# Power Electronics For Very High Power Applications

Mohsen Abedian zadeh

Master of Azas University of Scientific and Research of Iran
mohsenabedinian@yahoo.com

**Abstract:** As we prepare to enter the 21st Century we stand on the threshold of a Power Electronics Revolution. The last 50 years have seen the growth of power conversion to the point at which today about 15% of the electric power produced undergoes some form of electronic conversion. However, most of this occurs at the "consumer end" of the supply chain from battery chargers to locomotives. Although HVDC transmission has exploited line-commutated power electronics for the past three decades, it is the 1990s which have witnessed the commissioning of self-commutated power electronics at the transmission level. Developments in semiconductors and their packaging technology will drive power electronics into distribution applications as device efficiency and reliability increases whilst the cost of the switched megawatt falls. The key semiconductors enabling this predicted transition will be reviewed and the anticipated demands of system builders on device suppliers discussed

Keywords : Thyristors, Criteria

## 1 Introduction

Industry and Traction. Power electronics is introduced in areas where its benefits are cost effective. Early applications were power supplies, battery chargers and motor drives. The'60 saw the introduction of line commutated control (thyristor and diodes) in traction applications followed, in the '70s, by fast thyristors and diodes in self-commutated applications (choppers and inverters). The '80s saw a rapid expansion of industrial motor drives thanks to the development of the bipolar power transistor in the form of Darlington and "Triplingtons" and that of the GTO (Gate Turn-off Thyristor) and the IGBT (Insulated Gate Bipolar Transistor).

During the early '80s the transistor-based structures pushed the thyristor-based structures (fast thyristors and GTOs) towards higher powers such that by the early '90s GTOs had become "very high power devices" suitable for traction and high power (> 1MW) or medium voltage (>2.3 kV) industrial drives. IGBTs with their simple drive requirements (voltage control) displaced Darlington transistors (current control) as the device of choice Low Voltage Drives (LVDs) up to 480 Vrms and by the mid '90s they had displaced GTOs in LVDs up to 690 Vrms thanks to the widespread availability of devices with ratings of up to 1800V. This availability (low cost) has turned the LVD industry into a B$3 market with a growth rate of about 7% p.a. The emergence of the IGCT (Integrated Gate- Commutated Thyristor) [S. Klaka et al, 1] in the late '90s has given a new impetus to the drives industry by doing to Medium Voltage Drives (MVDs) up to 6900 Vrms what IGBTs did for LVDs up to 690 Vrms. This market represents B$0.5 with a growth rate of about 15%

p.a. due to the large number of MV motors in the field, 95% of which operate without torque and speed control due to the absence, until now, of cost-effective drives solutions at these voltage levels. Generation, Transmission and Distribution. The above illustrates that over the last 30 years the driving forces behind power electronics lay in the cost-effective implementation of control at the *user* level either to stabilize voltages (power supplies) or to control motor speed, acceleration and torque (industrial processes or transportation). The transmission and distribution industry also has its problems to solve but has traditionally not had cost-effective solutions for them. Notable exceptions have been High Voltage DC (HVDC) to transmit DC power over large distances at up to 1MV and Static VAR Compensators (SVC) to control inductors or capacitors for voltage stabilization. All these have relied on Phase Control Thyristors (PCTs) to control power primarily because these devices offer the highest power control and hence the *most cost-effective* (though not necessarily the *best*) solutions. The generation industry has had little call for power electronics at the output stage since the powers are typically very large (250 MW) and generators operate in synchronism with the infinite grid.

## Emerging Markets

New applications are emerging that lie between the worlds of Traction and Industry making the efficient transmission and consumption of electricity important but also rendering the installation of supplementary transmission lines difficult. **New Applications**. These non-traditional power electronics applications have been variously estimated to represent a world equipment market of

219

up to B$3 in the early years of the next century and have therefore the potential of matching the importance of the traditional Traction and Industrial Drives markets.

## COMPONENTS

The choice of semiconductor devices to meet the needs of these emerging markets seems limited for the coming years. Though many device structures are repeatedly presented and discussed, most remain either in the domain of low power or in the realm of research. Some of these device structures are summarized. The only devices under serious consideration for the present and the foreseeable future are the IGBT, the GTO and the IGCT [1] whereby the GTO is destined to be replaced by the IGCT since it offers no advantages over the latter.

This in effect leaves only two contenders for high power applications and in any discussions of their relative merits, the oft forgotten but crucial fast recovery diode must be considered as it plays a deciding role in whether a thyristor or a transistor should be the self commutated element.

Semiconductor packaging is also an important Parameter in determining the appropriate technology for a given topology. Although all present power Semiconductors are made from silicon and as such all Packaging options are equally available to IGBTs, IGCTs and diodes, the device's structure conditions its preferred encapsulation which in turn influences circuit layout.

## DEVICE SELECTION CRITERIA

Although the semiconductor device may only 1% of the cost of a large installation such as a 100 MW intertie, its influence on the performance and indeed on the final system's capital and running costs are disproportionately large. Equipment design criteria are the same for all applications but the weight that each one carries depends on the application. The equipment parameters are, in order of their general ranking:

- COST
- device cost
- circuit cost
- RELIABILITY
- wear out
- Random failures
- EFFICIENCY
- Full load
- Partial load
- SIZE
- Weight
- Volume
- Foot-print

These system requirements translate into the following device requirements:

1) Low device costs
2) Rugged operation (few ancillary components)
3) High reliability (low random failures, high power And temperature cycling, high blocking stability)
4) Simple assembly & repair(modularity)
5) High currents (turn-off, rms, average, peak, surge)
6) High voltages (peak repetitive, surge, dc-continuous)
7) Fast switching (short on/off delays, short rise/fall Times, short turn-on/off times)
8) Low losses (conduction, switching)
9) High frequency (fast switching, low switching losses).

## THYRISTORS AND TRANSISTORS

Self-commutated devices fall into one of two categories: thyristors or transistors each with its very distinctive differences which translate into real and perceived advantages and disadvantages as the above listed goals are sought. It is not coincidental that the two practical contenders for high power are each from one of these categories.

Transistors are *amplifiers* which can allow large collector currents to be varied by a small controlling *base* current in conventional bipolar transistors or, in the case of the more sophisticated IGBTs by a *gate voltage* requiring very little current and hence little control power. The gate control circuit can vary the speed at which switching *on* or *off* occurs.

Thyristors are *switches* composed of a regenerative pair of transistors as illustrated in Fig. 1. Once the regenerative action is initiated (or interrupted) the thyristor switches very rapidly from "on" to "off" and vice versa with little, if any, control of the speed at which this occurs being exercised by the *gate unit*.
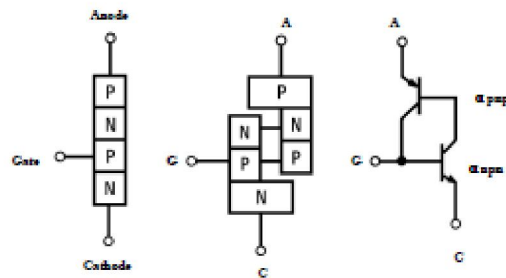


Fig 1 – Equivalent circuit of a Thyristor

Any adjustment of the speeds at which anode voltage and current transit during switching (di/dt and dv/dt) must be adjusted by external components or designed into the intrinsic behavior of the device. In the case of the IGCT this is easily achieved for turn-off dv/dt through anode design. This cannot be so easily achieved for *di/dt* at turn-*on*

220

which results in the basic circuits of Figs. 2 and 3 respectively for IGCT and IGBT 3-phase, 2-level inverters. Because many of the emerging high power applications of Table 1 will be based on self commutated voltage-source inverters, the discussions of these two key components will relate to this simple inverter topology.
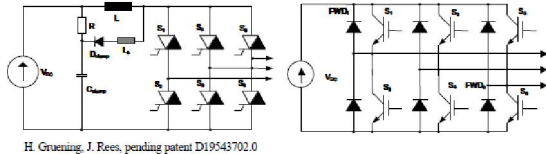


H. Gruening, J. Rees, pending patent D19543702.0
"Stromrichters.chaltungsanordnung".
Fig. 2 - Typical *IGCT* Inverter          Fig. 3 - Typical *IGBT* inverter

Figure 2 shows a typical IGCT inverter with a di/dt limiting circuit inserted between the quasi zero impedance supply (dc-link) and the inverter.

Inductance L limits the rate-of-rise of current in the inverter when one of the IGCTs (switches S1 to S6) is turned on. The limitation of current rise is determined by the allowable rate-of-*fall* of current in the associated diodes which in most IGCTs is integrated onto the same wafer (see Fig. 4). The energy stored in the inductance L, once the diode is commutated, is subsequently dissipated in resistance R and the optional clamp capacitor, Cclamp, can be used to minimize voltage overshoot.

In the event of failure of two devices in one phase the resulting current is limited by the inductance to a value *Ifault =Vdc • C/L* where C is the capacitance of the DC-link. Fig. 3 shows an IGBT inverter consisting solely of semiconductor components which can be realized in a *single* module for low power systems but is generally composed of multiple modules comprising IGBT and diode chips parallel-connected to achieve the desired rating as illustrated in Fig. 5.
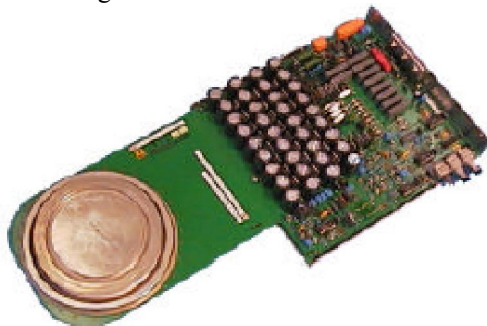


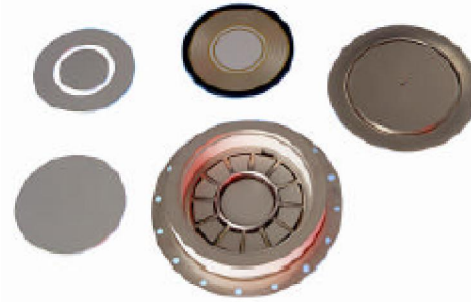Fig. 4b - Complete 4.5 kV/2.6 kA IGCT



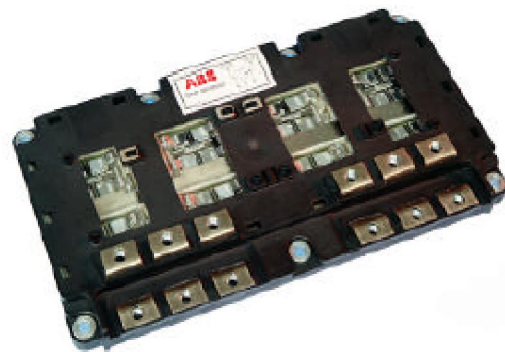Fig.4a - Open GCT showing reverse-conducting silicon wafer (top centre)



Fig. 5 - 2500 V/1200 A IGBT module (single switch)

The advantage of the topology of Fig. 5 lies in the complete absence of ancillary components, the di/dt controlling function being implemented by gate control whereby the turn-*on* of the IGBT is slowed to match the allowable turn-*off* speed of the diode. It can be shown [Carroll & Galster, 2] that the resulting losses generated in the IGBT are the same as those dissipated in the resistance of Fig. 2. In Fig. 3, the absence of impedance (e.g. an inductance) between the power electronics (inverter) and the dc-link results in extremely high fault currents in the event of simultaneous failure of two devices in the same phase. This fact limits the direct applicability of the topology of Fig. 3 to low voltages (up to about 1.5 kV) or small dc-link capacitors. At higher voltages and powers a decoupling of link and inverter via inductance or resistance is required to limit co-lateral explosion damage caused by vaporization of the chip bond wires and the electromagnetic forces of the fault current An exception to this may be found in very high voltage systems involving massively seriesed IGBTs where a large number of redundant devices may be used (e.g. 100 devices in a 100 kV stack). Here, if the proper service intervals are respected, nothing short of a direct lightning strike would cause simultaneous failure of all redundant devices of a

221

phase leg, such that the omission of link impedance becomes once again feasible. Fig. 6 shows an IGBT "press-pack module" specially designed for series connection [3]. Here the parallel connected IGBT and diode chips are pressure contacted with each contact designed to take full load current should a chip fail. The series operation of the stack is thus assured (with appropriate redundancy) if one chip (hence one "pack") fails short.
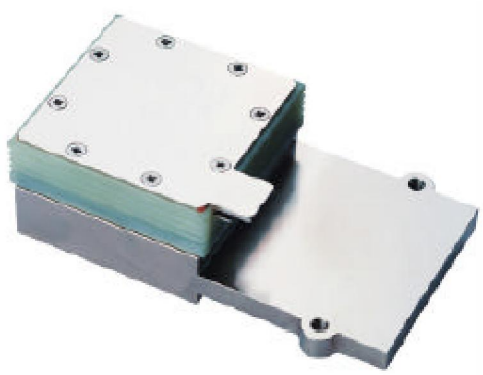


Fig. 6 - 2500V/700 A IGBT Press-Pack Module for Series Connection

**DIODES**

As indicated above, the diode plays a determining role in the topology chosen, by dictating the allowable turnon di/dt of a voltage source inverter and hence determining the principal part of the turn-on losses which will be dissipated in the silicon (Fig. 3) or in the resistance (Fig. 2). The relevant waveforms are shown in Fig. 7.
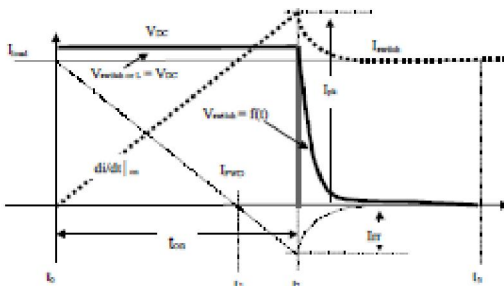


Fig. 7 - General turn-on wave-forms for Figs. 2 and 3

It has been shown [2] that the circuit-specific turn-on losses are approximately given by:

$$E_{on-circuit} = \frac{V_{dc}^2 \cdot I_{pk}^2}{2 \cdot k \cdot Pr_{rmax}} \dots\dots\dots\dots(1)$$

where k is a constant and $Pr_{rmax}$ is the maximum diode reverse recovery power for safe operation. The higher the diode's $Pr_{rmax}$, a measure of its Safe Operating Area (SOA), the lower the circuit specific turn-on loss and it can be shown that minimum circuit-

specific losses occur when the reverse recovery peak is roughly equal to the load current [3].

Fig. 7 shows the voltage collapse over the device generating a subsequent *device-specific* loss:

$$E_{on-device} \approx I_{pk} \cdot \int_{t2}^{t3} V_{switch}(t) \, dt \dots\dots\dots\dots(2)$$

Exploiting an increased diode SOA per equation (1) will reduce *Eon-circuit* but increase *Eon-device* so that in the absence of a di/dt limiting choke, IGBT turn-on losses can only be reduced by increasing diode speed whereas if a choke is used both an increase in speed and SOA will reduce losses and ensure that they are not dissipated in the silicon of the active switch. Present silicon diodes are reaching their performance limits and will probably reach their SOA limits by the end of this century. Thus the turn-on loss limitations of chokeless topologies will not change until the advent of silicon carbide diodes with 100 times lower switching losses [Silber, 4]. Though laboratory samples exist at voltages up to 5 kV, it will probably not be until the later half of the next decade that reliable cost-effective components become common.

**COST, RELIABILITY, FREQUENCY and EFFICIENCY**

In the transmission applications of the future, the above will become important goals. The first two objectives are compatible because they derive from minimal component-count. Frequency however, as required by active filtering, is at odds with all the goals because switching losses increase with frequency and reduce the useful power a component may handle thus increasing component-count and reducing reliability. In the very high power applications listed in Table 1, IGCTs allow instantaneous switching powers of 16 MW today but will nevertheless require series or parallel connection to fulfil those application requirements. Since these are generally for medium to high voltages (10 kV and above), it is principally the *series* connection which comes into consideration. Inverters of 100 MW have already been realised using first generation IGCTs in direct series connection [Steimer et al, 5], albeit at line frequency. Today, 5 MW IGCT inverters operating directly on the 4160 V MV line, without snubbers or series connection, are entering commercial service at 500 – 1000 Hz pwm.

Second generation IGCTs with 30 % lower losses than those of only 3 years ago are now being designed into 50 MW interties and STATCOMs with the *snobberies* turn-off ratings (4 kA) of conventional GTOs fitted with 6 µF snubbers.

222

IGBTs and IGCTs both fulfil the requirements of "rugged switching" which implies the ability to turn off without commutation networks or "dv/dt snubbers". These networks are "undesirable" not only because of the added costs and losses they engender, but because they impose time constants which in turn limit operating frequency. Because of their low losses and snubberless operation, 6 kV IGCTs can operate at 500 Hz with burst operation up to 25 kHz at full rating [Klaka et al, 6]. Higher frequencies – thermally determined – are possible with lower voltage devices namely 1 kHz for 4.5 kV and 3 kHz for 3.3 kV devices. Equipment volume, or more frequently, *footprint*, are also cost drivers in any major installation. It is believed that IGCT inverters hold the record for compact construction with values of 13 to 20 kVA per litre having been reported along with efficiencies of 99.65% at 200 Hz pwm [1].

IGCTs and IGBTs are both transistors when turning *off* and as such they generate the same losses. The turn-*on* losses have already been discussed and are negligible for IGCTs with their obligatory di/dt controlling chokes and hence the "external" circuit-specific losses (which are recoverable at the cost of additional circuitry) do not enter the devices's thermal budget. In the conducting state, the IGCT is a thyristor with two injecting emitters giving it half the conduction loss of a transistor structure allowing "more room" in the thermal budget for dynamic losses, hence frequency.

The traditional workhorse of power electronics, the GTO, has exhibited a constant component cost-per-MVA reduction of 20% p.a. over the last decade. The GCT has arrested this trend but has halved driver costs, reduced cooling costs by 30 % and eliminated snubber and even free-wheel diode costs, resulting in over 30% cost reductions in power electronics in a single step.

## TRENDS and IMPROVEMENTS

Currently IGBTs and IGCTs are commercially available to 3.3 and 6 kV respectively. These voltages can be increased to 6.5 and 9 kV respectively by the end of the century if the increased losses of such devices can be tolerated by their prospective applications. Current 4.5 kV IGCTs on 4" wafers are rated up to 4 kA but the potential for reaching 6 kA at 6 kV has been demonstrated [3].

Inorganic passiveness such as *Diamond Like Carbon* will allow higher dc voltage ratings or operating junction temperatures and new materials such as the metal matrix Aluminum Silicon Carbide may reduce thermal resistance by allowing wafer bonding to the package. IGBT modules with built-in water-cooling are already being developed for Traction applications and the principal could be applied to monolithic IGCTs. Conventional Phase Control Thyristors (PCTs) will continue to dominate traditional HVDC [Kamp et al, 7] and the newly introduced BCT, "Bi-directionally controlled Thyristor", will become an important component in conventional VAR compensation.

## CONCLUSIONS

In the multitude of emerging FACTS applications, IGBTs and IGCTs will be the principal component players in the next decade. In very high current and medium voltage applications, the thyristor structure will be the favoured approach especially where decoupling chokes are deemed desirable or mandatory.

The IGBT in the choke-less configuration of Fig. 3 will greatly benefit from the rapid progress in silicon carbide diodes though commercial arrival of the latter on the FACTS scene is not imminent. Nevertheless, the IGBT will continue to be favoured in the lower cost choke-less topology where this adequately off-sets the higher cost of the component itself.

## ACKNOWLEDGEMENTS

## REFERENCES
[1] Klaka S., Frecker M. and Gruening H., 1997, "The Integrated Gate-Commutated Thyristor: A New High-Efficiency, High-Power Switch for Series or Snubberless Operation", PCIM'97 Europe.
[2] Carroll E., and Galster N., 1997, "IGBT or IGCT: Considerations for Very High Power Applications", Forum Européen des Semiconducteurs de Puissance.
[3] Zeller H-R., 1998, "High Power Components: From the State of the Art to Future Trends", PCIM'98 Europe.
[4] Silber D., 1998, "Leistungsbauelemente: Functionsprinzipien und Entwicklungstendenzen", ETGFachbericht.
[5] Steimer P., Gruening H., Werninger J., and Schroeder D., 1996, "State-of-the-Art Verification of the Hard Driven GTO Inverter Development for a 100 MVA Intertie", PESC'96 Baveno.
[6] Klaka S., Linder L. and Frecker M., 1997, "A Family of Reverse Conducting Gate

223

Commutated Thyristors for Medium Voltage Drive Applications", PCIM'97 Asia.

[7] Kamp P., Neeser G. and Bloecher B., 1998, "Hoechstsperrende Halbleiter-Bauelemente in stationaeren Hochleistungs-Stromrichtern", ETGFachbericht.

[8] Thomas K., Backlund B., Toker O. and Thorvaldsson B., 1998, "The Bidirectional Control Thyristor", PCIM'98 Asia. Intel Corporation, "Intel CE6353 DVB-T Demodulator." Datasheet available online.

[9] M. I. Skolnik, Radar Handbook. New York: McGraw-Hill, 3rd ed., 2008. Y. Wu and L. M. Davis, "Fixed-point fast decoding of the silver code," in Australian.

[10] Communication Theory Workshop, pp. 1–5, Feb. 2009. P. Howland, D. Maksimiuk, and G. Reitsma.

[11] "FM radio based bistatic radar," in IEE Proceedings - Radar, Sonar and Navigation. 3 June 2005, vol. 152 of IEE Proceedings - Radar, Sonar and Navigation. 3 June 2005, pp. 107–15, IEE, 2005.

[12] H. Griffiths and C. Baker, "The Signal and Interference Environment in Passive Bistatic Radar," in Information, Decision and Control, 2007. IDC '07. 12-14. Feb 2007, Information, Decision and Control, 2007. IDC '07. 12-14 Feb 2007, (Adelaide), pp. 1–10, 2007.

[13] N. J. Willis and H. D. Griffiths, Advances in Bistatic Radar. SciTech Publishing, 2007.

[14] D. K. Barton, Modern Radar System Analysis. Artech House, 1988.

[15] L. V. Blake, Radar Range-Performance Analysis. Artech House, 1986. P. M.Woodward, Probability and Information Theory with Applications to Radar. Norwood,

[16] MA: Artech House, 1980. H. A. Harms, J. Palmer, and L. M. Davis, "Understanding the signal structure in dvb-t signals for passive radar detection," in IEEE International Radar Conference, 2010.

[17] J. E. Palmer, H. A. Harms, S. J. Searle, and L. M. Davis, "DVB-T passive radar signal processing," IEEE Trans. Signal Processing, Apr. 2012. Submitted.

[18] M. A. Richards, Fundamentals of Radar Signal J. Palmer, S. Palumbo, T. Cao, and S. Howard, "A new illuminator of opportunity bistatic radar research project at dsto," Tech. Rep. TR-2269,

[19] The Defence Science and Technology Organisation, 2008. S.J. Searle, S.D.Howard, and J.E.Palmer, "Remodulation of DVB–T signals for use in passive bistatic radar," in 44th Asilomar Conference on Signals Systems & Computers,

[20] S.P. Sukhatme, "Solar Energy Principle of Thermal Collection and Storage" , edition, Teta Mc Graw-Hill Company Limited, New Delhi, 1996.

[21] vS.V. Patankar, "Numerical Heat Transfer and Fluid Flow" , First Edition, Taylor & Francis, January 1980.

[22] C. Angeli and E. Leonardi, "The effect of thermo-diffusion on the stability of a salt gradient solar pond" , International Journal of Heat and Mass Transfer, vol.48, 2005, pp. 4633-4639.

[23] R.B. Mansour, C. T. Nguyen and N. Galanis, "Numerical study of transient heat and mass transfer and stability in a salt-gradient solar pond", International Journal of Thermal Sciences, vol.43, 2004, pp.779-790.

[24] M. R. Jaefarzadeh, "Thermal behavior of a small salinity-gradient solar pond with wall shading effect", Solar Energy, vol. 77, 2004, pp. 281-290.

[25] M. Hammami, M. Mseddi and M. Baccar, "Transient natural convection in an enclosure with vertical solutal gradient", Solar Energy, Vol. 81, 2007, pp. 476-487.

[26] H. Kurt, M. Ozkaymak and A. K. Binark, "Experimental and numerical analysis of sodium-carbonate salt gradient solar-pond performance under simulated solar radiation" , Applied Energy, vol. 83, 2006, pp. 324-342.

[27] M. Husain, S. R. Patil, P. S. Patil, and S. K. Samdarshi, "Simple methods for estimation of radiation flux in solar ponds", Energy Conversion & Management, vol. 45, 2004, pp. 303-314.

[28] M. C. Giestas, H. L. Pina, J. P. Milhazes and C. Tavares, "Solar pond modeling with density and viscosity dependent on temperature and [9] salinity" , International Journal of Heat and Mass Transfer, vol. 52, 2009, pp. 2849-2857.

.[29] M. Karakilcik, K. Kiymac and I. Dincer, "Experimental and theoretical temperature distributions in a solar pond", International Journal of Heat and Mass Transfer, vol. 49, 2006, pp. 825-835.

[30] Intel Corporation, "Intel CE6353 DVB-T Demodulator." Datasheet available online www.intel.com/design/celect/datashts/D55752.htm, accessed 21 June 2012.

[31] M. I. Skolnik, Radar Handbook. New York: McGraw-Hill, 3rd ed., 2008.

[32] Y. Wu and L. M. Davis, "Fixed-point fast decoding of the silver code," in Australian Communication Theory Workshop, pp. 1–5, Feb. 2009.

[33] P. Howland, D. Maksimiuk, and G. Reitsma, "FM radio based bistatic radar," in IEE Proceedings - Radar, Sonar and Navigation. 3 June 2005, vol. 152 of IEE Proceedings - Radar, Sonar and Navigation. 3 June 2005, pp. 107–15, IEE, 2005.

[34] H. Griffiths and C. Baker, "The Signal and Interference Environment in Passive Bistatic Radar," in Information, Decision and Control, 2007. IDC '07. 12-14. Feb 2007, Information, Decision and Control, 2007. IDC '07. 12-14 Feb 2007, (Adelaide), pp. 1–10, 2007.

[35] N. J. Willis and H. D. Griffiths, Advances in Bistatic Radar. SciTech Publishing, 2007.

[36] D. K. Barton, Modern Radar System Analysis. Artech House, 1988.

[37] L. V. Blake, Radar Range-Performance Analysis. Artech House, 1986.

[38] P. M.Woodward, Probability and Information Theory with Applications to Radar. Norwood, MA: Artech House, 1980.

[39] H. A. Harms, J. Palmer, and L. M. Davis, "Understanding the signal structure in dvb-t signals for passive radar detection," in IEEE International Radar Conference, 2010.

[40] J. E. Palmer, H. A. Harms, S. J. Searle, and L. M. Davis, "DVB-T passive radar signal processing," IEEE Trans. Signal Processing, Apr. 2012. Submitted.

[41] M. A. Richards, Fundamentals of Radar Signal Processing. McGraw-Hill, 2005.

[42] J. Palmer, S. Palumbo, T. Cao, and S. Howard, "A new illuminator of opportunity bistatic radar research project at dsto," Tech. Rep. TR-2269, The Defence Science and Technology Organisation, 2008.

[43] S.J.Searle, S.D. Howard, and J.E.Palmer, "Remodulation of DVB–T signals for use in passive bistatic radar," in 44th Asilomar Conference on Signals Systems & Computers, Nov. 2010.