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出國報告（出國類別：實習）

赴荷蘭能源研究中心風能量測技術團隊實習報告

服務機關：核能研究所
姓名職稱：余政融　研究助理
派赴國家：荷蘭
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摘　要

配合再生能源開發，核能研究所致力於風能研究，如風機葉片設計、模型建立、結構分析與軟體驗證等。為建立測試技術以透過實驗驗證相關模擬結果並改善風機效能，特遣本所研究助理余政融赴荷蘭能源研究中心(ECN)風能研究部門，接受量測技術團隊 Jan Willem Wagenaar 博士指導，學習風機機械負載量測技術與光達(LiDAR)裝置相關應用。本次主要學習現行風機實施負載測試方式與瞭解所使用之量測標準(IEC 61400-13, 2001)，同時預覽並研究現行版本與即將發行之新版標準間之差異。此外藉由參與光達研究成果發表會，瞭解目前光達裝置應用於風場參數量測之可行性及成熟度，結果顯示光達裝置具有成為氣象觀測塔替代方案之潛力。本次實習心得：ECN 廣納各國人才為其特別之處，除專業各有所長外，來自不同環境所產生之多元化觀點有助於更圓融地解決研究難題。而建議事項主要為：未來規劃風機機械負載測試時，可由感測器與資料擷取系統配置著手，並引入光達技術進行風場資源評估，數據蒐整後再研擬合適之資料後處理與分析方法，以評估風機機械負載測試結果。

內容

一、 目的

我國節能減碳之能源政策中，風力發電為再生能源計畫所推行之主力項目之一。行政院原子能委員會核能研究所（以下簡稱本所）為配合再生能源計畫執行，已於 2005 年起投入人力與資源，執行風機相關設計、分析與開發，包含風機葉片設計、結構分析、噪音改善、軟體模擬及應力計算等研究，至今已發展至第二代 150kW 風機。NEP II 離岸風電知識網指出，台灣海峽及桃園至雲林一帶海域之風況極佳，以離岸風力而言極具開發潛力，故本所除持續研究陸上風機外，亦積極推動離岸風機相關研發，拓展風能應用區域。

然而各項計算及軟體模擬之結果，例如風機葉片在不同風場條件中所需承受之機械負載、風機轉子(Rotor)之轉速、位置等隨時間之變化，仍需經由實驗所獲得之測試數據加以評估比對，作為結果驗證與改善軟體模型之參考；而藉由分析實驗結果可調整風機各項設計參數，進而提升風機運轉效率能。為建立本所於風機實驗機械負載測試之量測技術，配合現有之軟體模擬與實體測試以達相輔相成之效，派遣本所研究助理余政融赴歐洲於再生能源研究領域享譽國際之荷蘭能源研究中心(Energy research Centre of the Netherlands, ECN)，於風能研究部門之量測團隊，進行機械負載量測與光達(LiDAR)裝置應用之實習。目前 ECN 風能研究部門約有 50 人，研究領域涵蓋風機系統控制、結構設計與計算、離岸風機設計以及機械量測等。其中量測團隊約有 12 人，負責風機量測系統架設與評估、介面連結、資料處理及分析等工作，於風機系統量測方面具豐富經驗，故派員前往 ECN 量測團隊實習。

本次實習目的共有兩點：其一為學習於現行標準架構下，風機實施機械負載量測之實驗方法，並研究預定於近期內發行之新版測試標準與現行標準間之差異，以及這些差異對未來實施機械負載量測所可能產生之影響，作為本所未來規劃建置機械負載測試技術之參考。其二為瞭解光達技術於風機應用之可行性。相較於現行量測氣象參數所採用之氣象觀測塔(Meteorological Mast)，光達具有可攜帶、安裝便利及建置成本較低等優點，透過 ECN 於光達裝置應用於風場資料蒐集與量測之研究，可瞭解光達具有取代氣象觀測塔之潛力，對於本所未來建置相關風場量測技術，有正面幫助。

二、 過程

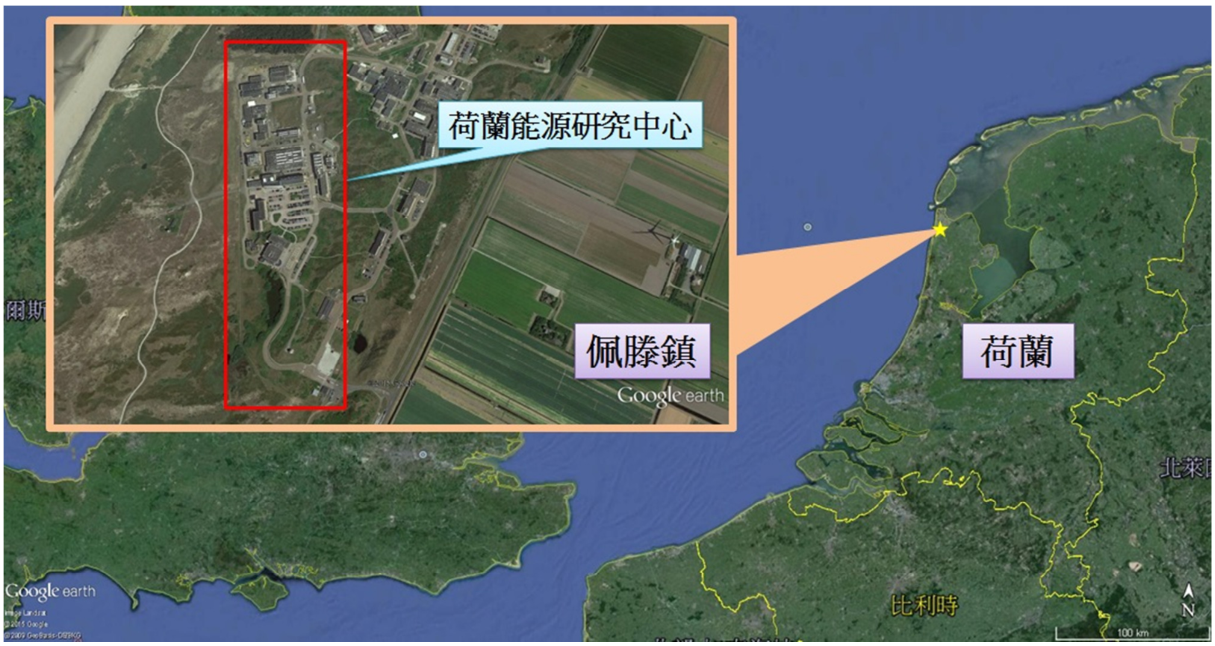
本次出國行程於 104 年 11 月 6 日於桃園國際機場搭機前往荷蘭阿姆斯特丹，於 11 月 9 日至 26 日於荷蘭能源研究中心(ECN)實習風機相關機械負載量測技術與光達裝置應用，詳細行程如表一所示。本次實習由 ECN 風能研究部門量測團隊 Project Leader Dr. Jan Willem Wagenaar 擔任指導員，進行相關量測技術實習，並依其指示研讀相關手冊與標準，判別新舊機械量測標準間之差異。實習期間，於 11 月 12 日參與由 Dr. Jan Willem 主講之「Ring analysis floating LiDAR, static LiDAR and offshore meteorological mast」研討會，瞭解 ECN 於光達應用方面研究與未來發展潛力；11 月 25 日由輔導員帶領，參觀 ECN 位於 Wieringermeer 之風機測試場，ECN 除於此測試場內進行研發與測試外，亦對外承接風機製造商委託，進行風機原型測試工作；11 月 26 日由工程師 G. Bergman 帶領參觀 ECN 風能研究部門之量測實驗室，實地瞭解相關儀器及系統於機械負載量測之應用。完成實習後，於 11 月 27 日自荷蘭搭機啟程，並於 11 月 28 日返抵國門。本次出國實習自 11 月 6 日至 28 日，為期 23 日。

表一　行程表

<table>
<tr><th colspan="4">行程</th><th colspan="2">公差地點</th><th rowspan="3">工作內容</th></tr>
<tr><th rowspan="2">月</th><th rowspan="2">日</th><th colspan="2">地點</th><th rowspan="2">國名</th><th rowspan="2">地名</th></tr>
<tr><th>出發</th><th>抵達</th></tr>
<tr><td>11</td><td>6~7</td><td>桃園</td><td>阿姆斯特丹/佩滕</td><td>荷蘭</td><td>佩滕</td><td>去程</td></tr>
<tr><td>11</td><td>8</td><td></td><td></td><td>荷蘭</td><td>佩滕</td><td>整理實習資料</td></tr>
<tr><td>11</td><td>9~11</td><td></td><td></td><td>荷蘭</td><td>佩滕</td><td>Wind Energy Handbook 研讀與討論</td></tr>
<tr><td>11</td><td>12</td><td></td><td></td><td>荷蘭</td><td>佩滕</td><td>參加 Floating LiDAR 研討會</td></tr>
<tr><td>11</td><td>13~16</td><td></td><td></td><td>荷蘭</td><td>佩滕</td><td>IEC 61400-12-1 規範指導與研讀</td></tr>
<tr><td>11</td><td>17~19</td><td></td><td></td><td>荷蘭</td><td>佩滕</td><td>IEC 61400-13 現行與新版規範研讀指導及差異比較</td></tr>
<tr><td>11</td><td>20~24</td><td></td><td></td><td>荷蘭</td><td>佩滕</td><td>IEC 61400-13 現行與新版差異報告撰寫</td></tr>
<tr><td>11</td><td>25</td><td></td><td></td><td>荷蘭</td><td>佩滕</td><td>ECN 風機測試場(EWTW)參訪及規範差異討論</td></tr>
<tr><td>11</td><td>26</td><td></td><td></td><td>荷蘭</td><td>佩滕</td><td>ECN 風能量測實驗室參訪</td></tr>
<tr><td>11</td><td>27~28</td><td>佩滕/阿姆斯特丹</td><td>桃園</td><td></td><td></td><td>回程</td></tr>
</table>

(一) 荷蘭能源研究中心(ECN)簡介

荷蘭能源研究中心為夙負盛名之能源研究機構，為歐洲最大能源研究所之一，致力於開發永續能源系統之知識與科技。其總部位於荷蘭北部的佩滕鎮(Petten)，即本次實習之地點，詳細位置如圖一所示。同時 ECN 亦於阿姆斯特丹(Amsterdam)、恩荷芬(Eindhoven)、魏英格米爾(Wieringermeer)、布魯塞爾(Brussels)與中國(China)等地設有據點，員工約有 500 人。



圖一 荷蘭能源研究中心(ECN)位置

關於 ECN 之歷史可追溯至 1955 年，當年荷蘭成立了荷蘭反應器中心(Reactor Centrum Nederland, RCN)，即為今日荷蘭能源研究中心之前身。直到 1977 年，阿拉伯切斷對荷蘭的石油供應，以及核廢料的處置問題受到關注後，荷蘭開始思考國內能源系統的其他可能性。由於荷蘭境內地勢平坦，風力資源豐富，故 RCN 著手進行新能源相關研究計畫之第一項任務即是開發風能，荷蘭反應器中心(RCN)亦因此更名為荷蘭能源研究中心(ECN)。

ECN 主要有太陽能、風能、生物質能、能源效率、環境評價、工程與材料及政策研究等七項核心研究主題，分述如下：

太陽能(Solar Power)：ECN 與太陽能板、製造設備與材料之製造商配合，將最新的科學知識應用於有關太陽能電池、模組與製程等技術，並朝向降低太陽能成本之目標邁進，以期更進一步地推廣太陽能。

風能(Wind Energy)：ECN 致力於風力發電場(Wind Farm)、風機與風機組件之改善設計，以及建立具較佳效能之維護計畫與風力發電場系統技術之整合應用，試圖大幅降低離岸風能之成本。

生物質能(Biomass)：在生物質能領域，ECN 專注於生物經濟，並著眼生物質之熱化學轉化，進行預處理、氣化、淨化以及生物精煉等領域之研發。

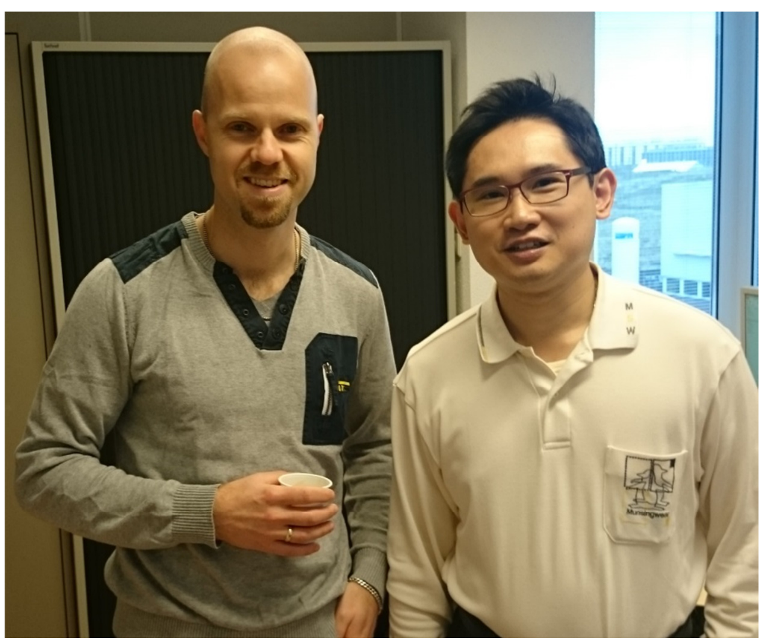
能源效率(Energy Efficiency)：有關能源效率，ECN 運用熱泵、分離技術與革命性的化學反應器等，以提升工業生產過程之效率。

環境評價(Environmental Assessment)：為求健康及環境永續發展，ECN 投入資源進行環境計畫研究，著眼於開發知識、技術與實用之解決方案。

工程與材料(Engineering & Materials)：在工程與材料方面，ECN 設計並製造實驗裝置、原型以及高科技元件，透過尖端科技對創新企業與研究機構提供技術支援。

政策研究(Policy Studies)：ECN 匯集工程師、經濟學家、社會學家與環境專家以及技術部門之努力，探討與研究能源政策發展方向，並提供策略建議。

本次實習之指導員 Dr. Jan Willem Wagenaar 為 ECN 專案經理兼研究人員，專長為風機性能量測分析、風力資源評估與機械負載量測，同時參與國際上許多光達專案研究，且為 MEASNET 功率性能專家團隊一員。實習人員與指導員合影如圖二。



圖二　指導員 Dr. Jan Willem（左）與實習人員余政融（右）

(二) 風機機械負載量測說明

進入風機機械負載量測主題前，依指導員要求，首先研讀與討論 Wind Energy Handbook 與 IEC 61400-12-1。Wind Energy Handbook 為風機入門之重要參考，內容敘述早期風力應用發展至今之歷史沿革，並介紹風場資源及評估方式，進而深入說明現代風機對於風力發電之理論基礎，如風機之空氣動力學、風機性能評估方式與模型、水平軸風機之負載分析及設計、風機元件如葉片、軸承、轉子與齒輪箱等之設計、風機控制型式與方法及電力系統等，適合作為初學者進入風機研發領域之引導教材。

目前風機之相關標準諸多均出自於國際電工委員會(International Electrotechnical Commission, IEC)，如 IEC 61400 國際標準系列，此系列內容包含不同型式風機所應具備之規格與設計，以及對應之性能測試與負載量測方式。其中有關風機功率性能測試之標準訂於 IEC 61400-12-1，該標準敘述測試風機時，測試場所與風機所應具備之條件，和測試時針對各項參數如功率、風速、風向與空氣密度等所使用儀器與設備之要求，並說明功率測試時之量測程序與量測數據後處理方法，以及完整測試報告應具備之格式。

圖三 運轉中之風機

相較於 IEC 61400-12-1，IEC 61400-13 為風機機械負載測試之標準，現行版本自 2001 年發行後沿用至今，目前預定於 2016 年發行新版。以現行版本而言，標準內除說明風機之不同運

轉狀況以外，針對不同運轉狀況，定義了與設計負載案例(Design Load Cases, DLC)相對應之量測負載案例(Measurement Load Case, MLC)，說明風機在特定運轉狀況下，進行負載測試時風場所應具備之條件。各式測試狀況確立後，標準進一步說明測試時所應擷取數據之捕捉矩陣(Capture Matrix)。所謂捕捉矩陣係用以整理所測得之時間序列使用，主要目的有二：欲將資料擷取系統之擷取模式設定為自動時，捕捉矩陣可作為自動擷取條件之參考；此外捕捉矩陣亦可作為判斷量測要求達成與否之工具。捕捉矩陣事實上為一系列滿足特定要求（如紊流強度）、以十分鐘為基準所測得之風速時間序列（由於現行版本與即將發行之新版有顯著差異，捕捉矩陣要求請參閱附錄）。

IEC 61400-13 定義應實施機械負載量測之負載量測案例及所需統計之捕捉矩陣後，規定實驗中所必要與建議量測之各項參數，參數可分為三類如表二：

表二　機械負載量測參數分類

參數類別	說明
負載量(Load Quantities)	葉片彎矩、轉子扭矩、塔柱彎矩等
氣象量(Meteorological Quantities)	風速、風向、空氣密度等
風機運轉量(Wind Turbine Operation Quantities)	功率、轉子速度、旋角、轉向、剎車狀態等

針對標準所定義應量測之參數，現行標準概略性地描述對於感測器之要求如初始校正、校正方式、安裝位置與精確度等，以及實施負載量測時，相關量測量如葉片彎矩、轉向與傾斜彎矩、轉子扭矩、風速及風向等之儀器架設與校正資訊，並說明對資料擷取系統之要求。針對量測結果，標準提供處理量測數據之方法，透過對資料之驗證與後處理，可將結果應用於風機機械負載分析，進而評估等效負載與疲勞破壞。標準最末則說明對於機械負載量測報告內容至少應涵蓋之項目，如測試目的、風機基本規格與性能說明、量測地點與條件、儀器架設情形、儀器校正、風機動態及不確定度評估等。

依據前述標準對於機械負載量測之要求，對於風機實施機械負載測試時，可歸納以下流程供建立測試程序參考：

1. 確認測試目的、受測風機之規格、測試場所位置及條件（含氣象觀測塔），並依循 IEC 61400-12-1 進行測試地點之地形及障礙評估，如經評估後測試場未能滿足標準要

求，應進行測試場校正。

2. 規劃受測風機本次實施之量測負載案例(MLC)，確認相關參數與要求。
3. 依受測風機型式與測試場條件，確認各項量測量，包含負載量、氣象量以及風機運轉量等三類。
4. 依前項確立之量測量，選擇相對應之適當儀器、感測器及資料擷取系統，各項設備須能符合所要求之量測負載案例及捕捉矩陣。
5. 各項設備之校正要求應能符合標準內之相關規定，於測試前後均應檢查是否仍在有效校正範圍內。
6. 依標準要求，縝密規劃感測器及資料擷取系統之安裝位置，以及不同量測場所內（如風機之葉片、機艙內之轉子等），各項感測器與資料擷取系統間之連接與數據傳輸方法（如有線或無線）。
7. 各項儀器、感測器與資料擷取系統設置完成時，應檢查量測設備是否可依設定（如各頻道資訊、量測時間、取樣頻率、靈敏度設定、單位轉換…等）正常擷取各項感測器之訊號，並存放於所規劃之儲存媒介中（如遠端資料庫、雲端硬碟或資料擷取系統之記憶體）。
8. 依據選定之量測負載案例與捕捉矩陣，設定資料擷取系統後，調整風機運轉模式，進行各項機械負載、氣象參數與風機運轉狀態量測，並記錄所測得之資料。
9. 測試進行中即可對所測得之資料實施驗證，確認數據之正確性，一旦過程中發現異常，須依標準要求，判定重新測試或繼續測試。測試後所得之完整資料仍須實施驗證，以確保量測數據之正確性，並將異常狀況記錄於測試報告中。
10. 測試完成後，對於各項設備均應進行校正檢查，確認各項設備是否仍在有效校正範圍內。
11. 蒐集並驗證完成之數據，可利用雨流法(Rainflow Counting Method)以及 bin 方法(bin method)進行數據後處理與統計。
12. 依規劃目的，進行結果分析與評估，取得選定運轉條件下，風機之負載情形。
13. 撰寫總結報告時，格式應依循標準之要求，內容至少須包含以下項目：

(1) 測試目的與內容

(2) 風機基礎技術規格

(3) 測試場位置與地形

(4) 儀器架設方法（包含感測器及資料擷取系統之型式、安裝位置與連接方法）

(5) 儀器校正資訊與校正方法

(6) 量測資料庫（含捕捉矩陣、資料驗證與結果資料庫）

(7) 測試時間歷程及負載統計資料

(8) 風機動態特性

(9) 疲勞負載分析

(10) 量測不確定度評估

(11) 參考文件

(12) 其他補充資料

圖四　矗立於海邊之運轉中風機

(三) IEC 61400-13 現行版本與新版之差異

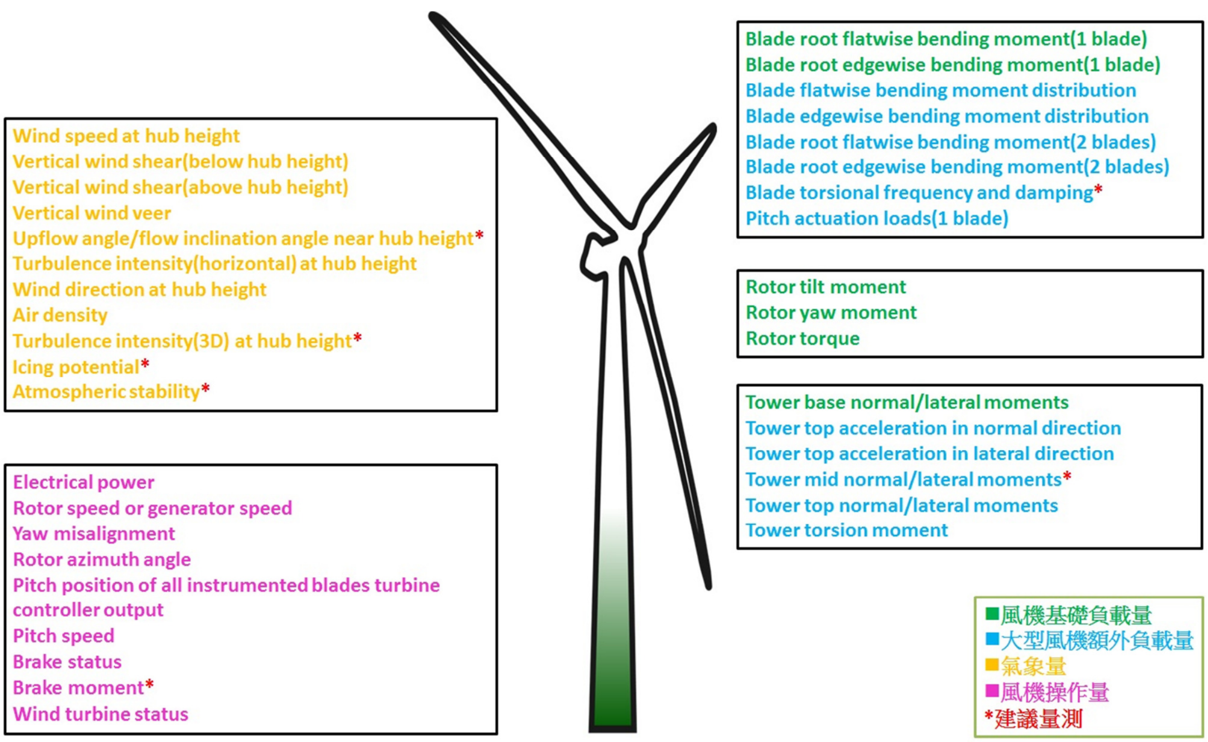
目前風機之機械負載測試標準 IEC 61400-13 自 2001 年發行至今約有 14 年之久，IEC 已著手進行標準修訂，除增加許多附錄以強化標準本身之完整性外，對於所規範之測試要求、儀器架設、校正方式、資料驗證與量測數據處理均有更清楚之說明。本次實習重點之一即在於瞭解及辨識現行版本與新版間之差異，以利未來規劃機械負載測試實驗時參考。

新版標準在架構上有明顯改變，以儀器校正為例，原先各項感測器之校正資訊均列於所屬之量測量項下，並收編於現行標準第四章「量測技巧」內；新版則將「量測技巧」重新改寫，分為「測試要求」與「校正因子決定」兩章，並加入更多量測量之要求與細節，供規劃實驗時參考。以下為新舊標準間最主要之差異：

- 一般而言，風機於實施負載量測活動時，均有通用之程序可依循。為此，新版標準之架構作出大幅度地修改，目的為提供通用程序予測試人員參考。
- 葉片彎矩定義之方向由”flap”與”lead-lag”分別修改為”flatwise”以及”edgewise”。
- 新版標準加入對於測試場之要求。
- 負載量測案例(MLCs)做出許多修正，部分案例被移除，同時新版標準增加對於風機動態特性(dynamic characterization)之負載量測案例。
- 對於正常發電功率、待機/停機情況以及暫態事件等風機運轉狀況，新版標準修訂了相對應捕捉矩陣之條件與要求。
- 有關額定輸出功率大於 1500 kW 且轉子直徑大於 75 公尺之風機，新版標準增加了需額外量測之負載量。
- 相較於現行版本對儀器架設之概略性描述，新版提供了獨立之儀器架設章節，並增加對於測試所要求之負載量、風機運轉量及資料擷取系統等更詳盡之敘述，而有關氣象量之量測要求則精簡化，僅敘明應依循 IEC 61400-12-1 標準執行。
- 新版之儀器校正改為獨立章節，內容完整地涵蓋有關量測各項負載量與運轉量時，各量測量所對應之負載頻道與非負載頻道之校正資訊，以及可採用之校正方式。

- 資料驗證章節新增對於葉片力矩、主軸與塔柱信號等資料進行驗證之實例，作為資料驗證時之引導與參考。
- 有關實施雨流法計算時，所要求之負載範圍分區最小數由 50 提高為 100。
- 雨流法乃用以決定等效破壞負載(Damage Equivalent Loads, DEL)與累積雨流範圍(cumulative rainflow spectra)之方法。
- 現行版本中有關不確定度估計之敘述被整併為單一章節，配合更新之附錄 B 可提供計算不確定度之方法與範例。
- 新版對報告應包含項目與格式之要求依其修訂內容有所調整，並增加相關說明。
- 新版標準除刪除現行版本之附錄 D 外，新增離岸風機量測建議、負載模型驗證、辨識風速趨勢之方式、資料擷取相關考量、負載之校正、溫度飄移及垂直軸風機之機械負載量測等七項附錄。

由前述主要差異可知，新版除具更清晰之架構外，對於實施負載測試時應注意之量測量亦有更具體之說明，量測量示意圖如圖五所示。新版標準於增加內容同時，也新增許多附錄，提供不同風機與量測技巧在實施負載測試及分析時作為參考。附錄為實習期間完成並交給指導員之差異辨識報告，有關兩版本間重大差異與細節，請參閱附錄。



圖五　風機各項必須與建議量測參數

(四)　LiDAR 光達裝置應用評估

光達技術(LiDAR Technology)為以光線偵測及測距(Light Detection And Ranging)，是由光線(light)與雷達(radar)組合而成的遠端遙測技術。透過發出脈衝雷射光並分析回到裝置之反射光，可測量裝置對地面之距離，因此可用來繪製高解析度之地圖。光達裝置除可遙測距離以外，可依使用目的選擇不同波段之光束，達成包含地貌、水氣及空氣分子等之特性量測，因此應用範圍甚廣，如地理與土壤科學（藉由空載光達進行高精密度量測與地圖繪製）、自動駕駛技術（偵測障礙物以調整路線避免碰撞）、採礦業（定期掃瞄並計算已開採礦石體積）、道路測速照相（偵測車輛是否超速）…等。由於光達可遙測空氣特性如溫度、壓力、風速、風向…等多項參數，故相當適合作為評估風場資源使用。市售之光達裝置如圖六所示，該裝置為英國 ZephIR Lidar 所生產之 zephir 300。

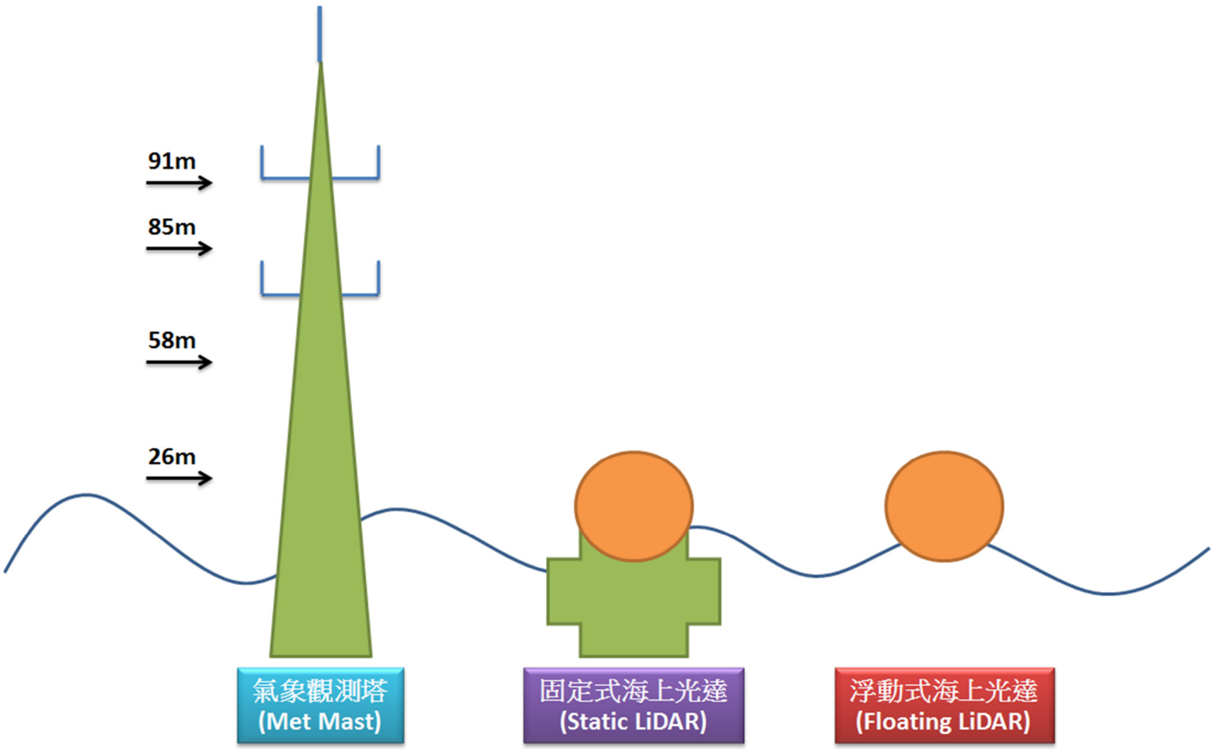
圖六　光達裝置 zephir 300（引用自 ZephIR Lidar 網站）

IEC 61400-12 及-13 標準中均規定需量測相關氣象參數，以進行功率性能測試與機械負載測試，傳統作法為設立氣象觀測塔（如圖七），塔高需隨測試風機之高度變化，以目前高功率風機動輒上百米之高度而言，架設氣象觀測塔之成本、時間與施工風險亦隨之增加。相形之下，逐漸成熟之光達技術建置成本較為低廉，同時兼具可攜帶及安裝迅速便捷等優點，極具發展潛力。

圖七　立於陸地之氣象觀測塔

本次實習所參加之光達應用研究成果說明會，其計畫目的在於研究離岸風場中，蒐集離岸氣象觀測塔、固定式海上光達與浮動式海上光達等三種不同裝置所測得之風場資料，進一步分析與比對其中之差異性，以檢視光達裝置是否能取代氣象觀測塔。該計畫在荷蘭西側一處名為 Ijmuiden 之水域進行，於距離岸邊 75 公里處設置氣象觀測塔，並在高度 26 公尺、58 公尺、85 公尺及 91 公尺處量測風速與風向，浮動式海上光達蒐集相同高度之風場資料，量測期間為 2014 年 1 月至 11 月。實驗設置示意圖如圖八所示。

浮動式海上光達對離岸氣象觀測塔、固定式海上光達對浮動式海上光達以及離岸氣象觀測塔對固定式海上光達之資料驗證分析盡可能依循 OWA (Offshore Wind Accelerator)之 KPI 與 IEC 61400-12-1 附錄 L 執行。由於架設形式不同，資料間之偏差可能是量測技術造成，亦可能是因為海洋流動產生，故需引入固定式海上光達之資料驗證，以確認原因所在。

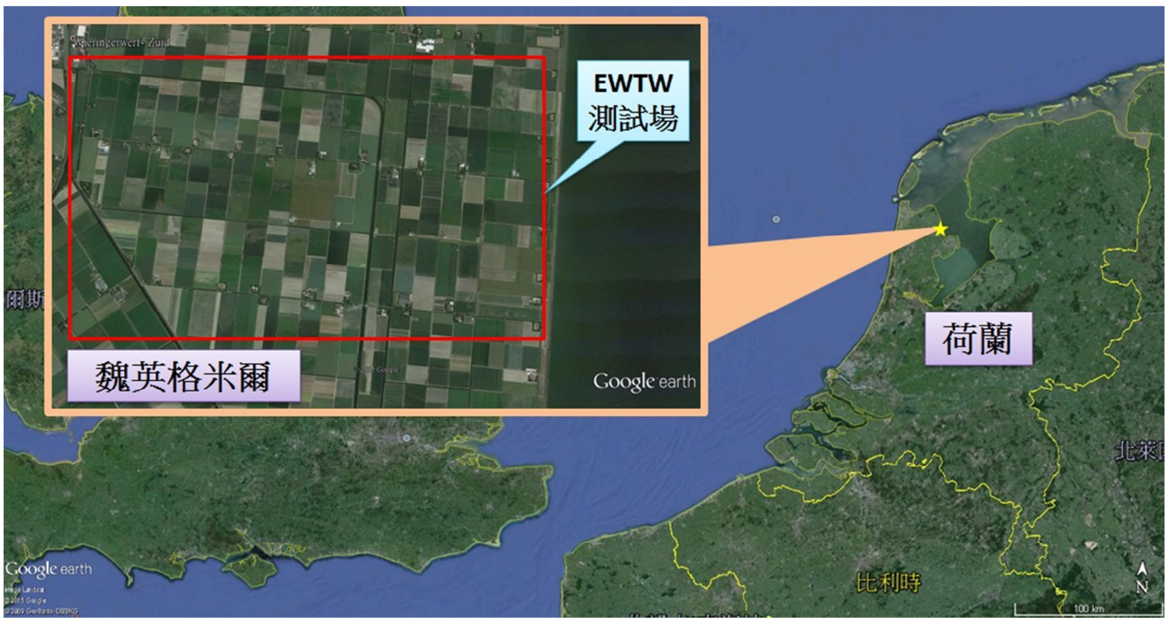


圖八　光達實驗裝置架設示意圖

依資料驗證與分析之結果，浮動式海上光達與固定式海上光達雖有差異，但仍在可接受之範圍，同時光達所測得之風場資料，部分雖與離岸氣象觀測塔略有差距，但整體而言表現仍屬接近。目前以光達評估風場資源可謂已進入預商用階段(Pre-commercial phase)，未來隨著技術再進步，可再拉近與氣象觀測塔之距離，有望成為量測風場之替代方案。

(五)　風機測試場(EWTW)與量測實驗室參訪

ECN 為進行風機研發與測試，在 2003 年於距離 ECN 總部約 30 公里之魏英格米爾設置風機測試場(ECN Wind Turbine Test Site Wieringermeer, EWTW)。選擇測試場址時，除考量地形、周遭建築物及風場資源等與測試息息相關之因素外，同時也考慮了風機零組件運送與安裝作業。在距離測試場約 8 公里處有一名為”De Oude Zeug”之小型港口，相關風機材料與組件均透過此港口運輸至測試場進行安裝。圖九為風機測試場之位置圖。



圖九　風機測試場(EWTW)位置圖

EWTW 內設置控制中心 1 處、6 座風機原型(Prototype)測試點、5 座氣象觀測塔（可量測高度範圍由 25 公尺至 108 公尺）與 5 座 Nordex N80 2.5MW 風機（由 ECN 測試）。控制中心設有會議室與電腦機房，可提供各座風機測試與監控之資料儲存使用。風機原型測試點可提供額定功率最大至 12MW、轉子直徑最大至 175 公尺或高度(hub height)最高至 150 公尺之大型風機進行測試。

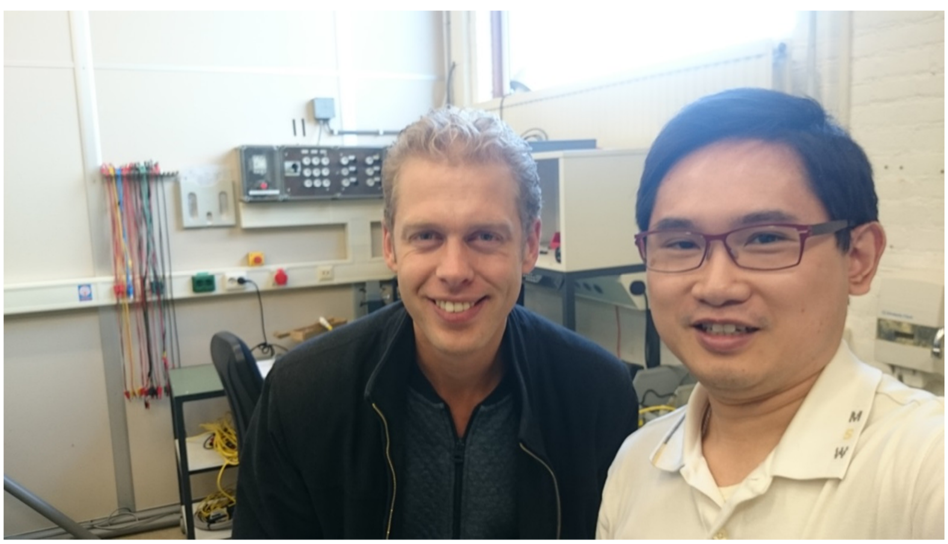
ECN 不僅專注於提升風機之輸出功率，對於風機運轉與維護策略、控制方法、狀態監控與開發新式測量技術等之研究亦不遺餘力。ECN 除於測試場進行特定研究計畫外，也出租場地給風機製造商如 Siemens Wind Power、General Electric、XEMC-Darwind、Alstom...等，讓風機製造商於此處進行產品測試，或原型之研發、驗證與最佳化調整，或代替製造商進行風機測

試，並協助彙整測試結果。

測試與監控之資料除存放於控制中心機房外，每日定時將資料回傳至位於佩滕鎮之 ECN 總部儲存，以確認資料保存安全無虞，而資料之後處理與結果分析均由 ECN 之測試實驗室執行。ECN 測試實驗室係通過 ISO 17025 評鑑合格，實驗室內各項所使用之儀器、設備與感測器均具可追溯性。該實驗室主要功能為風機測試規劃、EWTW 儀具管理、資料統計與分析及軟體開發等。

在儀具管理方面，實驗室不僅須確認測試前各項於 EWTW 所使用之儀器如風速計、風向計、應變規…等均校正合格，且測試後亦須再次檢查儀器是否仍在校正範圍內，以確保資料之正確性。如測試後發現儀器未能滿足校正要求，需通知委託單位並保留相關紀錄，在尋求發生原因同時，檢討所測得資料之處理方式，例如全數丟棄或仍可使用。此外特定之儀器如應變規，均由 ECN 依 IEC 標準要求與實驗室作業程序，以計算法或載重法進行校正，其餘如風速計及風向計等均委託具公信力之第三方實施校正。

在測試資料統計與分析方面，實驗室最重要為驗證資料之正確性，驗證後之資料才能依測試目的進行分析、統計與評估，最後依標準要求產出報告。ECN 除利用商用軟體 MATLAB 撰寫程式進行後處理外，針對標準內之要求（如設備處理）與不同目的（如測試規劃），亦自行開發許多軟體，提升資料處理之效率與附加價值。



圖十　測試工程師 G. Bergman（左）與實習人員余政融（右）

ECN 於風機測試領域建置測試場與實驗室不僅強化研究技術，與業界合作測試之成果亦傑出非凡，其成功經驗值得本所於規劃建立風機機械測試技術時學習與參考。

三、 心得

荷蘭境內幾乎全為平坦地形，領土僅有約 50%高於海拔 1 公尺，故 16 世紀開始荷蘭人便利用風車將積水排除，並建造堤防以避免田地或住宅遭水淹沒。因地形缺乏變化且無高山阻擋，荷蘭除天候變化非常迅速以外，風勢甚為強勁，靠近海邊的城鎮其強風更是不在話下，加上風車（機）在荷蘭發展較早，種種特殊情形使得荷蘭擁有發展風能得天獨厚的環境條件，因此在荷蘭四處皆可發現風機的蹤影。

圖十一　隨處可見之風機

歐洲因地緣關係，在 ECN 不難發現跨國合作情形十分普遍，除荷蘭本國人以外，約有一半以上的研究人員來自德國、印度、英國、愛爾蘭、羅馬尼亞、義大利…等不同國家。來自世界各地的專家學者齊聚一堂，學有專精自然不必多提，最大不同點在於多元化與國際化的思考面向。從交談中可發覺，有人特別關注問題的解決方法，有人考慮解決方法背後隱藏的環境影響，有人在降低成本的思維中嘗試降低問題所帶來的衝擊，有人不計代價想在解決問題的同時完整保護生態與環境。

來自相同國家的人，思維模式可能較為相近，有時易因囿於舊習而產生盲點，處理問題

難免不盡理想。而 ECN 猶如國際縮影，這裡除了可以尋求專業支援，也可看見單一問題有著各式各樣不同的切入角度，也許統合意見需要較長時間，但就結果而言似乎更為圓融完整。建議本所可透過強化與國際間學術研究機構合作，拓展國際視野，以更宏觀的角度進行能源相關技術開發，在能源與環境間尋求最佳的平衡點。

ECN 在風機機械負載測試方面尤其令人印象深刻，從規劃測試開始，包含場地選擇、測試目的、儀器架設與管控、專業人員訓練、實驗室管理及結果整理與分析等，不僅人員妥善分工，軟硬體資源亦相當充分，使得工作執行有事半功倍之效，值得本所參考。除一系列依循標準之測試活動與技術研究以外，對於開發新型測試技術與方法亦不遺餘力，如光達裝置與氣象觀測塔間之量測比較、對離岸風機運輸成本與耗時計算間之最佳化分析等，部分係以專案計畫配合大專院校研究生進行實習合作，共創學術與研究雙贏局面。

此外，ECN 展現其研究成果之方式相當特別，除在網頁上可獲知近期最新消息，ECN 將其著作（機密文件除外），包含簡報資料、型錄、研究及技術報告等於其網頁公開，供有興趣人士下載閱覽。如有意深入瞭解特定研究技術，可至 ECN 網站查詢相關技術報告，以尋求進一步資訊。

四、 建議事項

本次實習與參訪，謹提供以下建議做為參考：

（一） 不同於 ECN 擁有獨立之風機測試場、多座測試中風機系統與長年累積之測試經驗，本所尚處於風機研發初期階段，因此建議於開發量測系統時，可配合現有之第二代 150kW 風機系統，依國際標準對負載測試之要求，配置相對應之感測器、資料擷取器與氣象參數觀測設備等。因風機許多量測點均位於轉動件上，故須深入探討感測器與資料擷取器間之連接與資料傳輸模式，並研擬大量量測數據之後處理方法，建立資料統計與分析技術，瞭解負載測試或性能測試結果，以進一步提升風機性能。

（二） 進行負載量測實驗時，相關風場資源之氣象參數亦須一併量測。國內目前於苗栗與彰濱均開始設置氣象觀測塔，建議本所可考慮建置光達遙測系統，作為現有第二代 150kW 風機之風場氣象參數量測使用。使用光達裝置除可節省建造氣象觀測塔之費用外，未來亦可考量與其他單位合作，攜帶至設有氣象觀測塔之處所進行量測，以便與氣象觀測塔測得資料比較，分析兩種測量方式間之差異，評估光達裝置之適用性。

（三） 於 ECN 實習期間，幾乎每周均有同仁發表近期專題或計畫之研究成果，除提供交換意見平台之外，其他領域研究人員亦參與研討會並分享不同見解，討論十分熱烈。此類研討會相似於本所機械系統專案計畫每二周舉辦之組織學習活動，不僅有助於同仁瞭解不同領域之研究內容，亦可藉由不同觀點意見，提供研究人員更寬廣之角度審視研究成果。建議此類成果分享活動可持續於所內辦理，強化不同領域研究人員瞭解彼此專業，鞏固跨領域研發合作基礎。

（四） 除各項不同之再生能源研究領域，ECN 更設有政策分析及環境影響之研究部門，在追求綠色能源同時，創造永續發展環境。建議本所於研擬未來新能源發展方針時，除配合國家政策，可參考 ECN 作法，設想開發新能源時對環境及生態可能造成之潛在衝擊，以降低對環境之負面影響，於新能源發展與生態環境保護取得雙贏，留給下一代潔淨、美好、有希望的未來。

五、 附錄

Key Differences between the 2001 and the CDV 2014 Versions of IEC 61400-13

The contents of the CDV 2014 version of IEC 61400-13 have been re-structured to follow a general process while performing mechanical load measurements to wind turbines. Some clauses have been split into two with extra information in order to provide better clarity to measurement campaigns. For instance, “Measurement techniques” has been divided into “Instrumentation” and “Determination of calibration factors”. The CDV 2014 version also provides more detailed instructions on performing specific testing, calibration, and instrumentation. Information about mechanical load measurements for recent developments such as offshore wind turbines, vertical axis wind turbines and wind turbines with a rated power output above 1500 kW can also be found in CDV 2014 version.

Table 1 – Comparisons of the contents of two versions

2001	CDV 2014
1. General	1. Scope
2. Safety during testing	2. Normative references
3. Load measurement programmes	3. Definitions
4. Measurement techniques	4. Symbols, units and abbreviations
5. Processing of measured data	5. General
6. Reporting	6. Test requirements
Annex A (informative) Co-ordinate Systems	7. Instrumentation
Annex B (informative) Procedure for the evaluation of uncertainties in load measurements on wind turbines	8. Determination of calibration factors
Annex C (informative) Sample presentation of mechanical load measurements and analysis	9. Data verification
Annex D (informative) Extrapolation to other turbulence conditions	10. Processing of measured data
Bibliography	11. Uncertainty estimation
	12. Reporting
	Annex A (informative) Example co-ordinate systems
	Annex B (informative) Procedure for the evaluation of uncertainties in load measurements on wind turbines
	Annex C (informative) Sample presentation of mechanical load measurements and analysis

Table 1 – Comparisons of the contents of two versions (Cont’d)

2001	CDV 2014
	Annex D (informative) Recommendations for offshore measurements Annex E (informative) Load model validation Annex F (informative) Methods for identification of wind speed trends Annex G (informative) Data acquisition considerations Annex H (informative) Load calibration Annex I (informative) Temperature drift Annex J (informative) Mechanical load measurements on Vertical Axis Wind Turbines Bibliography

Separated from clauses of 2001 version   Revised with more information

Separated and with detailed information or significant modifications   Newly Added

The table above reveals some differences between these two versions, key differences can be concluded as follows:

- Re-structured to follow a general process while performing a load measurement campaign.
- Blade bending moments measurements change from "flap" and "lead-lag" to "flatwise" and "edgewise", respectively.
- Test site requirements are added.
- Measurement Load Cases (MLCs) are modified with removal of some cases and MLCs for dynamic characterization have been added.
- Capture matrices for normal power production, parked condition, and transient events are updated with revised conditions and requirements.
- Additional load quantities for wind turbines with a rated power output greater than 1500 kW and rotor diameter greater than 75m are provided.
- Instrumentation is provided with more detailed information about load quantities for test requirements, wind turbine operation quantities and data acquisition system, while leaving measurements of meteorological quantities to IEC 61400-12-1.

- Calibration of load and non-load channels for each load and operational quantities are covered thoroughly with specific descriptions in Determination of Calibration Factors.
- Examples of verification checks for blade moment, main shaft, and tower signals are added to Data Verification.
- When performing rainflow counting, the minimum number of divisions of the load range raises from 50 to 100.
- Rainflow counting is used to determine damage equivalent loads and the cumulative rainflow spectra.
- Notices of estimation for uncertainties have been collected into a single clause, together with the updated Annex B to offer methods and examples for calculating uncertainties.
- Requirements for reporting have been revised in order to follow the instructions provided by the CDV 2014 version.
- Several annexes have been added to the CDV 2014 version to give extra information, methods and examples of mechanical load measurements, calibration, analysis, wind speed trend detection, etc.

Compare CDV 2014 with 2001, differences with respect to each clause are listed below:

Title

The title changes from "*Wind Turbine Generator Systems*" to "*Wind Turbines*".

Clause 1 – Scope

- Originally, "Scope" was in "Clause 1 – General".
- Clearly states that methods provided by the standard are intended for onshore electricity-generating, horizontal-axis wind turbines (HAWTs) with rotor swept areas of larger than $200m^2$. But these methods may also apply to other wind turbines after appropriate evaluations or modifications.

Clause 2 – Normative references

- Originally, "Normative references" was in "Clause 1 – General".
- The reference "IEC 61400-1" has been updated to 3rd edition, 2005, and the reference for uncertainty of measurement "ISO/IEC Guide 98-3, 2008" is included as well.

Clause 3 – Definitions

- Originally, "Definitions" was in "Clause 1 – General".
- Co-ordinate system of blade moments changes from blade root reference system ("flap" and "lead-lag") to local blade reference system ("flatwise" and "edgewise").
- Some terms have been removed from, added to, replaced of, or supplemented in Definitions as Table 2 on the next page:

Table 2 – Changes in Definitions

Added	Removed	Replaced	Supplemented or Corrected
Brake Status Calibration Cut-in Wind Speed Cut-out Wind Speed Parked Wind Turbine Rated Power Rated Wind Speed Reference Wind Speed Wind Shear Wind Veer Yaw Misalignment	Calibration Load Chord Partial Safety Factors Radial Position Spanwise Test Load	"Flap" is replaced by "Flatwise" "Lead-Lag" is replaced by "Edgewise"	Chord Line Steady-state Operation Turbulence Intensity Yaw Position

Clause 4 – Symbols, units and abbreviations

- Originally, "Symbols, units and abbreviations" was in "Clause 1 – General".
- Some of the symbols are changed or added according to the changes in Definition.

Clause 5 – General

- This clause is a combination of the description of the structure of the CDV 2014 version and the "Clause 2 – Safety during testing" of the 2001 version.

Clause 6 – Test Requirements

- This clause "Test requirements" is revised from "Load measurement programmes" in the 2001 version.
- The requirements about a test site are included.

○ An obstacle assessment and terrain assessment shall be completed per IEC 61400-12-1.

○ It should be noted that flat terrain with low turbulence is not ideal for a mechanical loads test due to potential lack of excitation of the wind turbine dynamics.

- Blade moments are measured as flatwise and edgewise.

- Several modifications have been made to MLCs. For example, the "Power production plus occurrence of fault" MLC has been removed. Comparisons of these changes are listed in tables on page 28.
- New MLCs for dynamic characterization have been added to 6.3.4, inclusive of power production, parked, emergency stop, yaw start/stop, and manual excitation.
- Capture matrix for normal power production has been replaced by two capture matrices which are for stall controlled and non-stall controlled wind turbines with revised requirements. Other changes such as removal of capture matrix for power production plus occurrence of fault, please refer to page 31 for further information.
- In some cases, importance level of a few load quantities have been changed from "Recommended" to "Mandatory", and also some extra load quantities are introduced into consideration, thus the number of mandatory load quantities is increased.
- For larger wind turbines with $P_r \geq 1500$ kW and $R \geq 75$, additional load quantities need to be measured are listed in Table 10 on page 34.
- "Turbine configuration changes" is added to the end of this clause.

Clause 7 – Instrumentation

- This clause is divided from "Measurement techniques" of the 2001 version.
- Concerning about the temperature effects, the surface temperature is recommended to be measured near strain gauge locations.
- With the additional requirements for load quantities of larger wind turbines ($P_r \geq 1500$ kW and $R \geq 75$), instrumentation for following load quantities are specifically addressed in "7.1 Load quantities".

    7.1.4 Blade bending moment distribution
    7.1.5 Blade torsion frequency/damping
    7.1.9 Tower top bending moments
    7.1.10 Tower mid bending moments
    7.1.11 Tower torsion moment
    7.1.12 Tower top acceleration

7.1.13 Pitch actuation loads

- For blade bending moment distribution (7.1.4), it can be measured by using additional sets of strain gauges located at a cross section at least 30% or as far as practically possible up to 50% of rotor radius. Other requirements from 7.1.2 and 7.1.3 also apply. For the bending moment distribution the used coordinate system shall be clearly defined.
- The meteorological quantities are requested to be measured in accordance with IEC 61400-12-1.
- Compared with the 2001 version, CDV 2014 version provides more detailed and specific measurement information for wind turbine operation quantities. Those quantities are listed as below:

  7.3.1 Electrical power
  7.3.2 Rotor speed or Generator speed
  7.3.3 Yaw misalignment
  7.3.4 Rotor azimuth angle
  7.3.5 Pitch position
  7.3.6 Pitch speed
  7.3.7 Brake moment
  7.3.8 Wind turbine status
  7.3.9 Brake status

- “Sensor accuracy and resolution” has been removed.

Clause 8 – Determination of Calibration Factors

- This clause is isolated from “Clause 4 – Measurement techniques”.
- Rather than scattering in different paragraphs in the 2001 version, calibrations of load and non-load channels are thoroughly covered in Clause 8 in the CDV 2014 version with more specific description about each quantity.
- Three different ways which can be used to perform the calibration for each quantity in load channels are discussed in the CDV 2014 version and are listed in Table 13 on page 37.
- Non-load channels provided with calibration methods are listed in Table 14 on page 37.

Clause 9 – Data Verification

- This clause is separated from “Clause 5 – Processing of measured data”.
- Most of the contents in this clause remain, while examples of verification checks for blade moment, main shaft, and tower signals are added to it.

Clause 10 – Processing of Measured Data

- Purposes of this clause “Processing of measured data” are basically the same for these two versions. But the 2014 CDV version is supplemented with “Load quantities for larger turbines” and “Wind speed trend detection” thus is more complete.
- The minimum number of divisions of the load range for rainflow counting raises from 50 to 100.
- Rainflow counting is used to determine the cumulative rainflow spectra and damage equivalent loads (DEL) rather than only be used to calculate the load spectra corresponding to lifetime operation of the turbine.
- Method for wind speed binning and requirements for calculation of power spectral density are added to the end of this clause.

Clause 11 – Uncertainty Estimation

- This clause contains a general description about uncertainty estimation, and notices one should keep in mind when performing uncertainty calculations.
- Guidance for estimation of uncertainty can be found in Annex B, inclusive of an example.

Clause 12 – Report

- The clause “Report” in the 2001 version has been rearranged with specific requirements in order to make the structures of measurement reports in accordance with the general process provided in the CDV 2014 version.

Annex A (informative) Example co-ordinate systems

- Most of Annex A remains the same.

Annex B (informative) Procedure for the evaluation of uncertainties in load measurements on wind turbines

- Calculations of uncertainties for more load quantities are discussed in Annex B. There are also tables for uncertainty components and values and uncertainties for the calculation.
- An example of an uncertainty evaluation has been added.

Annex C (informative) Sample presentation of mechanical load measurements and analysis

- Revised to meet new requirements of the CDV 2014 version.

Annex D (informative) Recommendations for offshore measurements

Annex E (informative) Load model validation

Annex F (informative) Methods for identification of wind speed trends

Annex G (informative) Data acquisition considerations

Annex H (informative) Load calibration

Annex I (informative) Temperature drift

Annex J (informative) Mechanical load measurements on Vertical Axis Wind Turbines

- Annex D to J are newly added to the standard to include more information which are helpful when performing mechanical load measurements, calibration and analyses.

Comparison of MLCs in the 2001 and CDV 2014 versions

- For MLCs during steady-state operation, the case "Power production plus occurrence of fault" has been removed, and the DLC number of the case "Parked" has changed from 6.2 to 6.4.
- For MLCs for transient load cases, the case "Overspeed activation of the protection system" has been removed. And the both target conditions for the cases "Emergency shut-down" and "Grid failure" vary from "v_{in} and >v_r+2" and "v_r and >v_r+2" to "P_r".
- Table of MLCs for dynamic characterization is added.
- Differences are highlighted with ■.

Table 3 – Comparison of MLCs during steady-state operation

2001			CDV 2014		
MLC Number	MLC	DLC Number	MLC Number	MLC	DLC Number
1.1	Power production	1.2	1.1	Power production	1.2
1.2	Power production plus occurrence of fault	2.3			
1.3	Parked, idling	6.2	1.2	Parked	6.4

*The case "Power production plus occurrence of fault " has been removed.
**According to the Definitions in CDV 2014, idling is included in the parked condition.

Table 4 – Comparison of MLCs of transient load cases related to the DLCs defined in IEC 61400-1

2001				CDV 2014			
MLC Number	MLC	DLC Number	Target Wind Speed	MLC Number	MLC	DLC Number	Target Condition
2.1	Start-up	3.1	v_{in} and $>v_r+2$	2.1	Start-up	3.1	v_{in} and $>v_r+2$
2.2	Normal shut-down	4.1	v_{in} , v_r and $>v_r+2$	2.2	Normal shut-down	4.1	v_{in} , v_r and $>v_r+2$
2.3	Emergency shut-down	5.1	v_{in} and $>v_r+2$	2.3	Emergency shut-down (by pushbutton)	5.1	P_r
2.4	Grid failure	1.5	v_r and $>v_r+2$	2.4	Grid failure	2.4	P_r
2.5	Overspeed activation of the protection system	5.1	$>v_r+2$				

*The case "Overspeed activation of the protection system" has been removed.

Table 5 – MLCs for dynamic characterization

MLC Number	Measurement load case	Wind condition at MLC	Target frequencies	Comment
3.1	Power production	$V_{in}<V_{hub}<V_{out}$[a]	Blade, tower and drivetrain frequencies	Normal operation below rated wind speed and above rated wind speed with relatively steady rotational speed
3.2	Parked	High wind speed[a]	Blade and tower frequencies	Turbine is parked (standstill or idling)
3.3	Emergency stop	$V_{hub}>V_r$	Blade tower and drivetrain frequencies	Emergency stop from rated power
3.4	Yaw start/stop	Low wind speed[b]	Blade frequencies	With an instrumented blade in a horizontal position, the blade gets excited by starting and stopping the nacelle yaw rotation. Test shall be conducted with blades in normal operating position (targeting the flatwise frequencies) and with blades feathered (targeting the edge frequencies)
3.5	Manual excitation	Low wind speed[b]	Blade frequencies	
[a] High enough to get sufficient excitation, this will be wind turbine specific. [b] Low enough wind speed to not have the excitation affected by other aerodynamic loads.				

*Table 5 is newly added.

Differences of Capture Matrices between the 2001 and the CDV 2014 Versions

- Time series record length becomes 10 minutes for all cases except transient events in the CDV 2014 version.
- Instead of the capture matrix for normal power production, the CDV 2014 version provides two capture matrices according to different control methods of wind turbines. These two capture matrices are with revised requirements for stall controlled and non-stall controlled wind turbines for normal power production. The current capture matrix for normal power production has been replaced by these two. Both these capture matrices use 1m/s wide wind speed bins and 2% wide turbulence intensity bins range from. And wind speeds v_{in}, v_r and v_{out} should be rounded up to the nearest integer.
  - Capture matrix for normal power production for stall controlled wind turbines:

    The measured wind speeds (m/s) are divided into four different intervals, which are v_{in} to 12, 12 to 16, 16 to 20, and 20 to v_{out}. Each interval has different requirements for data collection as the table below:

    Table 6 – Requirements for capture matrix for normal power production for stall controlled wind turbines

Wind speed (m/s)	v_{in} to 12	12 to 16	16 to 20	20 to v_{out}
Minimum data requirements	20 time series for each 1 m/s bin* OR One TI bin with 6 time series for each 1 m/s bin*	20 time series for each 1 m/s bin OR One TI bin with 6 time series for each 1 m/s bin	8 time series for each 1 m/s bin	8 time series (in total, not for each 1 m/s bin)

    *Only time series with TI larger than 5 % can meet the requirements.

  - Capture matrix for normal power production for non-stall controlled wind turbines:

    The measured wind speeds (m/s) are divided into three different intervals, which are v_{in} to v_r-2, v_r-2 to v_r+2, and v_r+2 to v_r+4. Each interval has different requirements for data collection as the table on the next page:

Table 7 – Requirements for capture matrix for normal power production for non-stall controlled wind turbines

Wind speed (m/s)	v_{in} to v_r-2	v_r-2 to v_r+2	v_r+2 to v_r+4
Minimum data requirements	20 time series for each 1 m/s bin* OR One TI bin with 6 time series for each 1 m/s bin*	20 time series for each 1 m/s bin	10 time for each 1 m/s bin

*Only time series with TI larger than 5 % can meet the requirements.

- Capture matrix for power production plus occurrence of fault has been removed.
- Mean wind speed of recorded data for capture matrix for parked condition shall be greater than v_r, and at least one time series shall be collected with target values of 30° yaw misalignment, one with 0° yaw misalignment and one with -30° yaw misalignment.
- For normal transient events, capture matrices differ in the recorded "wind speed" as follows:

Table 8 – Difference between two versions for capture matrices for normal transient events

	2001	CDV 2014
Wind Speed	It is the ***average wind speed*** over the duration of the transient event is used.	It is the wind speed when the ***transient event gets triggered.***

- For capture matrix for other than normal transient events, two events "Overspeed combinations" and "Other design critical transients" have been removed, and target conditions change from most critical wind speed to rated power output. The recorded wind speed also changes from the wind speed when the transient event gets triggered.

Comparison of Load Quantities in the 2001 and the CDV 2014 Versions

- Wind turbine fundamental load quantities are basically the same in two versions, except for the different reference coordinate system for blade rotor bending moments (Table 9).
- The table of additional load quantities for turbines with a rated power output greater than 1500 kW and rotor diameter greater than 75m is added to the CDV 2014 version. (See Table 10)
- Differences in meteorological quantities (Table 11):
  - "Air temperature" and "Temperature gradient" have been removed.
  - The recommended "Vertical wind shear below hub height" becomes mandatory.
  - "Turbulence intensity (horizontal) at hub height" is added with level of importance as mandatory, while "Vertical wind shear above hub height", "Vertical wind veer", "Upflow angle / flow inclination angle near hub height", "Turbulence intensity (3D) at hub height", ' Icing potential", and "Atmospheric stability" are added with level of importance as recommended.
- Differences in wind turbine operation quantities (Table 12):
  - "Grid connection" has been removed.
  - Four quantities, namely, "Rotor speed", "Pitch angle", "Yaw position", and "Rotor azimuth", and their level of importance has been revised.
  - "Pitch speed" is added with level of importance as mandatory, while "Brake moment" is added with level of importance as recommended.
  - Level of importance of "Brake status" and "Wind turbine status" become mandatory.
- Differences are highlighted with ; newly added one is denoted with ; and removed one is denoted with .

Table 9 – Wind turbine fundamental load quantities comparison

2001		CDV 2014	
Load quantities	Level of Importance	Load quantities	Level of Importance
Blade root flap bending moment	Blade 1: mandatory Other blades: recommended	Blade root flatwise bending moment(M_{bf})	1 blade mandatory Additional blade recommended
Blade root lead-lag bending moment		Blade root edgewise bending moment(M_{be})	1 blade mandatory Additional blade recommended
Rotor tilt moment		Rotor tilt moment(M_{tilt})	Mandatory
Rotor yaw moment		Rotor yaw moment(M_{yaw})	Mandatory
Rotor torque		Rotor torque(M_x)	Mandatory
Tower loads – bottom bending in two directions		Tower base normal(M_{tn})	Mandatory
		Tower base lateral moment(M_{tl})	Mandatory

Table 10 – Additional load quantities for turbines with a rated power output greater than 1500 kW and rotor diameter greater than 75m

Load quantities	Level of Importance
Blade flatwise bending moment distribution	2 blades mandatory Additional blade recommended
Blade edgewise bending moment distribution	2 blades mandatory Additional blade recommended
Blade root flatwise bending moment	2 blades mandatory Other blade recommended
Blade root edgewise bending moment	2 blades mandatory Other blade recommended
Blade torsional frequency and damping	Recommended
Pitch actuation loads	One blade mandatory
Tower top acceleration in normal direction	Mandatory when used for controller feedback
Tower top acceleration in lateral direction	Mandatory when used for controller feedback
Tower mid normal moment	Recommended
Tower mid lateral moment	Recommended
Tower top normal moment	Mandatory
Tower top lateral moment	Mandatory
Tower torsion moment	Mandatory

*Table 10 is newly added.

Table 11 – Meteorological quantities comparison

2001		CDV 2014	
Quantity	Importance Level	Quantity	Level of Importance
Wind speed (at hub height)	Mandatory	Wind speed at hub height	Mandatory
Wind sheer	Recommended	Vertical wind shear (below hub height)	Mandatory
		Vertical wind shear (above hub height)	Recommended
		Vertical wind veer	Recommended
		Upflow angle / flow inclination angle near hub height	Recommended
		Turbulence intensity (horizontal) at hub height	Mandatory
Wind direction (at hub height)	Mandatory	Wind direction at hub height	Mandatory
Air temperature	Mandatory		
Temperature gradient	Recommended		
Air density	Mandatory	Air density	Mandatory
		Turbulence intensity (3D) at hub height	Recommended
		Icing potential	Recommended
		Atmospheric stability	Recommended

Table 12 – Wind turbine operation quantities comparison

2001		CDV 2014	
Quantity	Importance Level	Quantity	Level of importance
Electrical power	Mandatory	Electrical power	Mandatory
Rotor speed	Mandatory	Rotor speed or generator speed	Mandatory
Yaw position	Mandatory	Yaw misalignment	Mandatory
Rotor azimuth	Mandatory	Rotor azimuth angle	Mandatory
Pitch angle	Mandatory	Pitch position of all instrumented blades turbine controller output	Mandatory for all instrumented blades Recommended for all blades
		Pitch speed	Mandatory
Grid connection	Recommended		
Brake status	Recommended	Brake status	Mandatory
		Brake moment (if not possible, brake pressure)[a]	Recommended
Wind turbine status	Useful	Wind turbine status	Mandatory

[a] If the mechanical braking device is part of the primary braking system (e.g. at stall controlled turbines), the measurement of the brake moment is mandatory

Calibrations for Load and Non-load Channels

- More calibration methods for load channels are provided by the CDV 2014 version. For instance, applying an external load is the only way the current version has mentioned to perform the calibration of the rotor torque load sensors, but the CDV 2014 version states that it can also be done by an analytical method.
- Non-load channels provided with calibration methods are listed in Table 14.

Table 13 – Summary of suitable calibration methods

Measured Quantity	Analytical	External Load	Gravity
Blade bending moments		S	S, O
Main shaft torque[a]	S	S	
Main shaft bending	S	S	S, O
Tower bending moments	S	S	S, O
Tower torque	S	S	
Note: S = suitable for slope O = suitable for offset			
[a] For suitable methods for determining the offset see subclauses 8.2.2.4 and 8.2.4			

Table 14 – Non-load channels provided with calibration methods

Non-load Channels
Pitch angle
Rotor azimuth angle
Yaw angle
Wind direction
Pitch actuation loads
Brake moment

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