100 MS/s 10-25 MHz Wireless Voltage Probe

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Abstract

For developing and testing of power electronic converters and circuits, voltages and currents have to be measured to verify the proper mode of operation. In cascaded converters or multi-level topologies, the voltages to be measured contain common mode components up to several kV with transients up to several tens of kV/µs.

Conventional isolated voltage measurement systems do either not meet the high voltage isolation requirements or exhibit a rather large coupling capacitance to ground. In combination with the high voltage transients, this coupling capacitance on the one hand impacts the circuit under test and on the other hand influences the voltage measurement. To reduce these effects, the coupling capacitance of the measurement system must be minimized.

In this paper, a wireless voltage probe (WVP) is introduced to measure accurately on a high and transient reference voltage with minimal impact on the circuit under test. The basic concept and practical realization of the WVP are discussed and finally verified with measurements on a high power medium voltage IGBT converter system.

1 Introduction

Cascaded converters become more and more important to meet the voltage requirements of medium voltage high power electronic systems. Typical examples are cascaded H-bridges or (modular) multilevel converters comprising IGBT or IGCT modules.

For such converters, electric control circuits, e.g. gate drive circuits, must be developed that meet high voltage isolation requirements up to several kV and must show an immunity to voltage transients up to several tens of kV/µs. Therefore, the impacts of the highly transient voltages on the circuit function must be investigated in the course of the developments. That's why it's important to measure voltages and currents, e.g. logic signals, gate voltages or gate currents, on a high reference potential to verify the proper mode of operation. The measurement must be minimally invasive to avoid an impact of the measurement system on the circuit under test (CUT). The input impedance of the measurement device must hence be maximized and the capacitive coupling to ground minimized. Furthermore, a high accuracy of the measured voltage in time and amplitude is naturally needed. A typical power electronics measurement situation with a floating reference potential is shown in **Fig. 1**.

1.1 State of the art measurement methods

Currently, isolated differential voltage probes or differential amplifiers are used to measure low voltages on high and transient reference potentials. The drawback of these probes is the limited isolation capability of a few kV.

Another common method is a floating battery-powered oscilloscope directly connected to the electrical CUT. Except for safety reasons, there is often not enough space in a high-power converter setup to place the scope close to the signal source. Furthermore, a relatively large capacitance to ground is introduced at the point of measurement.

A further drawback of all these measurement methods are the cable connections of the voltage probes that make the handling in physically large converters complicated and time-consuming as all cables have to be attached and isolated from non-isolated parts.
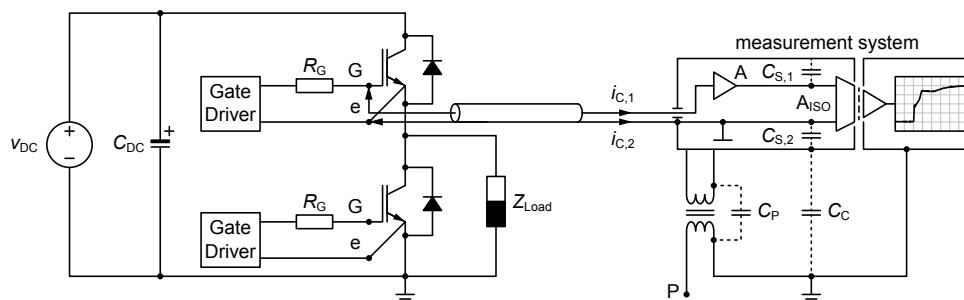
Figure 1: Simplified schematic of a typical power electronics measurement situation where the voltage of the circuit under test (CUT) to be measured, e.g. a high-side IGBT gate-emitter voltage, is on floating reference potential. The transients of this reference voltage cause common mode currents ($i_{C,1}$, $i_{C,2}$) due to the coupling capacitances of the measurement system (power supply: C_P, signal isolation amplifier: $C_{S,1-2}$, case / shield: C_C) from the CUT via the measurement system to ground.

1.2 Proposed measurement system

Based on the above-mentioned conditions, a system is needed that measures voltages with a high amplitude resolution and bandwidth and has a small coupling capacitance to ground. This demands small dimensions of the measurement device and isolators in the signal and supply path with lowest coupling capacitance. These features are achieved by a tiny battery-powered voltage measurement system that is attached to the reference voltage and transmits the measured signal via either an optical fiber or wireless to a receiver unit, e.g. a laptop.

With an optical system, the data can be transmitted either analog [1, 2] or digital [3]. Such a system allows to measure accurately on high and transient reference voltages but a cabling of the voltage probe is still required.

If the optical fiber connection is replaced by a wireless data transfer [4–7], the cabling can be omitted and the handling of the isolated voltage probe is significantly simplified. The main drawback of a wireless transmission is the reduced data transfer rate compared to optical fibres. However, as it is frequently only necessary to measure the time behavior of a signal within a short time interval, a continuous and real-time measurement is not mandatory. To anyhow achieve a high sampling rate, the signal could be stored temporarily in a memory unit during the measurement process and transmitted afterwards.

In this paper, a wireless voltage probe (WVP) for measuring on high and transient reference voltages is presented. Subsequently, the performance constraints of building a WVP with discrete components are investigated and a realized prototype is presented. Finally, measurement results of different isolated measurement concepts including the WVP prototype are comparatively evaluated.

2 Wireless voltage probe

In this section, the components and the operating mode of the WVP are described in detail.

In **Fig. 2** (a), the measurement system consisting of several WVPs and a PC is depicted schematically. On the PC, the user can set the individual configuration parameters for each WVP, e.g. the sampling rate, the trigger level and slope, the pre-trigger value or the coupling of the input stage, in a graphical user interface (GUI). These parameters are then transmitted from the PC to the corresponding WVPs via the wireless communication channel. After a WVP has measured a sequence of data, it transmits the sampled values to the PC, where they are visualized in a signal graph. As a consequence, no oscilloscope is required for the measurement process anymore.

The WVP itself, as shown in **Fig. 2** (b), contains basically a similar functional range as a DSO. The input stage (cf. **Fig. 3**) ensures high-impedance that is typically in the range of several MΩ. To reduce or eliminate, according to requirements, the aliasing effects of the sampling process, an anti-aliasing-filter can be inserted. The control unit activates the A/D converter (ADC) and stores the data values in a memory unit. In addition, it activates the trigger either out of the measured signal from the ADC or by an external trigger input. Via the communication interface the control unit both receives the configuration
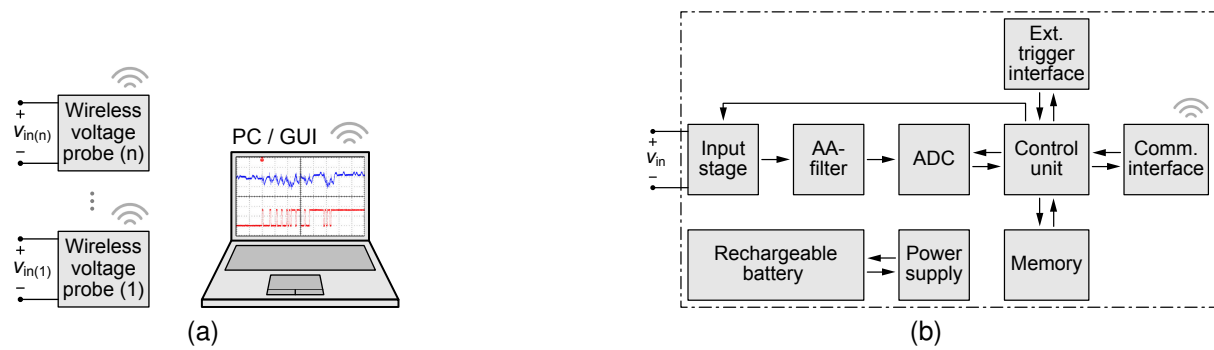
Figure 2: (a) Schematic of a measurement system consisting of WVPs and a PC with a graphical user interface (GUI) and integrated wireless communication. (b) Schematic of the WVP's integral functional units.
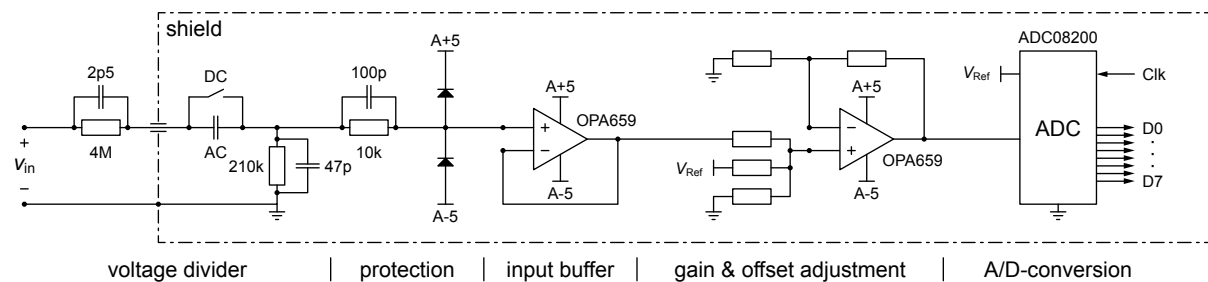
Figure 3: Schematic of the WVP's input stage. The RC-circuit outside the shield (dashed box) corresponds to an external input impedance, e.g. a passive probe.

parameters from the PC and transmits the captured data values to the PC. A rechargeable battery allows an autonomous operation of the WVP.

The analog input stage, as schematically depicted in **Fig. 3**, consists of a compensated passive voltage divider to adapt the voltage v_{in} to be measured to the WVP's input voltage range. A wideband operational amplifier with JFET-input stage and hence lowest bias current (10 pA) and offset voltage (1 mA) buffers the input voltage and provides the decoupling. It is also possible to build this type of input amplifier stage with discrete components [8]. To match the measured voltage to the ADC, a gain & offset adjustment stage is inserted between the input amplifier and the ADC.

After the WVP is configured and activated by the PC, the control unit initiates the ADC by providing a clock signal according to the sampling rate entered by the user. The sampled data values are read by the control unit and stored to the memory. When the memory has reached the user-specified amount of pre-trigger values, every new sample stored to the memory replaces the oldest one. If the WVP is in this state and the trigger condition is met, no more data of the memory are discarded and the new data values are stored to the memory until it is full.

All WVPs are able to individually trigger to an event of their own input signal by the internal trigger unit implemented on the digital control unit. As frequently not only individual but also synchronized measurements are needed, the WVPs must also be able to receive and provide external trigger signals. In addition, a communication channel must be established between the units: If the WVPs measure on the same reference potential, they can be electrically connected together via the external trigger interface (cf. **Fig. 2** (b)). In the case of different reference potentials, optical fibers could be used as isolated interconnection but they would impact the easy handling of a WVP due to the cabling needed for the trigger channel. By using the existing wireless communication on the WVPs to also broadcast and receive trigger events, no cabling is needed. However, due to the distance of typically few meters between different WVPs, a delay skew of typ. 20 ns with reference to a received trigger event is then inevitable.

An extended option to the wireless trigger broadcast would be the implementation of synchronized clocks on all WVPs, wherewith the individual measurements could be synchronized on the PC by using the

corresponding time stamps at the points of the trigger event. The problem of this kind of synchronization method is that even with precision time synchronization algorithms, e.g. the IEEE 1588 standard, an accuracy of only 200 ns is achieved [9].

If the WVPs are used in combination with a conventional DSO and all measurements must be synchronized, a wireless transceiver unit, that is able to communicate with the WVPs, must be connected to the DSO: In the case where the trigger is activated by a WVP, the transceiver unit receives a trigger command by the WVP and hence provides an electrical signal to the external trigger input of the DSO. If the trigger of the WVPs shall be activated by the DSO, the transceiver unit must be electrically triggered by an external trigger output of the DSO to be able to provide a wireless trigger command to all WVPs. In both cases, a deskew calibration should be performed prior to using the system.

3   Performance constraints

In this section, the constraints concerning performance and size of a WVP are investigated and presented. Aiming for low costs, the investigations are only considering a realization with discrete components. Improved performance could be achieved by integration.

The WVP can be described with several characteristics: sampling frequency, memory depth, runtime, data transfer rate and physical size. Most of these characteristics influence each other and are investigated in the following subsections.

3.1   Sampling rate

Several components, i.e. the ADC, the control unit and the memory, have to run at the ADC's sampling frequency to be able to store the sampled data temporary in the memory.

Discrete ADCs with a parallel interface and sampling rates up to several 100 MS/s are commercially available, whereupon ADCs faster than 200 MS/s are expensive and show rather high supply current.

A first-in, first-out (FIFO) memory topology is promising as the data values are always written to or read from chronologically organized memory addresses. To relieve the control unit from addressing the memory, which would decrease its operating frequency, an external FIFO memory can be applied. Such memory units are available up to a clock frequency of 166 MHz and up to storage word lengths of 72 Bit[1]. It is possible to reduce the memory clock by writing n values at a time to one storage word, as this is large enough to contain several 8 Bit data values. The memory clock then scales down to the ADCs sampling rate divided by n.

Time-discrete control units, e.g. FPGAs or CPLDs, are available up to clock frequencies of several hundred MHz. The achievable clock frequency is often limited by the software code. If the addressing of the memory is implemented directly in a FIFO memory, the requirements on the software logic are low thus a sampling frequency of several 100 MHz is achievable.

3.2   Memory depth

The FIFO memory units of IDT introduced in subsection 3.1 are available up to a memory size of 4 MBit what corresponds to 512 k sampled 8 Bit data values. The memory units can be connected in series to increase the total memory depth.

3.3   Data transfer rate

The data transfer rate between the WVP and the PC depends on the selected wireless topology, e.g. Wi-Fi, UWB, Bluetooth, ZigBee, etc. As the size of the WVP should be kept as small as possible, the application of a high power and space consuming wireless device, e.g. Wi-Fi or UWB, is not advantageous as their power consumption is typically in the range of several 100 mW up to few Watts. This would require a larger battery to achieve the same runtime compared to the low power devices like Bluetooth or ZigBee that typically have a power consumption of less than 100 mW.

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[1]IDT SuperSync II Series with 6 ns speed grade
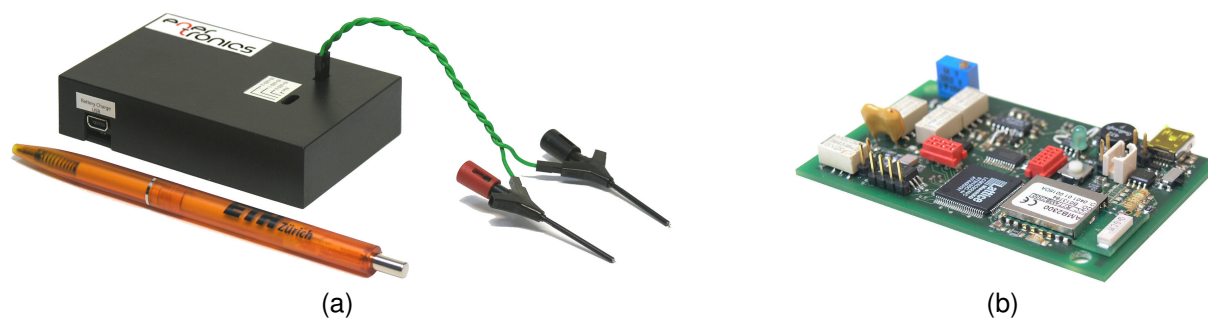
Figure 4: (a) Outside view and (b) PCB of the WVP prototype.

The Bluetooth technology is promising as it can operate fast (up to few MBit/s), has small controllers and antennas, works energy efficiently, and is compatible to the built-in Bluetooth modules of today's notebook computers. With a typical Bluetooth data transfer rate of 115 kBit/s a baudrate of 11.5 kBd results (8 Bit data and 2 Bit overhead). Therefore, it takes less than one second to transmit a typical measurement window of 10 k samples.

3.4 Runtime

For convenient application the WVP must be designed to operate several hours from a small-sized integrated rechargeable battery. A typical Li-ion battery of this kind measures about 5 x 4 x 0.5 cm, has a volume of 10 cm^3 and features an energy content of about 4.3 Wh. To achieve a runtime of several hours, the average power consumption of the system must be smaller than roughly 1 W. To extend the runtime of a WVP, the system should be able to operate in a sleep mode for the case of a deactivated trigger or by manual remote shut down. In this state, all parts except for the communication module have to be switched off. As the communication module in this state is running in a low-power mode, the WVP can be turned-on remotely by the PC via the wireless communication interface.

4 Realized prototype

A prototype of the WVP was developed [10] that features a sampling rate of 100 MS/s and contains a FIFO memory unit with a memory depth of 8 k samples with 8 Bit resolution. The analog bandwidth of the input stage is about 175 MHz for the used operational amplifier OPA659 (gain-bandwidth product of 350 MHz) operating at a gain of 2. The sampling rate limits the achievable analog bandwidth to about 25 MHz for the $\sin(x)/x$ interpolation [11], that is used for measuring sinusoidal signals, and to typically 10 MHz for the linear interpolation, that is applied for measuring rectangular voltage signals. The communication to the PC is implemented with a Bluetooth module (AMB2300) offering a data transfer rate of 115 kBit/s. As mentioned above, this results in a data transfer time of less than 1 s for a full measurement window consisting of 8 k samples. The WVP employs a 4.6 Wh Li-ion battery that provides a runtime of about 4 hours. The dimensions of the prototype are 90 x 60 x 20 mm and the weight is 95 g. The outside view of the WVP prototype and it's internal PCB are shown in **Fig. 4**.

5 Measurement results

To verify the low CM voltage sensitivity of the proposed WVP, measurement results of different differential voltage probes including the WVP prototype have been accomplished and are comparatively evaluated in the following.

The output voltage $v_{G,OUT}$ of a high-side IGBT gate driver, as depicted in **Fig. 5**, was measured with three different voltage probes: (1) Tektronix differential probe (P5200, 25 MHz), (2) LeCroy differential probe (ADP305, 100 MHz) and (3) prototype of the WVP. In the case of 0 V DC-link voltage and consequently no CM voltage, all voltage probes measure similar waveforms as shown in **Fig. 6** (a). With a DC-link voltage of 600 V, the measurements of the differential probes are disturbed by the CM voltage transients
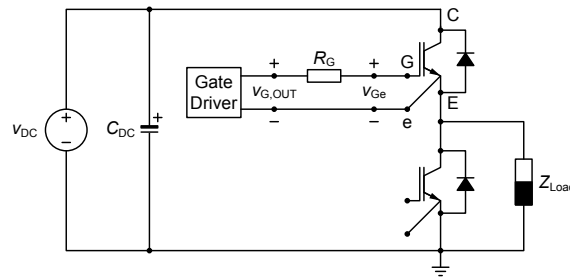
Figure 5: Schematic of the measurement situation. Both the high-side gate driver's output voltage $v_{G,OUT}$ and the high-side IGBT module's gate-emitter voltage v_{Ge} (gate terminals) were measured by the different voltage probes.

(a) without CM voltage   (b) with CM voltage
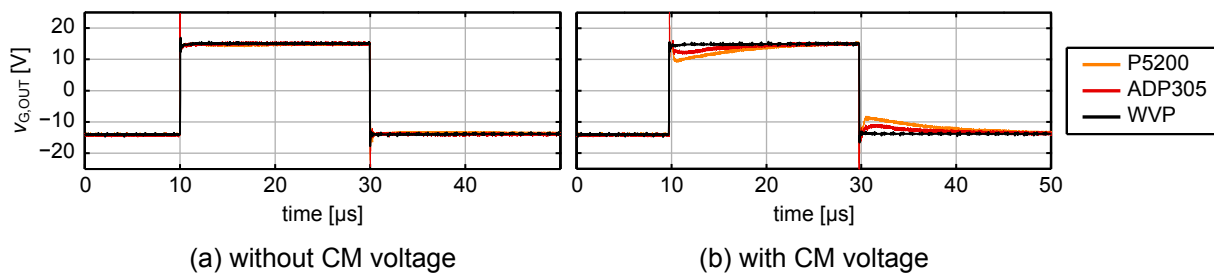
Figure 6: Measurement of a high-side IGBT gate driver's output voltage $v_{G,OUT}$ (a) without CM voltage ($v_{DC} = 0\,V$) and (b) with CM voltage ($v_{DC} = 600\,V$) during one pulse with different voltage probes. (1) Tektronix differential probe (P5200, 25 MHz), (2) LeCroy differential probe (ADP305, 100 MHz), (3) prototype of the proposed 100 MS/s WVP. The time derivatives of the collector-emitter voltage are about $dv_{CE,ON}/dt = -4\,kV/\mu s$ during turn-on and $dv_{CE,OFF}/dt = 1.7\,kV/\mu s$ during turn-off (see **Fig. 7**).

as depicted in **Fig. 6** (b). In contrast, the measured signal of the WVP prototype is not influenced by the CM voltage transients and does show no noticeable difference to the case where no CM voltage is present.

For a more detailed analysis and evaluation also the gate-emitter voltage v_{Ge} during the switching operation was measured at the IGBT module's gate terminals with the same voltage probes (cf. **Fig. 7**) for the case of (a) turn-on and (b) turn-off. Again, the voltage measurements of the conventional differential probes are disturbed by the CM voltage transients (present in the time interval indicated by dashed lines in **Fig. 7**). In contrast, the signal of the WVP is not disturbed and therefore the measured Miller plateau of the gate-emitter voltage is flat in accordance to the actual system behavior.

In summary, the WVP has essential advantages compared to a conventional differential voltage probe: First, there is no limitation on the maximum CM voltage amplitude as the WVP is floating on the reference voltage and there are neither voltage isolators in the signal- nor in the energy supply path. In addition, as the coupling capacitance can be kept low, the CM voltage interference to the measurement signal is significantly lower than for differential voltage probes. As the system is physically small and needs no cabling to a central unit, e.g. a DSO or PC, the handling of such a voltage probe is simplified fundamentally.

6   Conclusion

In this paper, a 100 MS/s 10-25 MHz wireless voltage probe (WVP) is presented. It allows to measure accurately on high and transient reference voltages with a minimal impact on the circuit under test. The performance constraints of building a WVP with discrete components are investigated. In comparison to other actual voltage measurement systems, the WVP's sensitivity to CM voltage noise is significantly lower resulting in more accurate voltage measurements. In addition, no oscilloscope is required, as the measurement result is displayed on a PC that also is used for the control of the measurement process. For the prototype of the WVP one could refer to [12].
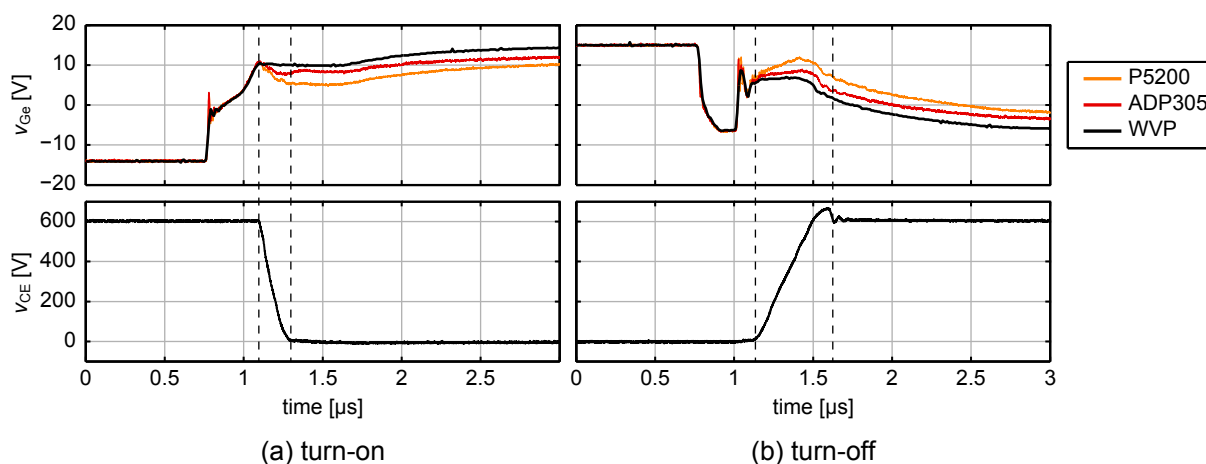
(a) turn-on   (b) turn-off

Figure 7: Measurement of a high-side IGBT module's gate-emitter voltage v_{Ge} (gate terminals) and corresponding collector-emitter voltage v_{CE} (power terminals) during (a) turn-on and (b) turn-off switching transients using different voltage probes: (1) Tektronix differential probe (P5200, 25 MHz), (2) LeCroy differential probe (ADP305, 100 MHz), (3) prototype of the proposed 100 MS/s WVP. The time derivatives of the collector-emitter voltage are about $dv_{CE,ON}/dt = -4$ kV/µs during turn-on and $dv_{CE,OFF}/dt = 1.7$ kV/µs during turn-off.

References

[1] R. E. Hebner, Jr., R. A. Malewski, and E. C. Cassidy. Optical methods of electrical measurement at high voltage levels. *Proc. of the IEEE*, vol. 65, no. 11, pp. 1524–1548, 1977.

[2] A. Nara. A measurement of the gate-emitter voltage waveform of IGBT in a motor driver circuit. *Proc. of the IEEE Instrumentation and Measurement Technology Conf. (IMTC 94)*, pp. 623–626, 1994.

[3] Y. Lobsiger. Realisierung eines Systems zur potentialgetrennten Spannungsmessung bei hohem und dynamischem Bezugspotential (in German). Master's thesis, Power Electronic Systems Laboratory, ETH Zurich, August 2009.

[4] W. H. Siew, Y. Wang, and M. Faheem. Digital wireless electromagnetic interference (EMI) data acquisition system. *Proc. of the Int. Symp. on Electromagnetic Compatibility (EMC 2005)*, vol. 2, pp. 342–345, 2005.

[5] W. H. Siew, Y. Wang, and M. Faheem. Wireless digital data acquisition system for EMI measurement in power substations. *Proc. of the 17th Int. Zurich Symp. on Electromagnetic Compatibility (EMC-Zurich 2006)*, pp. 288–291, 2006.

[6] Y. Wang, F. A. M. Mir, and W. H. Siew. Digital wireless data acquisition system for measurement in high voltage substations. *Proc. of the IEEE Power Engineering Society General Meeting*, 2006.

[7] W. H. Siew, Y. C. Liu, B. Musa, F. Mir, and Y. Wang. Basis for a wireless network for EMC measurements in electric substations. *Proc. of the IEEE Int. Symp. on Electromagnetic Compatibility (EMC 2007)*, pp. 1–5, 2007.

[8] N. Jackson. Bitscope. A mixed-signal capture engine. *Circuit Cellar*, vol. 97, pp. 1–8, August 1998.

[9] H. Cho, J. Jung, B. Cho, Y. Jin, S. Lee and Y. Baek. Precision time synchronization using IEEE 1588 for wireless sensor networks. *Proc. of the Int. Conf. on Computational Science and Engineering (CSE '09)*, vol. 2, pp. 579–586, 2009.

[10] P. Omlin and M. Wittmer. Entwicklung eines drahtlosen Messsystems zur potentialfreien Spannungsmessung (in German). Master's thesis, Power Electronic Systems Laboratory, ETH Zurich, September 2010.

[11] Agilent Application Note 5989-5732EN. Evaluating oscilloscope sample rates vs. sampling fidelity (2010). [Online]. Available: www.home.agilent.com.

[12] Enertronics GmbH. [Online]. Available: www.enertronics.ch