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Digital Object Identifier [10.1109/PEDG54999.2022.9923139](https://doi.org/10.1109/PEDG54999.2022.9923139)

2022 IEEE 13th International Symposium on Power Electronics for Distributed Generation Systems (PEDG)

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### **Suggested Citation**

F. Santos-Arana, Y. Pascal, J. Kuprat, M. Langwasser, K. Debbadi and M. Liserre, "Optical Sensing Applied to Thermal Observers for Enhanced Reliability of Power Modules," 2022 IEEE 13th International Symposium on Power Electronics for Distributed Generation Systems (PEDG), 2022, pp. 1-5, doi: 10.1109/PEDG54999.2022.9923139.

# Optical Sensing Applied to Thermal Observers for Enhanced Reliability of Power Modules

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**Abstract**—Condition Monitoring using thermal variables has been identified as one of the most critical aspects when assessing the performance and degradation of Power Modules (PMs). Different sensing technologies and algorithms have been proposed in order to develop high-performance reliability-driven control of PMs. This paper focuses on the application of contact-based fiber optic temperature sensors in thermal observers. These sensors have the potential to become key enhancers of real-time thermal monitoring applications. One specific power systems application is evaluated by assessing the dynamic capacity of converters under contingency operation via digital twins. The assessment of the dynamic capacity is limited to the most critical element, which normally corresponds to power electronics due to their small time constant. The application of these sensors extends the safety range of operation based on real-time operational data, rather than based on design.

**Index Terms**—Condition monitoring, dynamic capacity, optical temperature sensors, reliability, thermal observers.

## I. INTRODUCTION

The most limiting factor in the overall performance and degradation of power modules is the thermal heat dissipation [1], hence, condition monitoring and active control have great value in order to improve their lifetime. In the last decades, the industry has been gradually shifting from a “passive design” of power electronics modules, which relies on oversizing to ensure robust operation over the lifetime of the product, to an intelligent power actuator and sensor interface that can actively manage thermal characteristics [2], i.e. smart power modules. Thermal real-time monitoring plays a key role towards this transition. The possibility of scheduling maintenance before serious deterioration or breakdown avoids unscheduled maintenance operations [3], which depending on the specific application, can be extremely expensive (e.g. offshore wind farms). In [4], an industrial power electronics survey shows that only 50% of participants considered that existing reliability monitoring methods were good enough to meet customers’ requirements, which justifies the inclusion of

innovative temperature sensing in thermal monitoring via observers. This paper focuses on fiber optic temperature sensing and its applicability to thermal observers for developing enhanced reliability-driven control algorithms. Power converters’ dynamic capacity assessment during contingency operation of power systems is the case study here treated. The study shows how in certain time ranges ( $\sim$ ms and  $\sim$ s) the fiber-optic-based thermal observer has the potential to improve dynamic capacity assessment by providing fast, accurate and reliable temperature data in such time-window. This will allow for increased safety margins and therefore enhance curative actions.

The present article is structured as follows: In Section II, the main temperature sensing technologies are briefly described, specifically focussing on fiber-optics-based contact sensors. After being aware of the different sensing technologies, Section III covers the thermal observer concept, incorporating the suitable implementation of the contact fiber-optic-based temperature sensing technique. Section IV introduces the usage of the dynamic capacity of converters during contingency operation as well as an enhanced assessment of it by digital twins. The potential improvement in dynamic capacity assessment unlocked by thermal observers implemented with contact fiber-optic-based temperature sensors is also highlighted in this section. Conclusions of the paper are given at Section V.

## II. FIBER OPTICS TEMPERATURE SENSING OVER EXISTING TECHNOLOGIES

The most common temperature-sensing methods for power electronic modules used in real-time applications can be divided into physical-based sensors, temperature-sensitive electrical parameter (TSEP) based sensors, and temperature-sensitive optical parameter (TSOP) based sensors. This section provides a brief description of them, highlighting their main advantages and disadvantages. Contact-based fiber optics solution for temperature sensing is in the end analyzed.

### A. Module-integrated physical temperature sensors

The most common and low-cost method is to have a physical sensor integrated into the PM such as the Negative Temperature Coefficient (NTC) resistor placed on the Direct Bonded Copper (DBC) [5]. They have the disadvantage of recording the average temperature inside the PM on the DBC rather than the more critical junction temperature. Furthermore, there is a need for small signal conditioning circuits that should be designed to withstand the Electromagnetic Interference (EMI) that is generated inside the PM. In Fig. 1 an NTC inside a power module is shown.

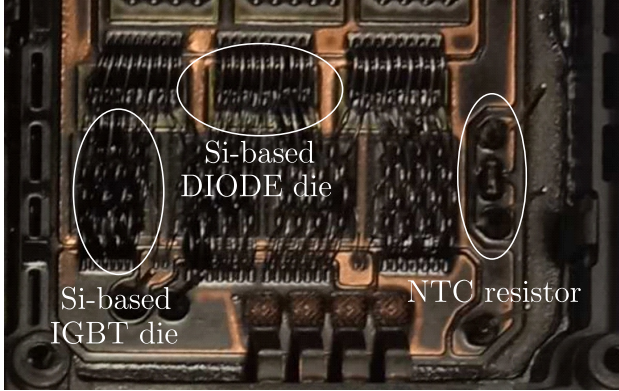


Fig. 1. NTC resistor inside an Si-based open power module, mounted close to the silicon.

Physical sensors can be applied to any power module regardless of the technology used, have substantial temperature sensitivity, and do not present a high calibration effort. However, they provide limited bandwidth, are highly sensitive to EMI, and require active area in the power module.

### B. Temperature-sensitive Electrical and Optical parameters-based temperature sensors

TSEP-based temperature sensing is non-invasive, however, it is characterized by complex extraction circuits which require monitoring either one or many of the device parameters such as threshold voltage, transconductance, internal gate resistance, parasitic capacitance, on-state voltage drop, etc [6]. The TSEP-based extraction requires high immunity to EMI from the PM. Another drawback of the TSEP-based method is that it cannot be applied for multiple dies in parallel, which might be critical when considering multiple parallelized dies' power modules as the one shown in Fig. 1. They provide higher bandwidth compared to physical sensors, as well as reflect the die's critical junction temperature. As an example, Fig. 2 shows the clear dependence of the voltage  $V_{CE\_ON}$  of an IGBT on the temperature. This voltage is very commonly used as TSEP for junction temperature estimation.

The TSOP-based method requires monitoring optical parameters, e.g. the electroluminescence of the power die [8]. As the TSEP-based method, it provides a high measurement bandwidth and reflect the die's junction temperature. However, it has a high insensitivity to EMI, and since the extraction

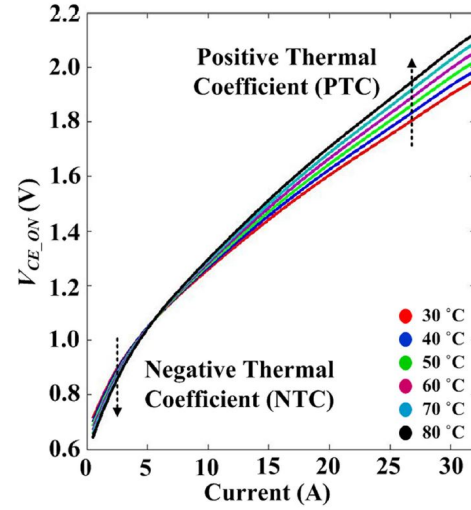


Fig. 2.  $I$ - $V$  characteristic curves of an IGBT. [7]

circuit can be placed far from the PM via fiber optic cables, the integration into the PM is also more favorable. In addition, TSOP-based method can extract temperature information from parallelized dies. Similar to TSEP-based approach, it requires high calibration effort. Both of these methods are dependent on the power semiconductor technology and are restrictive in this sense. Also, their temperature extraction capability depends on the operating point, so they might not be able to gather information from all semiconductors simultaneously (e.g., depending on the direction of the instantaneous current, some dies will not conduct).

### C. Contact-based fiber optic temperature sensors

Contact-based fiber optics temperature sensors constitute an accurate ( $\pm 1$  K) and highly sensitive (tens of mK) commercial solution, available from several manufacturers, for fast ( $\sim$  ms) contact temperature measurements. The sensors themselves consist in a small piece ( $\sim 100$ s of  $\mu\text{m}$ ) of semiconductor crystal (namely Gallium Arsenide GaAs) which is put in thermal contact with the device to be characterised.

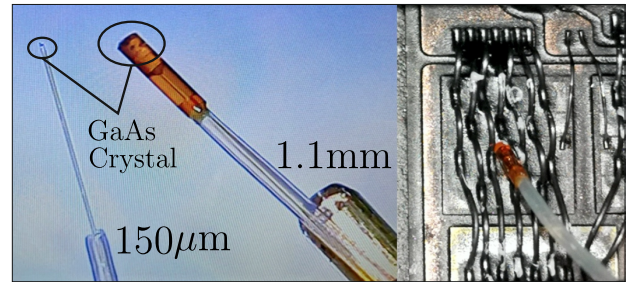


Fig. 3. Gallium Arsenide based optic sensors (opSens Solutions - 150  $\mu\text{m}$  OTG-F and 1.1 mm OTG-A models) with different diameters sensing between bond-wires.

The bandgap of the crystal, which varies with temperature, is then probed by optical means, using a fiber optic connecting the crystal to a signal conditioner. The GaAs-based optic

fiber temperature sensor can be used to monitor the junction temperature inside the PM [9], fitting it between the die's bond-wires (see Fig. 3). They can be thought of as a mixture of TSOP (since they use the temperature-sensitive optical characteristic of a semiconductor crystal) and physical sensors (since they are placed in physical contact with the surface to be monitored).

As this GaAs sensor's signal conditioner is calibrated by the manufacturer for temperature, there is no extra calibration effort necessity and can be integrated into the PM of any semiconductor technology. Contact-based fiber optic sensors require no or little space in the PM. Differently from TSEP-based approach, contact-based fiber optic sensors can be used to monitor independent parallelized dies' junction temperature, independently from the operating point. Fiber optic extraction has intrinsic galvanic isolation and is not influenced by EMI. The main limitations of such solutions are their invasion into the PM (which could limit them to laboratory setups), their cost, and the size of the conditioner. However, due to the demand for more reliable and dense smart power module solutions, it might be possible in the future to integrate fiber optic solutions in PMs for real-time applications. The inclusion of such a technology would provide very accurate thermal measurement and reasonable bandwidth.

Aspects like bandwidth, integration, temperature extraction capability, calibration, and immunity against EMI are weak points of on-PM and on-die physical sensors. As for TSOPs, they have limited flexibility and remain intricate to implement. In comparison, commercial contact fiber-optic-based sensors

are highly accurate and sensitive, isolated and EMI-immune, and require no calibration. Also, by placing them on top of the die, they require less active area than NTC sensors placed on the DBC. However, they remain an expensive solution that can be challenging to implement in-situ. In addition, bulky conditioner is required, which can be placed far from the PM. An overview of the advantages and disadvantages between TSEP-based, NTC resistor-based (which are the most popular option for real-time temperature-monitoring applications), and contact-based fiber optic temperature sensors is provided in Fig. 4.

### III. OPTICAL SENSING FOR ENHANCED THERMAL OBSERVERS PERFORMANCE

One promising application where optical sensing can be used is here highlighted, which is the development of thermal observers. Basically, a thermal observer is the fusion between thermal sensing technologies and thermal estimators [10] [11]. By joining the two of them, it is possible to suppress their intrinsic disadvantages in order to maximize their benefits. Considering that not every location of the PM is accessible [12], and that the system becomes more expensive when increasing the number of sensors, it becomes obvious that the placement of temperature sensors is limited. In order to tackle this issue, thermal estimators are developed. With this second approach, a reduced number of temperature sensors can be placed inside the power module, and by means of thermal characterization techniques, relatively simple (e.g. Foster and Cauer) or more complex (e.g. 3-D thermal models) thermal networks can be derived, which will allow the estimation

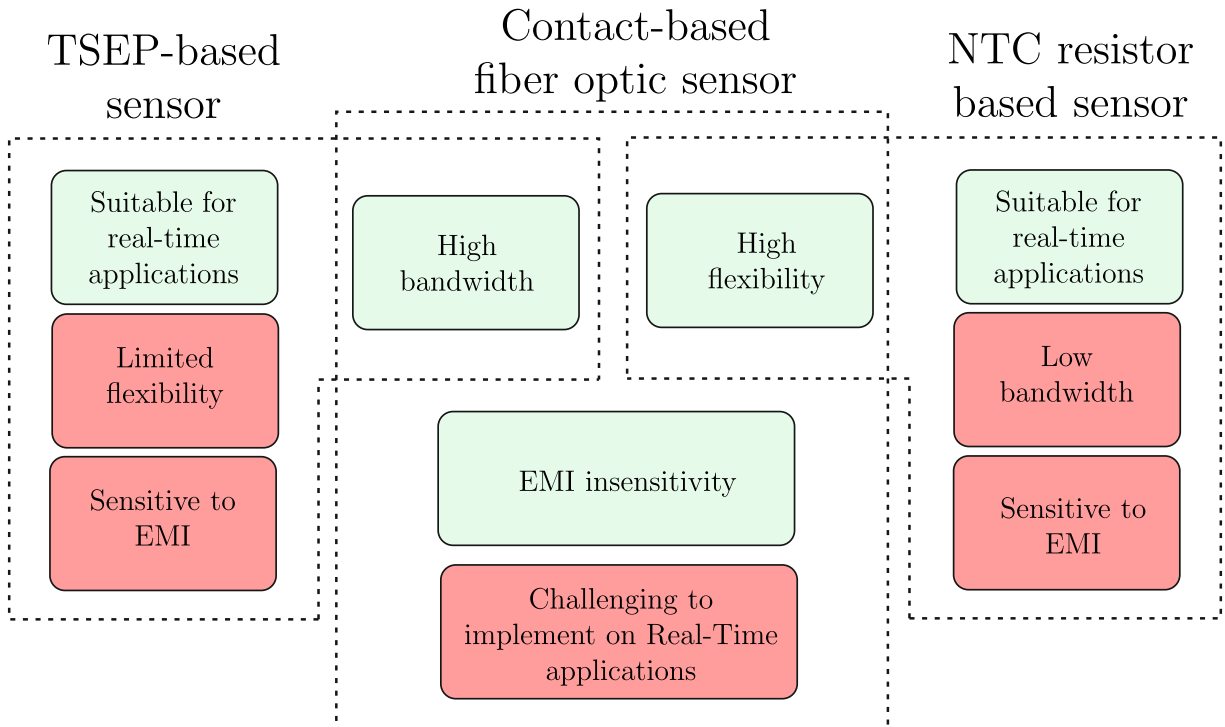


Fig. 4. Characteristics overview of most common sensing methods for real-time applications and contact-based fiber optic temperature sensors.

of different temperatures of the PM where no sensors are placed. The main disadvantage lies in the open-loop nature of the algorithm. The accuracy of the estimated temperatures is dependent on the model accuracy, which is static over the time (if not manually re-adjusted), so considering that the thermal behaviour of the PM will vary as the state of health changes, the accuracy of the thermal estimator will decrease. Thermal observers are finally proposed as an enhanced version of thermal estimators. By adding a closed-loop correction to the model (see Fig. 5), higher accuracy over the lifetime of the PM is obtained (also higher computational effort is needed [13]).

This closed-loop is made usually by sensing one temperature that is also being estimated, the error is then fed into a controller, whose corrective action (e.g. power losses estimation [11]) will effectively eliminate this error, correcting model deviations, and therefore enhancing the estimated temperatures over the thermal network. Thermal observers are mainly used in two scenarios: For monitoring thermal state variables, and for adaptive parameter estimation, which are key enablers for degradation monitoring and state of health estimation [1]. Additional features can be highlighted about thermal observers, such as their capability of estimating temperature with zero phase-lag, or the noise suppression present in Kalman-filter implementations. In comparison with thermal estimators, the accuracy and reliability of the observer are achieved by means of the mentioned temperature feedback loop, so the sensing performance of this temperature can be identified as the most critical aspect when assessing the quality of the thermal observer, thus the quality of the reliability-driven control.

Thermal observers implemented with contact-based fiber optic sensing technique could be justified in applications where

the critical time window needed for real-time temperature data collection is in the milliseconds to seconds range. Thermal observers based on standard NTC resistors are not suitable for junction temperature monitoring [10] [14]. Their low bandwidth limits their operation to average substrate temperature monitoring. While TSEP and TSOP-based observers would achieve higher bandwidths, their flexibility is limited due to a high dependence on the semiconductor technology.

#### IV. RELIABILITY-DRIVEN CONTROL FOR POWER SYSTEM APPLICATIONS: DYNAMIC CAPACITY OF POWER CONVERTERS

A recent challenge in power system operation is the reduction of redispatch costs, which result from the conventionally-used preventive remedial actions. Power-electronics equipment like high-voltage direct current (HVDC) systems or Smart Transformers are highly flexible and have short reaction times, which offers an easy and secure way to act curatively when congestion has occurred. Curative actions allow the power system assets to operate at higher power loading during nominal conditions, reducing the costs of no longer needed redispatch measures. In this scenario, the dynamic capacity of power electronic systems has recently gained attention, i.e. the possibility to operate the asset temporarily beyond their guaranteed active and reactive power limits in order to enhance their service capability and availability [15]. The most critical components in a power electronics station (e.g. HVDC station) are the semiconductors in the power electronic valves, which have small thermal time constants and strict thermal constraints depending on their respective junction temperature. The initial concept of dynamic capacity is based on the designed dynamic capacity, which arises from planned over-design margins. However, in order to make full use of the dynamic capacity, it is required to estimate the currently

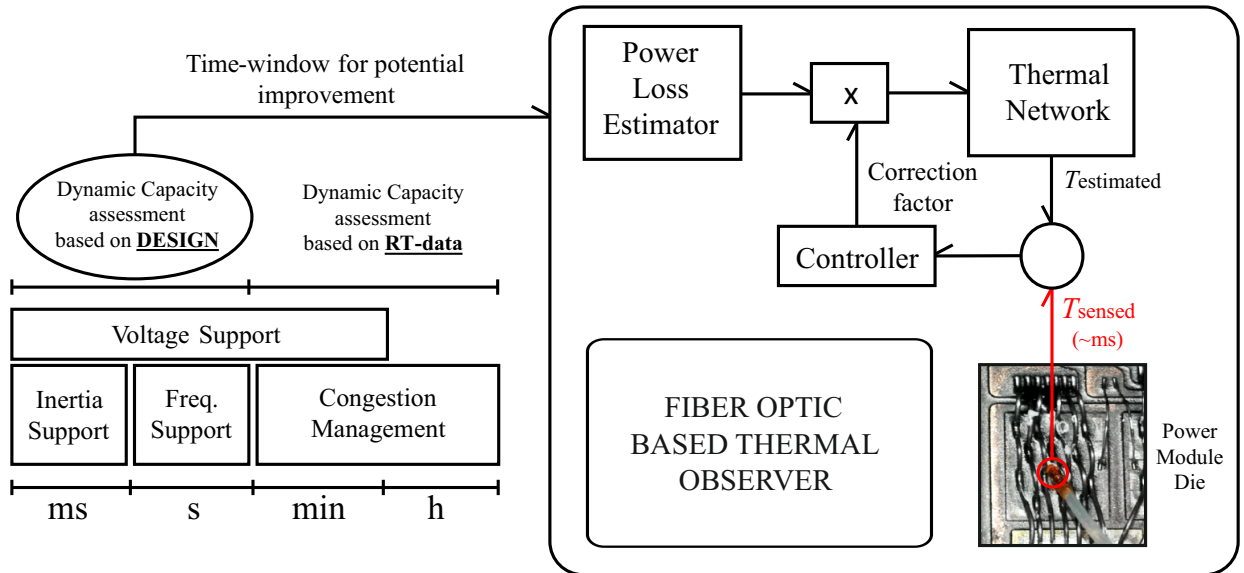


Fig. 5. Enhanced thermal observer scheme based on optical sensing techniques and its potential applicability to dynamic capacity assessment of power converters.



available dynamic capacity in real-time using live operational data on-site. Despite using direct thermal measurements the junction temperatures to evaluate the current available dynamic capacity of the converters can be obtained by thermal observers introduced in Section III.

Even though dynamic capacity can be separated into active and reactive power, the actual limitation lies in the thermal capabilities of the semiconductors [15]. As shown in Fig. 5, some of the curative services that could be provided (in this case by an HVDC system) are based on design, rather than observational data. This is due to the lack of reliable temperature information in such a short time-window. Some of these services include the provision of reactive currents during Fault Ride Through (FRT) ( $\sim 150$  ms), the dynamic voltage support after FRT ( $\sim 1$  s), or the Primary Frequency Regulation Controlling Voltage Dependent Loads (PFR-VDL) ( $\sim 10$  s). With contact-based fiber optic sensors as the smallest one shown in Fig. 3, with a time response of 5 ms, real-time data of all dies' most critical junction temperature could be monitored during this time-window. A more secure dynamic capacity assessment in this time range would allow enhanced curative actions, increasing for example the temporary load factor during contingency operation.

Furthermore, thermal digital twins [16] can be used for a better representation of the real thermal behavior by the model of the estimator part of the observer. A digital twin consists of three main parts: a real-time simulation of the physical system or a part of it in the virtual domain, measurements of the physical system, and an optimization algorithm adjusting the virtual model parameters for an optimal representation of the physical system by the virtual model. This definition fits also for what is known as adaptive thermal observer [1]. This approach gives an optimized representation of the real thermal behavior by the model in the estimator part of the observer. Therefore, it provides a lower error between measured and estimated junction temperature, which is fed into the corrector part of the observer. Further, it enables accurate predictions on how the junction temperatures would change if the usage of dynamic capacity involves a change of the respective active and reactive power set-points. Having these accurate real-time predictions of the junction temperature behaviors raise the possibility of implementing model predictive control to further enhance the usable dynamic capacity, enabling fast and optimized decisions on which of the converters should provide which services during contingency operation.

## V. CONCLUSION

This paper provided a comparison between contact-based fiber optic temperature sensing with possible alternatives. Contact-based fiber optic temperature sensing advantages were highlighted, such as EMI immunity, low-calibration effort, the possibility of measuring parallel dies, operating point independence, high bandwidth, and universal applicability. Such advanced temperature sensing can bring substantial advantages for thermal observers' performance, and therefore benefits the

reliability-driven control of power electronics modules. For reliability critical environments these advantages can justify the use of these sensors in real-time/industry-related applications, even though, they have been mainly used in laboratory set-ups until now. The same advantages facilitate assessing the dynamic capacity of converters under contingency operation via digital twins. Dynamic capacity assessment based on current observers limits the operation based on real-time data. With the usage of contact sensors based on fiber optic technologies, this design-based operation could be reduced, thus increasing reliability in such power systems applications.

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