage. There are two significant drawbacks of such solution: gate voltage control circuit itself is very challenging technical task and it is not easy to build. Second, reduced voltage varies with the load current that makes the control and measurement more complex. All deviations will lead to re-switching (for higher values) or higher overvoltage (for smaller).

2.3.3. Current controlled turn-off

Another way of solving of the mentioned problems is utilizing of a gate current control. Here, the voltage command is applied to the gate through a current regulator that ensures two levels of the gate current: lower – for the active phase and higher – for the rest of the process (Fig. 8.d). Switching process is not tied anymore to voltage levels and, hence, does not depend on the load. At the same time schematic for current regulators are not very difficult to implement.

2.3.4. Comparison

Some details of previously shown simulations are compared in Table 1. All mentioned approaches produces smaller overvoltage on the outgoing transistor and all at the cost of the slightly higher power losses. Gate current control requires more simple measurement and control circuit.
2.4. Experiments with active gate driver

Since it is necessary to control the value of the turn-off current, the turn-on and turn-off a control circuit is introduced (Fig. 9.a.) The turn-off process must be slowed down in order to reduce voltage spikes caused by breaking of inductive collector current, as it was simulated previously. The turn-off process can be divided into three stages: turn-off start, 0 gate current and final shutdown. Experiments were carried out at supply voltage \(V_{DC}=100\text{V}\), load \(R_{load} = 100\Omega\), \(L_{load} = 56\text{mH}\) and \(f_c = 5\text{kHz}\). Results (Fig. 9.b., c.) approve the influence of active gate current control on the reduction of the overvoltage stress of the collector-emitter voltage at active-inductive load commutation.

Table 1. Gate voltage or current control comparison

<table>
<thead>
<tr>
<th>Approach</th>
<th>(\Delta V) [V]</th>
<th>(\Delta T) [ns]</th>
<th>(\Delta P) [W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-level (V_G) @ (R_G=10\Omega)</td>
<td>155</td>
<td>800</td>
<td>18</td>
</tr>
<tr>
<td>1-level (V_G) @ (R_G=50\Omega)</td>
<td>145</td>
<td>1200</td>
<td>20</td>
</tr>
<tr>
<td>2-level (V_G) @ (R_G=10\Omega)</td>
<td>55</td>
<td>700</td>
<td>26</td>
</tr>
<tr>
<td>2-level (I_G) @ (R_G=10\Omega)</td>
<td>30</td>
<td>800</td>
<td>25</td>
</tr>
</tbody>
</table>

Fig. 8. IGBT turn-off commutation transients: a) gate voltage controlled at \(RG=10\ \Omega\); b) gate voltage controlled at \(RG=60\ \Omega\); c) 2-level gate voltage controlled; d) gate current controlled.

From top to bottom: voltage command, gate current, gate voltage, collector voltage and collector current.

Fig. 9. IGBT gate commutation a) experimental schematic; experimental results b) of passive gate voltage control; c) active gate current control.

From top to bottom: collector-emitter voltage, gate voltage, gate current, voltage command.
In Fig. 9.b. an overvoltage peak at power device turn-off reaches 750V. Experiment involving active gate current control (Fig. 9.c) has undoubted influence to commutation process: it increases commutation time, but the overvoltage spike has reduced to peak value of 200V.

3. Bus-Bars in Matrix Converter

In this work term bus-bars refers to low inductive laminated copper plates that are insulated one form another with thin insulation material that withstands maximum voltage that is possible between bus-bars.

The main feature of bus-bars is to reduce parasitic inductances in high current commutation loop hence reducing dangerous overvoltage spikes across the power IGBT.

Several bus-bar layouts were considered for integrated AC drive application [8]. It was concluded that the most space effective way of placing a bus bar construction is a circular way. In this case bus bars are shifted and overlap for 120° (Fig. 10.), hence maintaining the symmetrical distribution of capacitances.

This construction can be developed on a multilayer PCB with surface mounted components. Another advantage is a possibility to fit the structure in front or at the back side of an AC induction machine. This principle well corresponds to idea of fully integrated drives that is proposed, described and developed in [9].

4. Conclusions

The concept of integrated drive is not new, but there are few works that have been done in the field of integrated drive systems with matrix converters by means of implementation of bus-bar structure. Experiments approve efficiency of active gate current control and bus-bar implementation for overvoltage reduction across one power device however more experimental work must be done to determine the active gate driver influence on bi-directional switch and the matrix converter together.

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