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Technical Note to Facilitate Wind Turbine Inverter Change & Modification for MCS

April 2011

RenewableUK previously: BWEA

CONTENTS

1 Purpose

1.1 The purpose of this document is to provide guidance for approvals bodies to assess the impact of changing, up-dating or modifying an inverter for use on a wind turbine already qualified under MCS. Following the assessment, it may be deemed appropriate that further testing of the revised system configuration is required if the impact of the change is considered sufficient to cause a material deviation from the "representative configuration"* originally tested.

*NOTE: "Representative configuration" as per definition in the BWEA Small Wind Turbine Performance and Safety Standard (29 Feb 2008).

2 Inverter Definition

2.1 For the purpose of this assessment, an "inverter" is defined as the necessary electronic arrangement (hardware and software) required to condition and control the electrical output of a wind turbine generator to that required by the load. The term "converter" would be the technically correct definition for such an arrangement; however "inverter" is retained for convenience of recognition. In some arrangements, the inverter <u>may</u> also be responsible for the following (not exhaustive) functions:

- Adjusting the level of turbine power with respect to speed or generator voltage
- Controlling external turbine peripherals, such as brakes etc
- Assisting or starting the turbine

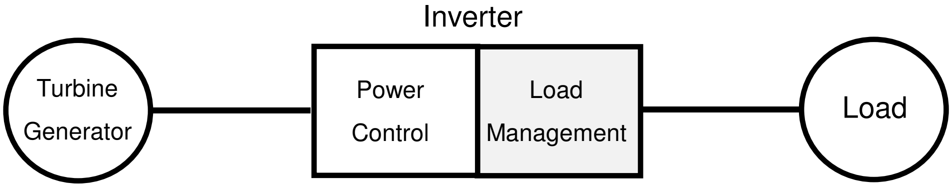


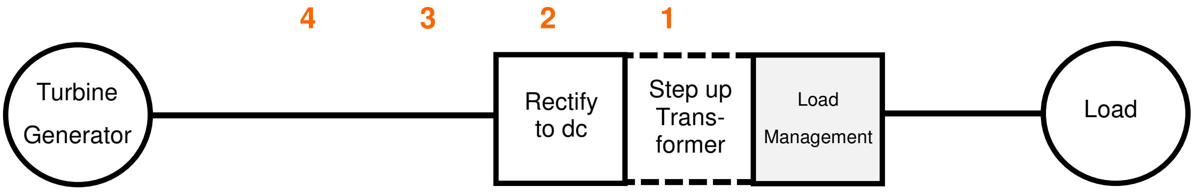
Fig 1, General functional description of an inverter

2.2 As per figure 1, the inverter can be considered as having two core functions – the techniques deployed, both in hardware and software, to achieve these two functions differ depending on the application and the architecture chosen. This is therefore fundamental to assessing the impact of inverter change.

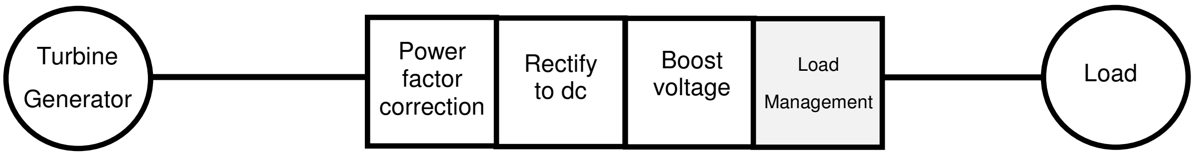
2.3 For a given load type, as defined in Annex A, the difference in turbine performance and behaviour will be defined by the techniques deployed to achieve effective power control. An assessment of impact of change should therefore take this into account. Whereas an assessment of impact of change to load management need only be considered when changing between the load types defined in annex A, providing that the inverter is certified for the grid code relevant to the region of use or the equivalent off-grid standards.

3 Electronic Architecture

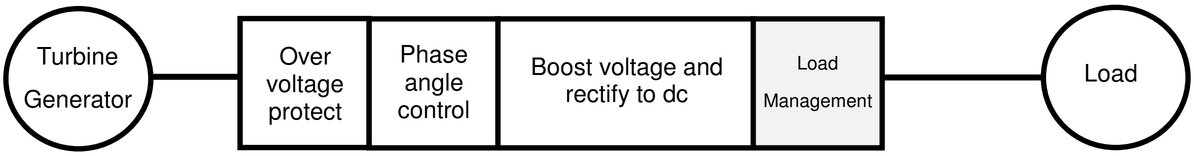
3.1 An inverter, as defined in section 2, will have an architecture that provides the functionality illustrated in figure 2, where conversion to ac or dc output is implied.



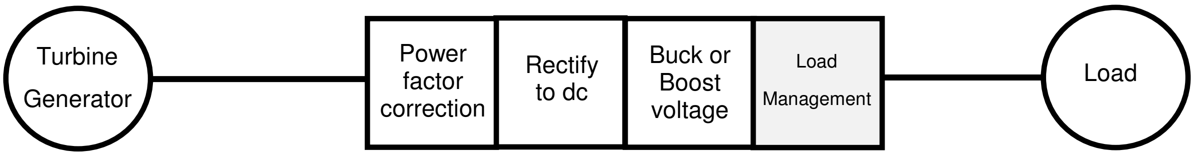
3.1.1 Inverter with passive rectifier and possible step-up transformer (ac)



3.1.2 Inverter with passive rectifier and voltage boost



3.1.3 Inverter with active rectifier



3.1.4 Inverter with passive rectifier and voltage buck & boost

Fig 2, Inverter architecture and resulting functionality

3.2 Like for like changes where the same electronic architecture is retained, as defined by 3.1.1 through 3.1.4, will have very little impact on the safety and performance aspects of the system, providing that the rating of the inverter and the control setup of the turbine, as defined in sections 5 through 10, are considered. Any replacement inverter however must be certified to the necessary regional grid code and/or safety standards.

3.3 When a change in electronic architecture has been proposed between the options illustrated in 3.1.1 through 3.1.4, differences in power control can result. Illustrated in figure 3 is a comparison of performance attributes that differentiate each architecture. Some differences are more significant than others in magnitude and hence overall turbine performance. However, a simple traffic light system has been illustrated to highlight incremental performance improvement, whereby red equates to worst case relative performance and green best case. An indicative scale of performance range is highlighted and the significance to overall performance assessed as low, medium or high.

Architecture (see fig 2)	Inverter Efficiency	Cut-in Voltage	Generator Efficiency	Generator Stress	Generator Noise	Over-Voltage Protect
Affected by	1,2,3	1	2,3	3	3	1,4
3.1.1	🟩 ssdsdsfff	🟥	🟥	🟥	🟥	🟥
3.1.2	🟨	🟩 ssdsdsfff	🟨	🟨	🟨	🟥
3.1.3	🟥	🟨	🟩 Ssdsdsfff	🟩 ssdsdsfff	🟩 ssdsdsfff	🟩 Dsdsf ff
3.1.4	🟨	🟩 ssdsdsfff	🟨	🟨	🟨	🟨
MEASURE (Indicative)	95-97%	50-200V	92-96%	0.65-1puA	Specific	Specific
Significance	L	H	M	M	M	H

Fig 3, Relative performance of electronic architectures

4 Performance Curve and Energy Yield

4.1 A modification to the “representative configuration” of inverter can be as simple as a minor change to the power curve or a change of architecture between those defined in 3.1.1 through 3.1.4. In the case of the latter, the architecture deployed can have a significant effect on the turbine cut-in and cut-out voltages and hence the operating turbine speed range. This can have a significant impact on the energy yield of the turbine, as indicated by the high (H) significance in figure 3.

4.2 Other parameters afforded to the inverter solution of choice that will affect the energy yield include:

- Over-voltage protection used to enable continued generation in high wind speeds
- Input current rating
- Generator and inverter efficiency
- Internal consumption and stand-by strategy
- Rate of load acceptance and rejection on the turbine
- Method by which control of power is achieved

4.3 Following consideration of sections 5 through 10, if doubt or ambiguity remains, the approval body can request practical evidence of a power curve to validate performance.

5 Cut-in, Cut-out and Over Voltage Protection

5.1 An architecture that enables a solution with low cut-in voltage will facilitate the turbine to start generating power from relatively low wind, and hence low rotational speeds. Naturally this should enable generation of relatively more energy, particularly in lower wind speed sites, when compared against a system with higher cut-in voltage. However, it is recommended that cut-in be set at a minimum speed where the power available from the turbine is greater than the consumption of the inverter to always enable positive output.

5.2 At higher wind and rotational speeds, the inverter will cut out if the maximum input voltage is exceeded and no additional over voltage protection has been included in the system. *Over voltage protection by additional components are not considered here, but may be specified by the turbine manufacturer*. Clearly an inverter with higher maximum input voltage will enable continued generation than one with a lower value, and hence a wider window of operation will be achieved. However, beyond a simple auto-disconnect contactor on the input of the inverter, some inverter architectures can provide means by which to limit the generator voltage to enable continued generation. This is clearly illustrated in figure 4, as is the relative cut in performance of two identically rated inverters with differing voltage threshold specification.

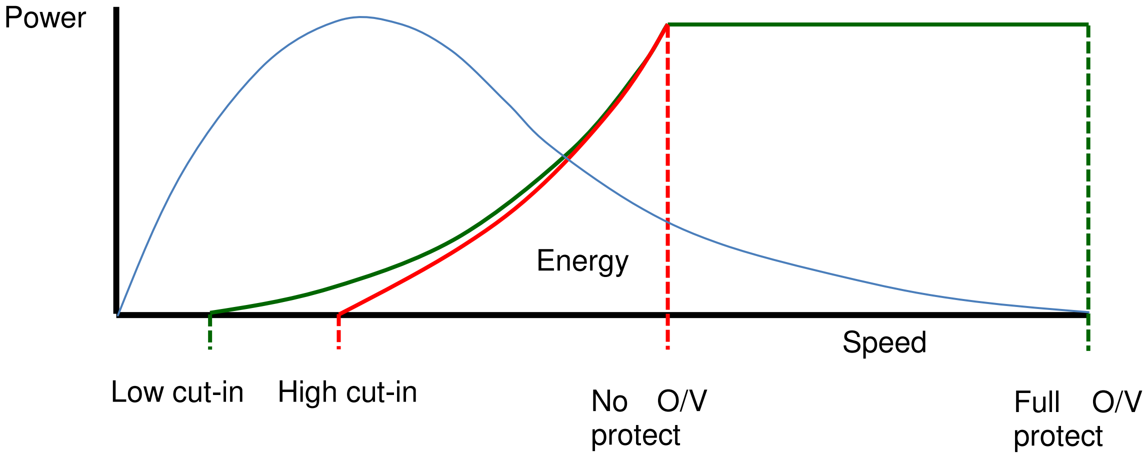


Fig 4, Effect of voltage threshold on turbine performance (O/V = Over Voltage)

6 Generator Current and Rated Speed

6.1 The inverter should be specified in such a way that its input current rating enables the power required at rated speed to be achieved. Illustrated in figure 5 is a comparison of two identically rated inverters with identical cut-in, cut-out and over voltage protection features. However, their input current rating differs, and hence inverter with red characteristic yields a higher rated speed than that of green, thus affecting overall turbine performance and acoustic output.

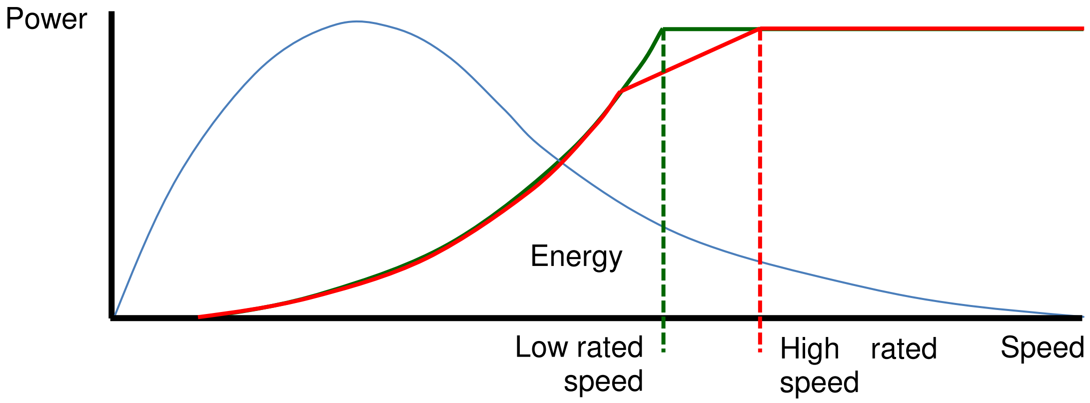


Fig 5, Effect of current rating on the performance of turbines with similar inverter architecture

6.2 Like for like comparison of input current rating is important when comparing identical architectures outlined in 3.1.1 through 3.1.4. However, when comparing the relative performance of the different architectures outlined in 3.1.1 through 3.1.4, a simple comparison of input current is not sufficient. This is due to the method achieved by the architecture to control generator phase angle – defined as block 3 in figure 2.

6.3 Without any phase angle compensation, the generator current will lag voltage and thus further contribute toward a relatively high voltage drop under load. Hence, the current drawn from the generator for a given power will be greater than that drawn by architecture capable of correcting this phase lag. An inverter with 'power factor correction' will require a lower input current rating to achieve the same power, due to the virtue of its ability to correct the angle between generator voltage and current to near zero. An inverter capable of full 'phase angle control' can enable the generator to operate at optimal phase angle to achieve rated power with lowest relative current.

6.4 Given the variation of current between architectures for given power conditions, other performance factors are affected such as generator efficiency, temperature and winding stress as per figure 3. The technique deployed to control generator current can also have an effect on audible noise as the harmonic content of the current – and hence ripple torques – will vary depending on the architecture and control used.

6.5 The effect of phase angle control on the generator voltage should be considered when defining the appropriate power curve. For example, programming inverters of differing architectures outlined in 3.1.1 through 3.1.4 using the same power curve with respect to voltage, can result in differing power curves with respect to speed and hence deviation in power control. Therefore, the programmed power curve should reflect the desired power performance versus speed.

7 Inverter and Generator Efficiency

7.1 Inverters of comparative architecture and rating outlined in 3.1.1 through 3.1.4 are likely to have in-material differences in efficiency. Inverters with differing architectures between 3.1.1 through 3.1.4 will have differing efficiencies due to the difference in the number of power handling switching semiconductors. In reality, this difference is small (95-97% at full load) and in isolation has a relatively small effect on energy yield when comparing inverters of similar rated outputs. However, the loss of inverter efficiency in moving to a solution with a greater number of power semiconductors (ie with voltage boost or active rectifier) can be compensated by the gain in generator efficiency achieved through power factor correction or full phase angle control. When considering inverter modification or change, it is advisable therefore not to primarily consider the impact of inverter efficiency on energy yield. Instead, working turbine envelope should be primarily considered, as outlined in figures 4 and 5.

8 Internal Consumption and Standby Strategy

8.1 An inverter will consume a small amount of power when in standby mode and not switching the power handling semiconductors; this can be as low as a few watts (providing that any cooling fans are switched off) and in isolation should not result in a material difference between inverters. However, once the turbine has cut-in and the power handling semiconductors begin to switch, these losses will start to become significant. In conditions where the inverter is connected to both turbine and load and is fully operational with power handling semiconductors switching, the inverter itself can become a consumer at running speeds where its consumption exceeds that available from the turbine.

8.2 Whilst seemingly attractive to have low cut in speeds, it is recommended that the cut-in voltage of the inverter be set such that the power available from the turbine at the corresponding speed at cut-in is at least equal to the losses of the inverter itself so as not to negatively affect energy yield. At speeds lower than cut-in and, if separately programmed, low speed voltage cut-out the inverter should ideally cease switching the power handling components.

9 Load Acceptance and Rejection

9.1 The rate at which load on the turbine can be both accepted or rejected should be set-able and ideally defined as separate parameters in the inverter. These ramp rates not only have an effect on the energy yield of the turbine, but also the mechanical shock loads applied to the turbine and generator components. Guidance should be provided by the turbine manufacturer as to the allowable limits of operation. This guidance should be reflected in the settings of the inverter. In making a modification or change to an inverter, the settings applied for load acceptance and rejection in the “representative configuration” tested under MCS should be retained or transferred to the new inverter unless alternative guidance is provided by the manufacturer; else further testing may be required.

10 Power Control

10.1 The technique used to control power, and the discretisation at which it is achieved, can be implemented either in the inverter or by way of controlling the inverter as a slave unit through instruction from a separate controller. In the event of considering the latter, straight forward inverter change or modification can be considered provided that the calibration of inverter output to demand signal is retained and the comparative performance metrics of figure 3 are considered.

10.2 Where the turbine power control is achieved through setup of the inverter itself, several control techniques are possible. For the purpose of consideration here, these techniques are categorised as two separate methods:

10.2.1 **Look–up Table**, Here a simple power output versus speed reference is programmed into the inverter. Speed reference can be made either with respect to generator speed, electrical frequency or voltage. The discretisation and flexibility in programming of this curve will determine the fit that can be achieved with respect to the ideal turbine characteristic. In making a modification or change to an inverter, best efforts should be made to replicate at least the characteristic tested in the "representative configuration". However, deviation in the characteristic that can be achieved may result due to the factors highlighted in sections 5 and 6, and as a result of a difference in the discretisation and flexibility of the curve that can be programmed. An assessment of any new power curve proposed will determine the likeness in fit and assure the integrity of energy output. ***It is recommended that the Power versus voltage/speed curve not deviate in area from cut-in to rated speed by more than 10% from that considered in the reference MCS test in order to retain certification. In addition, it is recommended that any single one point on the power curve beyond 50% of the rating of the turbine, should not deviate by more than 10% from that considered in the reference MCS test. Practical evidence of achieving the proposed power curve should be presented by the proposer of the change or modification. Else, if expecting to exceed the maximum allowable deviations, further certification testing may be requested which could extend to repeated durability testing if deemed appropriate due to product lifetime concerns*****.**

10.2.2 **Iterative, Adaptive and Intelligent Load Control**, Where an inverter does not require a power characteristic to be programmed, it uses a process of learning and/or load iteration to determine an optimal method of control. Embedded within these control methods is the ability to, amongst other techniques, hunt for optimal power at given running speeds and in some instances to stall the turbine. In changing from a technique described in section 10.2.1 to the method described here, evidence of accurate, consistent and reliable operation over a period of time is recommended in addition to an analysis of the power curve characteristic where the same measures of acceptance highlighted in section 10.2.1 apply.

11 Turbine Plant Control Integration

11.1 Inverter functionality can include the ability to read data from external sensors, such as anemometers, and perform control actions either internally within the inverter or as instruction to external peripherals, such as braking systems and disconnection devices. Where such functionality is to be integrated within the inverter, it is recommended that the approval body review the control strategy and assess evidence of reliable and repeatable control action and operation provided by the turbine manufacturer.

12 Durability

12.1 Inverters and their associated components are subject to extensive testing to validate their performance specification and adherence to safety standards. If conforming to the appropriate certification standards defined in Annex A, adherence of the inverter to the specification stated by its manufacturer should be considered a given.

12.2 The practice adopted by mature power generating industries to assure product robustness is one of 1000 hour Accelerated Life Testing of components or sub systems in a representative test configuration# and environment. It is recommended that this be considered by the approval body when considering <u>inverter replacement</u>. Alternatively, the following can be considered as valid:

- History of in-field inverter deployment presented and reviewed
- 2,500hr system test, carried out by the turbine manufacturer

#NOTE: Representative test environment considers turbine behaviour but does not explicitly have to be a turbine

13 Turbine Starting and Assist

13.1 Some VAWT turbines require assisted starting. Of the architectures illustrated in figures 3.1.1 through 3.1.4, only an active rectifier solution will provide the bi-directional power capability to start the turbine without a separate power stage. When considering a non self-starting VAWT, consideration should be given to this functionality and evidence provided by the manufacturer that the revised inverter solution will start the turbine either with or without separate power stage. Consumption of energy during the assisted start-up period should be considered. The ability to start the turbine may require an encoder to report position feedback to the inverter, alternatively this can be achieved using sensor-less position or speed techniques. Evidence should be provided by the turbine manufacturer to validate reliability where a position feedback device is used.

14 Grid Compensation

14.1 To date, reactive power compensation of the grid from distributed generators is forbidden by network operators in the UK. It is envisage that in the future this will change. This functionality is therefore not considered here at this time.

15 Multiple Inverters and Isolation

15.1 Where multiple output inverter stages are proposed to achieve higher powers onto common phases, consideration needs to be given to isolating the output of each inverter to ensure safe and reliable operation. Where n inverters are used, n-1 isolation transformers are recommended. For example, where connecting a 12 kW turbine to a single phase supply via two 6 kW inverters, one isolation transformer of at least 6kW rating will be required on the output of one of the inverters. Some inverters have transformers integrated within their design, others require additional transformers to achieve this protection. Where isolation is required, the additional losses in the transformers will need to be taken into consideration when evaluating power and energy output – particularly if a solution is proposed where transformers are introduced as an addition to the configuration originally tested under MCS. As a guideline only, isolation transformers of a torroidal design introduce relatively low losses when compared to more conventional laminated steel designs.

15.2 Alternatively, isolation of each inverter output may not be required where an appropriate transformer-less paralleling technique can be demonstrated

16 Checklist to assess the impact of inverter change and/or modification

16.1 **Step 1**: Compare the purpose of the inverter used in the “representative configuration” for MCS and for the proposed change or modification. If deviating from one generic load type considered in Annex A to another, further testing may be required at the discretion of the approvals body.

16.2 **Step 2**: Using Annex B, consider the necessary certifications required for an inverter be-fitting of use with load type described in Annex A. Ensure that the proposed inverter is certified accordingly.

16.3 **Step 3**: Compare inverter electronic architecture (fig 2) used in the “representative configuration” for MCS and the relative effect of the proposed change in figure 3. Where performance deviation is expected, consider the relevant measure further using sections 5 through 10 and/or discuss further with the turbine manufacturer and inverter supplier to assess the significance of the deviation where not covered in sections 5 through 10. Further test may be required if the potential deviation is considered significant.

16.4 **Step 4**: Consider the guidance in sections 5 through 10 and measures in 10.2.1 to assess the effect on turbine energy yield of the inverter change or modification. Where relevant, encourage the system installer to follow the guidance relating to relevant settings that will limit the impact of change. Consider:

- Cut-in, Cut-out voltages and over voltage protection capabilities
- Inverter input current and corresponding rated speed
- Significance of inverter and generator efficiency
- Internal consumption at low load and the standby strategy deployed
- The rate of load acceptance and rejection
- Technique used to control power drawn from the turbine

Where doubt or ambiguity remains, the approval body can request practical evidence of a power curve to validate performance using the new configuration.

16.5 **Step 5**: Assess the direct interaction of the inverter with measurement sensors and control peripherals. Where the inverter receives instruction from an external controller, or passes on instruction to an external controller or peripheral, ensure that the functionality has been tested and proved to be reliable and repeatable.

16.6 **Step 6**: Where proposing inverter replacement, evidence should be made available to confirm durable operation through one of the following:

- 1000hr Accelerated Life Test of the inverter in a representative test environment#
- History of in-field inverter deployment
- 2,500hr system test, carried out by the turbine manufacturer

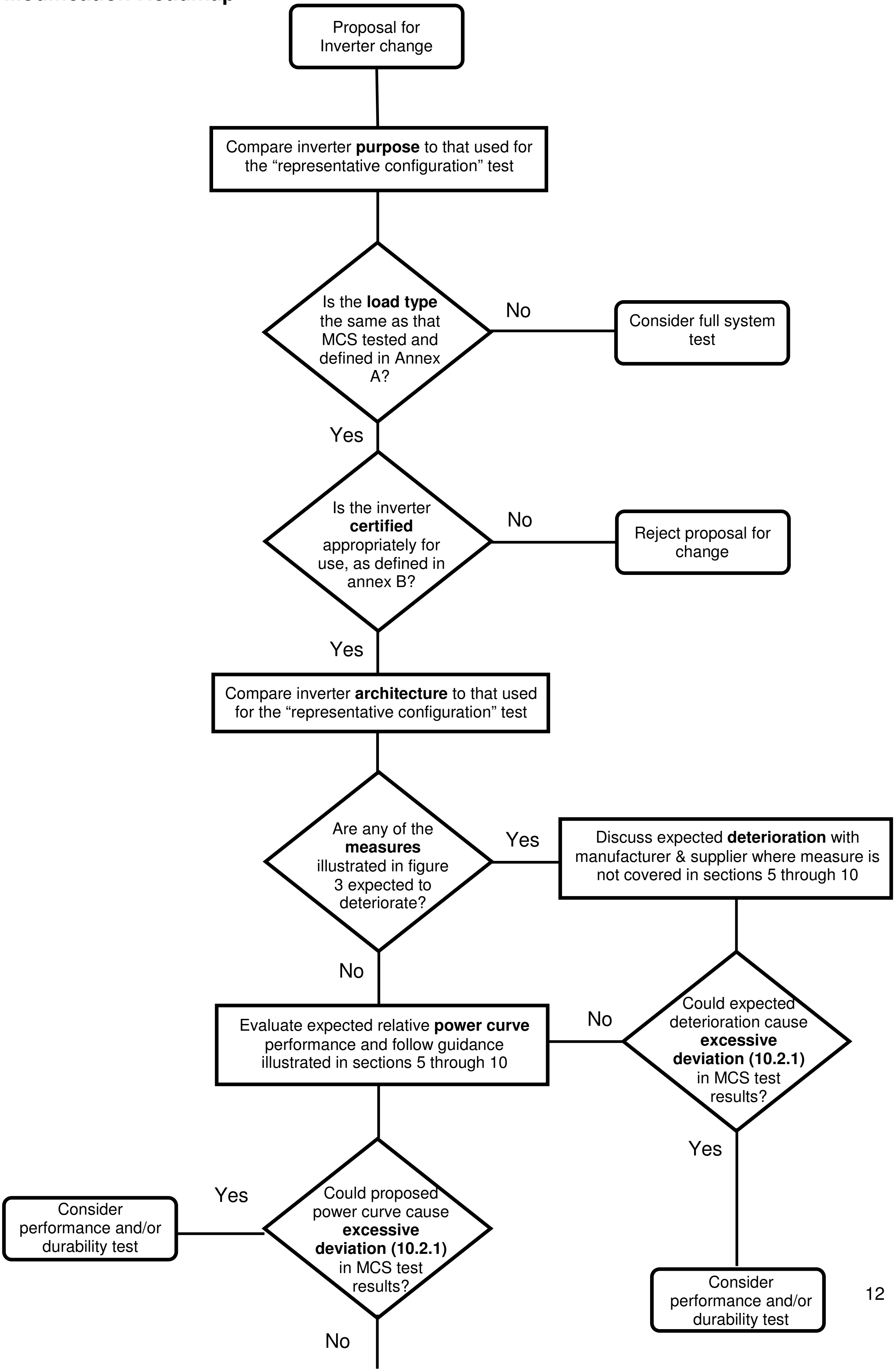
#NOTE: Representative test environment gives consideration to turbine behaviour but does not explicitly have to be a turbine

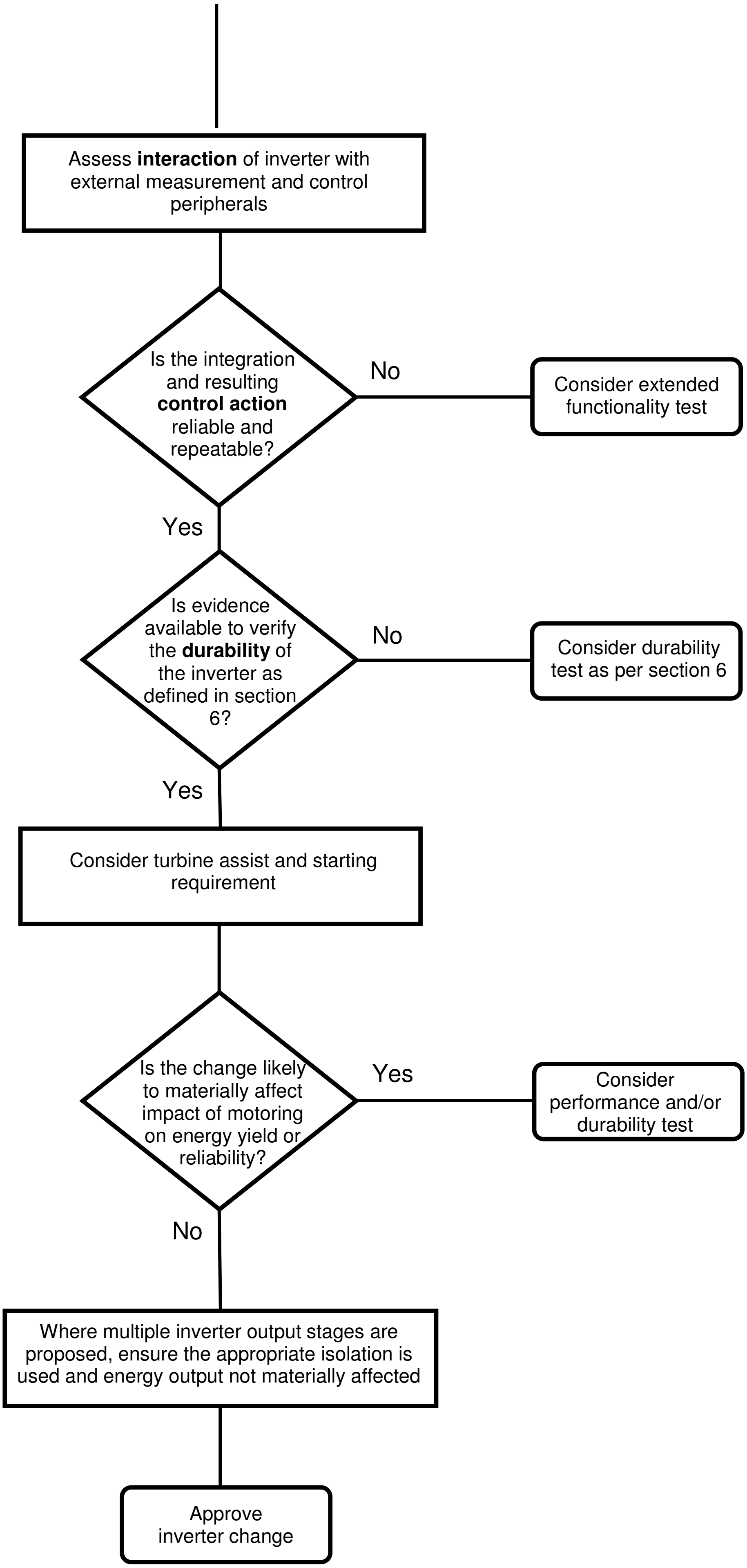
16.7 **Step 7**: Where appropriate and relevant, consider the turbine starting and motoring requirement and impact on energy consumption & reliability as outlined in section 13.

16.8 **Step 8**: Where multiple inverter output stages are to be used, ensure an appropriate means of isolation is considered, as outlined in section 15.

17 Inverter

Modification Roadmap




Assess **interaction** of inverter with external measurement and control peripherals
Is the integration and resulting **control action** reliable and repeatable?
No
Consider extended functionality test
Yes
Is evidence available to verify the **durability** of the inverter as defined in section 6?
No
Consider durability test as per section 6
Yes
Consider turbine assist and starting requirement
Is the change likely to materially affect impact of motoring on energy yield or reliability?
Yes
Consider performance and/or durability test
No
Where multiple inverter output stages are proposed, ensure the appropriate isolation is used and energy output not materially affected
Approve inverter change

Annex A – Load Type Definition

1. Grid Connected – as bound by G83 and/or G59 UK grid code requirements
2. Grid Connected with battery back-up
3. Off grid load
4. Off grid load including battery back-up
5. Hybrid on and off grid load
6. Hybrid on and off grid load including battery back-up

Annex B – Inverter Safety and Grid Code Standards

Grid connected inverters:

- BS-EN 50178:1998 Electronic equipment for use in power installations
- BS-EN 61000-6-1:2007 EMC: Generic standards – Immunity standard for residential, commercial and light industrial environments[#]
- BS-EN 61000-6-3:2007 EMC: Generic standards – Emission standard for residential, commercial and light industrial environments[#]
- Relevant Grid connection recommendation*, for example in the UK:
  - ER G83/1 - Recommendations for the connection of small scale embedded generators in parallel with public low voltage distribution networks, OR
  - ER G59/2 - Recommendations for the connection of generating plant to the distribution systems of licensed distribution network operators
- 2006/95/EC Low Voltage Directive
- 89/336/EEC Electomagnetic Compatibility Directive
- 93/68/EEC CE Marking Directive
- 2002/95/EC the directive on the restriction of the use of certain hazardous substances in electrical and electronic equipment
- WEEE 2002/96/EC, the directive on waste electrical and electronic equipment
- RohS compliance

[#] NOTE 1: Alternatively, BS-EN 61000-6-2 and 6-4 may be considered where environment of use is deemed "industrial"

*NOTE 2: Other European regions covered by EN50438 Requirements for the connection of micro generators in parallel with public low voltage distribution networks, including German requirement DIN VDE 0126-1-1 automatic disconnection device between a generator and the public low voltage grid

Off-Grid inverters:

Annex to be defined in next release.

RenewableUK
Greencoat House, Francis Street
London SW1P 1DH, United Kingdom

Tel: +44 (0)20 7901 3000
Fax: +44 (0)20 7901 3001

Web: www.renewable-uk.com
Email: info@renewable-uk.com