DE1_Appendix V

MICROGRIDS

Large Scale Integration of Micro-Generation
To Low Voltage Grids

WORK PACKAGE E

TASK TE2

FAULT CURRENT CONTRIBUTION FROM CONVERTERS

DRAFT Issue No 1

21st April 2004

Nilanga Jayawarna

UMIST

Access: Restricted to project members

Introduction

Most conventional distribution protection is based on short-circuit current sensing. Conventional rotating generating plants provide very considerable currents in the event of a short circuit. This high fault current capability of synchronous generators is very useful in detecting the occurrence of a fault. A majority of the micro-sources in a MicroGrid would be interfaced through power electronics. These power electronic based micro sources cannot normally provide the conventional high levels of short-circuit required. Typically they may only be capable of supplying twice the load current or less to a fault, unless the inverters are specifically designed to provide high fault current. Some conventional over-current sensing devices will not respond to this level of over-current, and those that do respond will typically take many seconds to respond, rather than the fraction of a second that is required.

A MicroGrid is required to operate when islanded as well as when grid-connected. In the grid-connected mode, the main distribution system would contribute to the short-circuit current and the use of traditional protection relays should not pose a problem. Using current based fault detection in an islanded MicroGrid however would be a great concern due to the lower short circuit to load current ratios. Sufficient fault current sources within the MicroGrid are a requirement for successful operation of over-current protection.

Clearing faults with conventional over-current devices in low voltage load circuits will require an available fault current of at least 3 times the maximum load current of the circuit [1]. Hence a study of the technical and commercial implications of using inverters with conventional over current protection was carried out.

Aims of the study

1. Investigate how much fault current is available from various converter designs
2. Investigate the possibility of increasing their short circuit capability at a reasonable cost. (At least 3 per unit fault current lasting between 1-3 seconds).

Short circuit capability of power modules

Each inverter design will have different parameters and the basic characteristics of each unit depend on the design goals of a particular manufacturer and/or application. The selection of power modules for any application is subject to the consideration of voltage rating, current carrying capacity (under realizable cooling conditions and with reference to the switching frequency) and safe operating areas (SOA).

The maximum continuous collector current I_c, indicated in the datasheets as typical currents for module designation and as maximum ratings may be calculated for a stationary fully controlled IGBT-module at a case temperature, T_{case}, according to the following formula [2].

$$I_c = \frac{\left(T_{j(\max)} - T_{case}\right)}{\left(V_{CEsat} \times R_{thjc}\right)}$$

Where T_j = Junction temperature

V_{CEsat} = Collector Emitter saturation voltage

R_{thjc} = Thermal resistance, junction to case

Fault currents

Fault currents are collector currents, which exceed standard operating values of a certain application due to control or load errors. They might lead to damage of the power semiconductors by the following mechanisms [2, 3, 4, 5]:

- Thermal destruction by high power dissipation
- Dynamic avalanche
- Static or dynamic latch-up

Components used in power electronics must be protected from non-permissible stress in any operational state. In other words, they are not allowed to leave the safe operation areas (SOA) indicated in the datasheets. Operating outside SOAs will cause damage and, therefore, reduce component life. In the worst case, the component might be destroyed immediately.

Behaviour of IGBT's during short-circuit conditions

Short circuit is a fault condition that will drive the operation of the IGBT outside its safe operating area [4]. When considering short circuits experienced by IGBT's, two different cases of short circuits have to be distinguished [2, 4, 6].

Short circuit I – Hard Switching Fault (HSF)

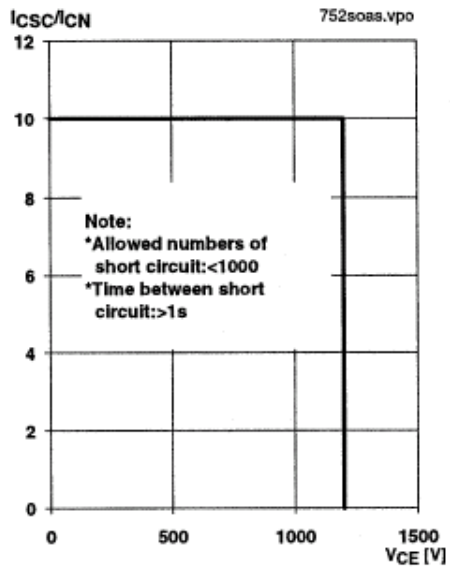
In case of a Hard Switching Fault, the transistor is turned on to an existing short circuit. The IGBT is in the linear mode operation. The rate at which the device begins to conduct current and the magnitude of the fault current are related to the charging rate of the input capacitance and the gate drive voltage. The stationary short-circuit current adjusts itself to a value that is determined by the output characteristic of the transistor. Typical values for IGBTs are up to 8-10 times the rated current.

Short circuit II – Fault Under Load (FUL)

In this case the transistor is already turned on, before the short circuit occurs. The IGBT is operating in the saturated mode. Compared to Hard Switching Fault, this case is much more critical with respect to transistor stress.

Hard Switch faults (HSF) result in much lower fault currents than the fault under load (FUL). Most manufacturers use HSF to quote the short-circuit capability of their devices because this test is less stressful on the device and yields more flattering results [4].

Figure 1 is a typical SOA-diagram at short circuit (SC SOA) shown in the IGBT datasheets. This shows the limits for safe control of a short circuit [2]. According to this SOA diagram, an IGBT is capable of delivering up to 10 per unit fault current. But these values are given for a short-circuit duration that is less than $10\,\mu s (t_{sc} \leq 10\mu s)$. There is no possibility of a conventional over-current relay responding in such a brief time interval. We require at least 3 per unit fault current lasting 1-3 seconds to operate existing over-current relays.



$T_j \leq 150$ °C
$V_{GE} = \pm 15$ V
$t_{sc} \leq 10$ µs
L < 25 nH
$I_{CN} = 75$ A

Where

T_j = Junction temperature

V_{GE} = Gate Emitter voltage

t_{SC} = Short-circuit duration

L = External collector inductance

I_{CN} = Nominal collector current

Figure 1: SOA at short circuit of an NPT-IGBT (SC SOA) - Normalized short-circuit current versus collector-emitter voltage (SKM100GB123D) [2]

According to our findings, the only way to achieve this is to increase the rating of the power module. If we want 3 pu fault current, we simply have to increase the rating of the module by three times its load rating.

Cost of increasing the rating of a power module

Price/ cost predictions of power modules in general are difficult to make since they tend to be strongly influenced by market forces. We can, with some assumptions, identify trends. The actual cost of a power module is dictated by its current rating because all other things being equal, the cross sectional area of silicon required increases in proportion to current. Therefore if we neglect the market distortions, the cost of an IGBT should be approximately proportional to its current rating. According to a study carried out by Williamson, S., et al, [7, 8], the breakdown of the cost of a 7.5 kW three-phase power module is as shown in Figure 2.

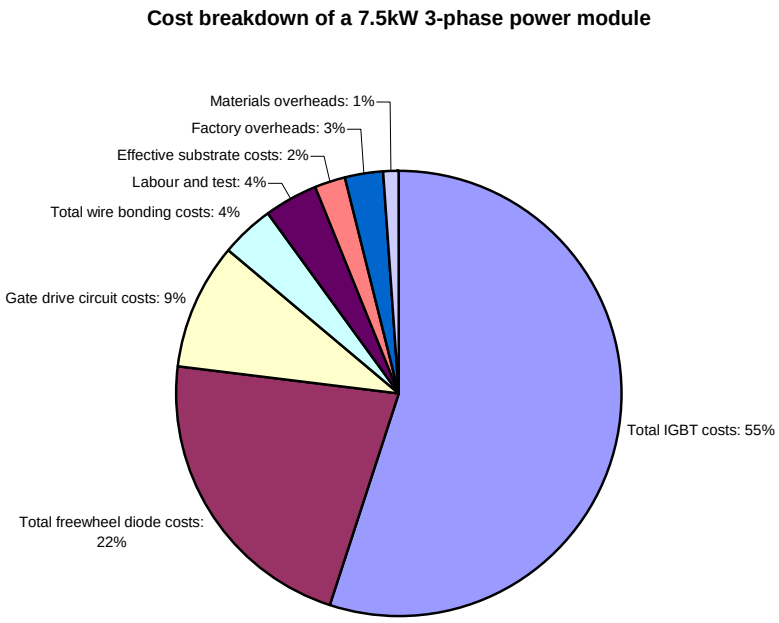


Figure 2: Cost breakdown of a 7.5 kW power module [6]

According to Figure 2, 77% of the module cost is for IGBTs and freewheel diodes, which depends mainly on the silicon cross section required. These costs would increase proportionally to the current rating of the module. the bulk of the other costs (gate drive circuit costs, total wire bonding costs, labour and test, factory overheads and materials overheads) could be assumed to be constant for a unit and not change with an increased rating.

Table 1 shows the current retail price (for one unit) of an IGBT power module of half-bridge configuration according to its voltage and current rating [9].

Collector current, $I_c @ T_c = 25°c$ (A)		25	50	75	100	150	200	400
Unit Price (UK £) 1 UK£ = 1.50078 EUR	$V_{CES} = 600V$	-	45.34	54.19	58.47	90.12	99.5	280.32
	$V_{CES} = 1200V$	64.49	39.56	49.60	104.76	125.25	100.57	-

Table 1: Unit Price of power modules [9]

Let us assume that the unit price for a module with I_c = 50A demonstrates its true cost and further that we can derive the actual cost of the modules with higher ratings according to the cost breakdown in Figure 1. Let us assume that 23% of the costs are independent of any increase in the rating of the module and the only factor influencing the cost will be a linear increase in the cost of greater volume of silicon required. Based on these assumptions, the expected variation of actual price of a power module is shown in figure 3. According to this plot, when the current rating is increased to four times from the original rating (say, 50A), the cost is incremented approximately by a factor of three. This implies that a module with 3 pu short circuit capability could be achieved at less than three times the original cost.

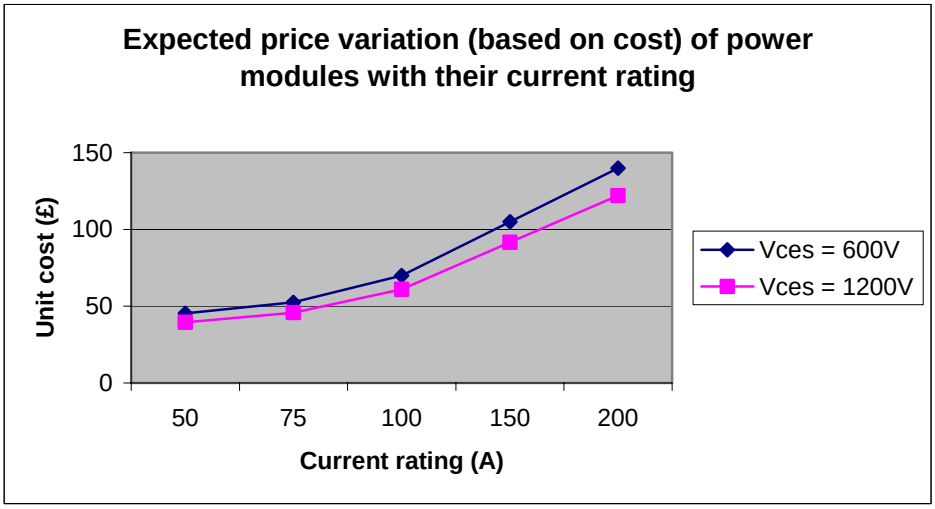


Figure 3: Expected unit cost vs. current rating of power modules

However if we look at the actual retail price of power modules, it creates another picture. Figure 4 shows the Unit Price vs. current rating of power modules according to Table 1.

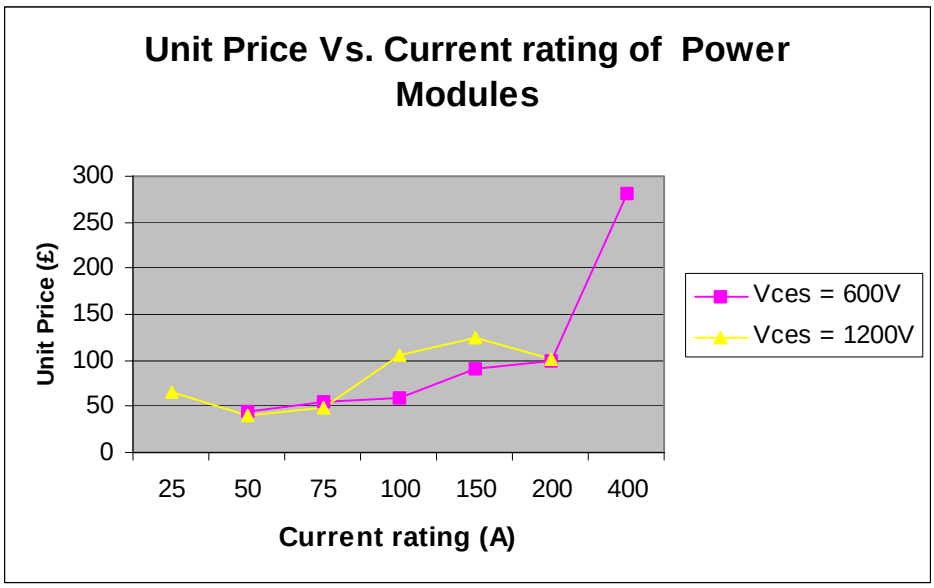


Figure 4: Unit price vs. current rating of power modules [9]

These actual retail prices are compared with the expected prices below. Figure 5 and 6 show the comparison between expected price based on cost and actual price of power modules with voltage ratings of 600V and 1200V respectively.

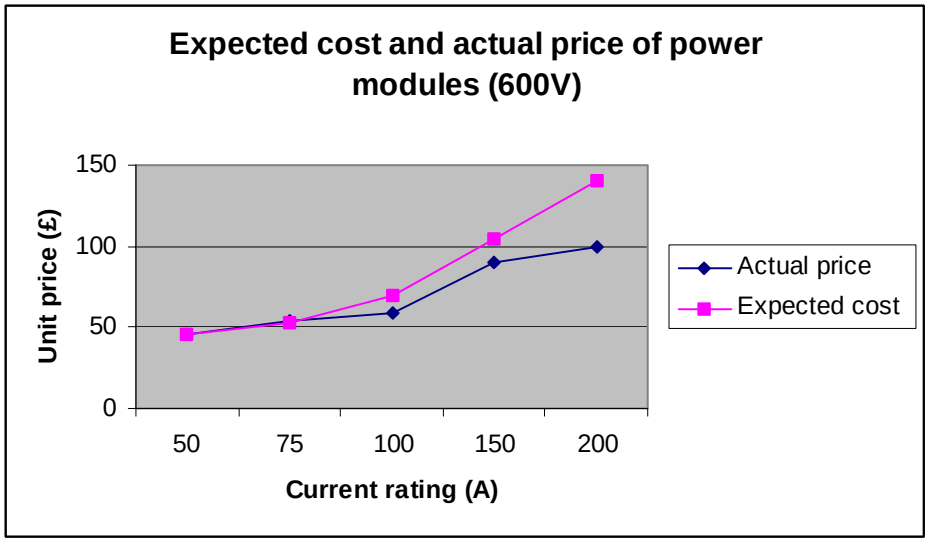


Figure 5: Comparison of expected price and actual price of a power module (600V)

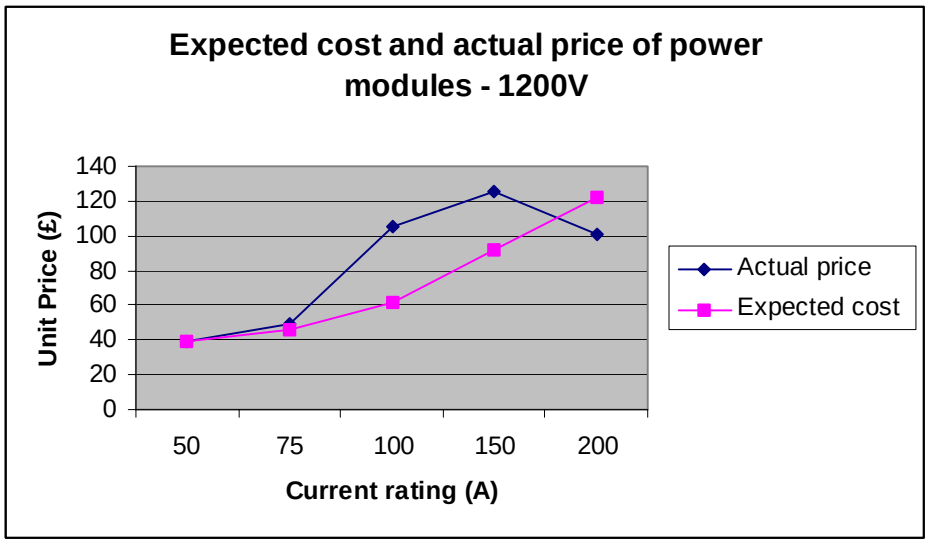


Figure 6: Comparison of expected price and actual price of a power module (1200V)

The above two figures clearly indicate that the actual price of a unit does not reflect the expected cost calculated based on the incurred cost. It is quite obvious that economy of scale/ market forces play a major role in the determination of the price of a power module. Although it is evident that we will have to incur a higher cost to install inverters with a higher rating, it is difficult to quote a specific amount at present.

Voltage control of inverters

The determination of voltage and current ratings of power devices in inverter circuits depends on the types of inverters, load and methods of voltage and current control. We can look at the possibility of an inverter with a higher ac voltage output in order to have a unit with an increased power rating. Consequently this unit could have a lower current rating for the same application. We will have two options open due to this.

1. Buy a unit with lower current rating at a lower price
2. Buy a unit with the original current rating, which will offer a higher short circuit capability.

There are various techniques to vary the inverter output voltage. The most efficient method of controlling the output voltage is to incorporate Pulse Width modulation (PWM) control within the inverters. The most commonly used techniques for three-phase inverters are Sinusoidal PWM, 60- Degree PWM, Third-harmonic PWM, and Space vector modulation (SVM) [3].

Sinusoidal PWM compares a high frequency triangular carrier with three sinusoidal reference signals (modulating signals) to generate the gating signals for the inverter switches. The main advantage of this technique is that it generates line-to-neutral ac spectra with no low-order third harmonics. The main disadvantage is that the maximum possible values for ac and dc output voltage are low.

In 60° PWM, the waveform is flat-topped from 60° to 120° and 240° to 300°. All triple harmonics are absent and switching losses are reduced. The 60° PWM creates a larger fundamental and utilizes more of the available dc voltage than the sinusoidal PWM.

Third harmonic injection PWM is implemented in the same manner as Sinusoidal PWM. The difference is that the reference ac waveform is not sinusoidal but consists of both a fundamental component and a third harmonic component. This technique is preferred in three-phase applications due to the cancellation of third harmonic components and better utilization of the dc supply.

Space Vector Modulation (SVM) is a digital modulation technique that generates PWM line voltages, which are in average equal to reference line voltages. This method offers the advantages of lower harmonics, a higher modulation index and digital implementation.

Different types of modulation schemes for three-phase inverters with Modulation index, M=1, are summarised in Table 2 [3, 10].

Modulation type	Normalised Phase Voltage, V_P/V_S	Normalised Line voltage, V_L/V_S	Output waveform
Sinusoidal PWM	0.5	0.5 * √3 = 0.8666	Sinusoidal
60° PWM	$1/\sqrt{3}$ = 0.57735	1	Sinusoidal
Third-harmonic injection PWM	$1/\sqrt{3}$ = 0.57735	1	Sinusoidal
SVM	$1/\sqrt{3}$ = 0.57735	1	Sinusoidal
Over-modulation	Higher than the value for M = 1	Higher than the value for M = 1	Non-sinusoidal

Table 2: Summary of modulation techniques

This table clearly shows that the ratio of ac output to dc link voltage rating of all other PWM techniques is better than the original sinusoidal PWM method and is equivalent among them.

We are mostly interested in voltage source converters (VSC) for MicroGrid applications. The third harmonic injection PWM technique could be identified as suitable for VSC applications for the following reasons [10].

1. It offers the overall best quality ac waveforms.
2. It demands the lowest ripple current from the input filter capacitor
3. Hardware implementation of this system is quite simple.

However SVM is increasingly used in power converter applications today due to its flexibility of manipulation and compatibility with microprocessor control. Therefore an inverter with third harmonic injection PWM or SVM could be the best option to be used in MicroGrids.

Conclusions

With conventional over-current protection of a MicroGrid, especially when islanded, Voltage Source Converters must contribute 3 pu fault current in the least for a minimum duration of one second. A viable means of achieving this level of short-circuit capability is to increase the rating of the power module (use a VSC with higher current capability compared to converter rating needs). This option implies incurring greater cost.

Third harmonic injection PWM or SVM are identified as the best methods of voltage control for the VSCs to increase their voltage ratings.

Further work is required on the following areas

- How to adapt from fault current levels available while utility connected to fault current levels after separation from the grid.
- Investigate a method of detecting faults that is not dependent on a large ratio between fault current and maximum load current.

References

1. Feero, W.E., Dawson, D.C., Stevens, J., "White paper on Protection Issues of the MicroGrid Concept", CERTS, March 2002
2. http://www.semikron.com - Application Assistance Notes. (Accessed in March – April 2004)
3. Rashid, M H., " Power electronics – Circuits, Devices and Applications", Third Edition, Pearson Education, Inc., 2004
4. Chokhawala, R S., Catt, J., Kiraly, L., " A discussion on IGBT short-circuit behaviour and fault protection schemes", IEEE Transactions on Industry Applications, Volume: 31, Issue: 2, March- April 1995, Pages: 256- 263.
5. Mohan, N., Underland, T.M., Robbins, W.P., "Power Electronics – Converters, Applications and Design", Second Edition, John Wiley and Sons, INC. 1995

6. Frisina, F., et al, “Short circuit transient behaviour of IGBT devices in series connections”, Proceedings of the 2002 IEEE International Symposium on Industrial Electronics (ISIE 2002), Volume: 3, 26- 29 May 2002, Pages: 878- 883.
7. Williamson, S., McDonald, S., Green, A. and Barnes, M., “Low-cost inverters for pump and fan drives”, in “Power Electronics and Electrical Drives” chapter of “Energy Efficiency in Motor Driven Systems”, editors Parasiliti, F. and Bertoldi, P., Springer Verlag, ISBN 3-540-00666-4, 2003, pp 426-431
8. Green, A M., Barnes, M., Williamson, S. and McDonald, S., “Reducing the cost of speed control”, 3rd International Conference on Energy Efficiency in Motor Drive Systems (EEMODS), Treviso, Italy, Sept. 18-20, 2002
9. FARNELL in one Catalogue, 2 – Electronic components, May 2003, page 431
10. Boost, M A., Ziogas, P D., “State-of-the-art carrier PWM techniques: A critical evaluation”, IEEE Transactions on Industry Applications, Volume: 24, Issue: 2, March- April 1988, Pages: 271- 280