

# **2013 48th International Universities' Power Engineering Conference**

**(UPEC 2013)**

**Dublin, Ireland  
2-5 September 2013**

**Pages 1-543**



**IEEE Catalog Number: CFP13569-POD  
ISBN: 978-1-4799-3255-9**

# TABLE OF CONTENTS

<b>Automatic Restoration Of Power Supply With Possibility Of Islanded Operation Of Distribution Network</b> .....	1
<i>D. Bernardon, L. Canha, A. Abaide, V. Garcia, M. Sperandio, L. Pfitscher, G. Lopes, E. Possebon</i>	
<b>Balancing Reserve Procurement And Operation In The Presence Of Uncertainty And Transmission Limits</b> .....	7
<i>M. Bucher, G. Andersson</i>	
<b>Cloud Computing Framework For Smart Grid Applications</b> .....	13
<i>B. Bitzer, E. Gebretsadik</i>	
<b>Electrical Circuit Analysis Using Four Dimensional Complex Numbers, In The Form Of Quaternions</b> .....	18
<i>N. Barry</i>	
<b>Probabilistic Modelling Of Parameter Variability For Analysing Grid-Connected LV Feeders With DG</b> .....	22
<i>R. Herman, C. Gaunt</i>	
<b>Urban Deployment Of Small Wind Turbines: Power Performance And Turbulence</b> .....	27
<i>K. Sunderland, T. Woolmington, M. Conlin, J. Blackledge</i>	
<b>An Investigation Of The Relationship Between Economic Growth And Electricity Consumption With Different Industrial Structures In Different Regions In China</b> .....	33
<i>L. Liu, X. Ma, J. Sun</i>	
<b>Integration Of A Superconducting Magnetic Energy Storage Into A Control Reserve</b> .....	39
<i>M. Terorde, H. Eckoldt, D. Schulz</i>	
<b>Implementation Of Multiplex-Switches For Power Feeder Balancing In Aircraft</b> .....	45
<i>M. Terorde, M. Jordan, H. Wattar, J. Lemke, J. Koch, D. Schulz</i>	
<b>Single-Ended Fault Location Method Based On Wavelet Theory: Application To A Double-Circuit Transmission Line</b> .....	51
<i>F. Xie, A. Haddad, H. Griffiths</i>	
<b>Test Of Anti-Islanding Protections According To IEC 62116: An Experimental Feasibility Assessment</b> .....	57
<i>F. Belloni, P. Gropelli, C. Chiappa, R. Chiumeo, C. Gandolfi</i>	
<b>Optimization Of Constant Power Control Of Wind Turbines To Provide Power Reserves</b> .....	63
<i>J. Vyver, J. Kooning, B. Meersman, T. Vandoorn, L. Vandeveldde</i>	
<b>The Effect Of Maintenance Costs On The Flexible Dispatch Of Thermal Units</b> .....	69
<i>M. Maenhoudt, G. Deconinck</i>	
<b>Economic Analysis Of A Stand-Along Residential Solar PV System For A Typical South African Middle Income Household</b> .....	75
<i>J. February, W. Mbav, S. Chowdhury</i>	
<b>Overview Of The 500MW EirGrid East-West Interconnector, Considering System Design And Execution-Phase Issues</b> .....	81
<i>J. Egan, P. O'Rourke, R. Sellick, P. Tomlinson, B. Johnson, S. Svensson</i>	
<b>The Electrical Performance Of Thermoplastic Polymers When Used As Insulation In Cables</b> .....	87
<i>W. Zhao, W. Siew, M. Given</i>	
<b>Decision Matrix: A New Approach To Voltage Quality Monitoring On The Irish Distribution Grid</b> .....	91
<i>D. Mongey, K. Niall, A. O'Kelly</i>	
<b>Reconfiguration Of Distribution Network Considering Distributed Generation And Multivariables Criteria</b> .....	96
<i>A. Mello, D. Bernardon, L. Pfitscher, L. Canha, V. Garcia, M. Sperandio</i>	
<b>Relay Coordination And Harmonic Analysis In A Distribution Network With Over 20% Renewable Sources</b> .....	102
<i>A. Olatoke, M. Darwish</i>	
<b>Pre-, Post-, And Delayed Post-Test Evaluation Of The Conceptual Understanding Of Direct Current Resistive Electric Circuits Of Cohorts Of First Year Electrical Engineering Students</b> .....	108
<i>A. O'Dwyer</i>	
<b>Postgraduate Student Priorities In Renewable Energy Research, As Revealed Through Their Development Of Dissertation Project Proposals</b> .....	112
<i>A. O'Dwyer</i>	
<b>A Multicriteria Approach For Meter Placement In Monitoring Of Smart Distribution Systems</b> .....	117
<i>R. Milbradt, L. Canha, P. Zorrilla, A. Abaide, P. Pereira, S. Schmaedecke</i>	

<b>Impact Of Unbalanced Penetration Of Small Wind Turbines On Voltage Violation In Residential Distribution Networks</b> .....	123
<i>C. Long, D. Hepburn, M. Farrag, C. Zhou</i>	
<b>Research On The Application Of Storage Battery To Restrain The Photovoltaic Power Fluctuation</b> .....	129
<i>S. Wu, Y. Yuan</i>	
<b>Voltage Dip Analysis Of Electricity Networks On Wind Energy Integration</b> .....	135
<i>P. Sekhoto, O. Ipinnimo, S. Chowdhury</i>	
<b>An Integrated Function Of Photovoltaic Generator Supplying To Nonlinear Load: Active Power Filter</b> .....	141
<i>N. Tuyen, G. Fujita, T. Funabashi, M. Nomura</i>	
<b>Design Considerations For Smart Microgrids</b> .....	147
<i>F. Wattjes, J. Slootweg</i>	
<b>Influence Of Wall Insulation Material In BPM Synchronous Servomotor</b> .....	153
<i>H. Sa, W. Hosny, S. Dodds, D. Staton</i>	
<b>Risk-Based Security Assessment And Effects Of Fluctuating In-Feed On Risk</b> .....	159
<i>O. Makela, G. Andersson</i>	
<b>Measurement And Computation Of The Excitation Curve And Loss Angle Of Instrument Voltage Transformers</b> .....	164
<i>M. Freiburg, F. Jenau</i>	
<b>A Review Of Rural Electrification Through Micro-Grid Approach: South African Context</b> .....	169
<i>Z. Xu, S. Chowdhury</i>	
<b>Investigations In Low Voltage Distribution Grids With A High Penetration Of Distributed Generation And Heat Pumps</b> .....	175
<i>M. Arnold, W. Friede, J. Myrzik</i>	
<b>A Review Of Turboelectric Distributed Propulsion Technologies For N+3 Aircraft Electrical Systems</b> .....	181
<i>K. Davies, P. Norman, C. Jones, S. Galloway, M. Husband</i>	
<b>The Transformation Of Germany's Energy System: What Is The Role Of Biogas In The Electricity Market</b> .....	186
<i>W. Stauss, R. Biernatzki, J. Braun, M. Mergenthaler</i>	
<b>Integration Scenarios To Improve Fuel Cell Dynamics For Modern Aircraft Application</b> .....	189
<i>A. Lucken, T. Kut, M. Terorde, S. Dickmann, D. Schulz</i>	
<b>A Novel Offering Strategy To Reduce Profit Risk</b> .....	195
<i>M. Maenhoudt, G. Deconinck</i>	
<b>Evolutionary Harmony Search Algorithm For Non-Convex Economic Dispatch</b> .....	201
<i>V. Dieu, K. Nguyen, N. Hop, L. Dung, W. Ongsakul</i>	
<b>Enhanced Bowtie UHF Antenna For Detecting Partial Discharge In Gas Insulated Substation</b> .....	207
<i>J. Muslim, K. Nishigouchi, M. Kozako, M. Hikita, Y. Arief, U. Suwarno</i>	
<b>Algorithm Using Discrete Wavelet Transform To Power Transformers Protection</b> .....	212
<i>J. Marques, A. Oliverira, G. Cardoso Junior</i>	
<b>Performance Comparison Of SVC With POD And Synchronous Generator Excitation System To Investigate Oscillation Damping Control On The GB Transmission System</b> .....	217
<i>R. Rabbani, A. Zobaa, G. Taylor</i>	
<b>Islanded Vs. Grid Connected LNG Plants</b> .....	223
<i>K. Combe, K. Smith</i>	
<b>An Overview Of Wind Energy Development And Associated Power System Reliability Evaluation Methods</b> .....	229
<i>S. Shi, K. Lo</i>	
<b>Arc Running Behaviour Between Parallel Rails Of Different Metals And Compounds Used In Miniature Circuit Breakers</b> .....	235
<i>D. Gonzalez, F. Berger</i>	
<b>New Strategies For Coordinated Control In Power Distribution Grids -Effective Integration Of Photovoltaic Plants Utilizing Sensitivity Analysis</b> .....	241
<i>Y. Fawzy, B. Bletterie, W. Deprez, T. Buelo, G. Bettenwort, B. Engel</i>	
<b>Factors That Influence Variable Transfers</b> .....	247
<i>R. Ramanathan, B. Tuck</i>	
<b>BPA's Experience Of Implementing Node Breaker Model For Power System Operations Studies</b> .....	253
<i>R. Ramanathan, B. Tuck</i>	
<b>A Method For Harmonic Analysis In Distribution System With Distributed Generator</b> .....	259
<i>Z. Peng, K. Lo</i>	
<b>Multitasked Maintenance Crews To Serve Emergency Scenarios In Electric Distribution Utilities</b> .....	264
<i>V. Garcia, D. Bernardon, G. Dhein, O. Bassi, A. Abaide, A. Neto, J. Fonini, E. Daza</i>	

<b>The Impact Of Urban Atmospheric Turbulence On The Generation Capability Of A Micro-Wind Generator .....</b>	<b>270</b>
<i>E. Beer, M. Conlin, K. Sunderland</i>	
<b>Autonomous Decentralized Control Of Preserving-Type Distributed Energy System .....</b>	<b>276</b>
<i>N. Kaneko, G. Fujita</i>	
<b>Visualization Of Electric Power By Module-Type Power System Training Device .....</b>	<b>282</b>
<i>T. Hoshino, G. Fujita</i>	
<b>Analysis Of Electric Vehicles Measurements .....</b>	<b>286</b>
<i>B. Vonk, D. Geldmeijer, J. Slootweg</i>	
<b>Implementation Of Wide Area Monitoring Systems And Laboratory-Based Deployment Of PMUs .....</b>	<b>292</b>
<i>M. Golshani, G. Taylor, I. Pisica, P. Ashton</i>	
<b>A Review Of Short-Term Hydro Scheduling Tools .....</b>	<b>298</b>
<i>G. Osorio, J. Matias, J. Catalao</i>	
<b>Economic Evaluation And Experimental Setup Of Biomass Energy As Sustainable Alternative For Textile Industry .....</b>	<b>304</b>
<i>L. Nunes, J. Matias, J. Catalao</i>	
<b>Experimental Validation Of The Influence Of Cable Losses In The Economic Analysis Of Electrical Equipment .....</b>	<b>310</b>
<i>J. Lobao, T. Devezas, J. Catalao</i>	
<b>Design And Implementation Of A Prototype Home Energy Management System .....</b>	<b>315</b>
<i>I. Pisica, G. Taylor, L. Tomescu, L. Laurentiu</i>	
<b>Building Energy Management Systems - Optimization Of Comfort And Energy Use .....</b>	<b>321</b>
<i>L. Hurtado, P. Nguyen, W. Kling, W. Zeiler</i>	
<b>Statistical Probability Based Transmission Congestion Cost Increasing Tendency Analysis .....</b>	<b>327</b>
<i>J. Li, L. Zhou, F. Li</i>	
<b>Measurement And Statistical Analysis Of Partial Discharges At DC Voltage .....</b>	<b>333</b>
<i>T. Klueter, J. Wulff, F. Jenau</i>	
<b>A Numerical Model Of Lithium-Ion Battery For A Life Estimation .....</b>	<b>338</b>
<i>N. Nagaoka</i>	
<b>Line Constants And Transient Simulation Of Wiring On L-Type Duct .....</b>	<b>344</b>
<i>T. Higo, N. Nagaoka</i>	
<b>An EMTP Simulation Of PLC Receiver Based On OFDM .....</b>	<b>350</b>
<i>S. Takemura, N. Nagaoka, A. Ametani</i>	
<b>Operations Modeling In The Iceland Hydro Dominated Power System .....</b>	<b>356</b>
<i>E. Hreinsson</i>	
<b>Discounted Value Of Economic Rent In Hydro And Geothermal Expansion Planning In Iceland .....</b>	<b>362</b>
<i>E. Hreinsson, K. Jonasson, G. Petursson</i>	
<b>Load Factor Based Transmission Network Pricing: An Evaluation For The Improved ICRP Method .....</b>	<b>367</b>
<i>J. Li, C. Yuan, Z. Zheng, F. Li</i>	
<b>Construction Of The Battery Model Considering Cycle Deterioration .....</b>	<b>373</b>
<i>T. Fujihashi, G. Fujita</i>	
<b>Energy Management And Dynamic Optimisation Of Eco-Industrial Parks .....</b>	<b>377</b>
<i>C. Deckmyn, T. Vandoorn, L. Vandeveldde, J. Lemcko, G. Eetvelde, J. Timmerman</i>	
<b>Shipboard High Voltage Operations And Management .....</b>	<b>382</b>
<i>M. O'Donovan, N. Barry</i>	
<b>Modeling Of Distributed Energy Resources Using Laboratory-Experimental Results .....</b>	<b>387</b>
<i>P. Papadopoulos, T. Papadopoulos, G. Papagiannis, P. Crolla, A. Roscoe, G. Burt</i>	
<b>Using IEC 61850 Data Transfer Beyond The Substation For Enhanced Protection For Distribution Networks .....</b>	<b>393</b>
<i>J. Miao, D. Dostanov, M. Redfern</i>	
<b>Analysis Of The Propagation Characteristics Of Single-Core Cables From Experimental Results Using Modal Decomposition .....</b>	<b>399</b>
<i>A. Chrysochos, T. Papadopoulos, G. Papagiannis</i>	
<b>Evaluation Of Washing Machine Load Potential For Smart Grid Integration .....</b>	<b>405</b>
<i>E. Klaassen, C. Kobus, M. Huijkelom, J. Frunt, H. Slootweg</i>	
<b>Systematic Sensitivity Analysis Regarding The Influence Of Distributed Generation Units Allocation To The Optimal Reconfiguration For Loss Reduction .....</b>	<b>411</b>
<i>A. Bouhouras, T. Papadopoulos, G. Christoforidis, G. Papagiannis, D. Labridis</i>	
<b>Simulation Levels In Teaching Power Electronics .....</b>	<b>417</b>
<i>M. Darwish, C. Marouchos</i>	

<b>Recent Advances On The Influence Of Power Transformers Inrush Current Over The Optimization Of Medium Voltage Feeder Protection .....</b>	<b>422</b>
<i>R. Radu, D. Micu, A. Ceclan</i>	
<b>Optimal Power Flow Computing GA Applications.....</b>	<b>428</b>
<i>F. Solomonescu, C. Barbulescu, S. Kilyeni, A. Simo</i>	
<b>A Simple Drive Induction Motor Based On Buck/Boost Inverter Topology .....</b>	<b>434</b>
<i>M. Moghadam, M. Darwish, C. Marouchos</i>	
<b>Use Of Modern Technology And Innovative Design To Upgrade A Distribution Substation To A Transmission Substation In An Urban Location .....</b>	<b>438</b>
<i>J. Bednarik</i>	
<b>Initial Development Of A Novel Stability Control System For The Future GB Transmission System Operation.....</b>	<b>444</b>
<i>S. Kerahroudi, G. Taylor, F. Li, M. Bradley</i>	
<b>Methodology For Adjustment Of Limits Of Power Supply Continuity By Linear Programming.....</b>	<b>450</b>
<i>L. Silva, A. Abaide, N. Neto, L. Canha, D. Bernardon, A. Martins</i>	
<b>Transient Event Detection And Analysis Of The GB Transmission System Using Synchrophasor Measurements.....</b>	<b>456</b>
<i>P. Ashton, G. Taylor, A. Carter</i>	
<b>Dynamic Modeling Of A VSC-HVDC Converter .....</b>	<b>462</b>
<i>M. Imhof, G. Andersson</i>	
<b>Generation Of Simulated Time Series For Wind Speed Based On A Statistical Wind Atlas For Iceland .....</b>	<b>468</b>
<i>K. Jonasson, G. Petursson, E. Hreinsson</i>	
<b>Partial Discharge Pulse Propagation, Localisation And Measurements In Medium Voltage Power Cables .....</b>	<b>473</b>
<i>D. Clark, R. Mackinlay, R. Giussani, L. Renforth, R. Shuttleworth</i>	
<b>Assessing The Benefits Of Compressed Air Energy Storage On The 2020 Irish Power System .....</b>	<b>479</b>
<i>B. Cleary, A. Duffy, A. O'Connor, M. Conlin, V. Fthenakis</i>	
<b>The Domestic And Export Market For Large Scale Wave Energy In Ireland And The Economics Of Export Transmission .....</b>	<b>485</b>
<i>F. Sharkey, K. Honer, M. Conlon, K. Gaughan, E. Robinson</i>	
<b>Integrating Renewable Energy With Flexible Storage Systems: A Case Study Of GB And Greece .....</b>	<b>491</b>
<i>A. Hassan, E. Xydias, C. Marmaras, L. Cipcigan, N. Jenkins</i>	
<b>Airborne Wind Energy: Simulation Of Directly Interconnected Synchronous Generators For A Novel Wind Energy Technology.....</b>	<b>497</b>
<i>J. Coleman, E. Pican, H. Ahmad, D. Toal</i>	
<b>Forecasting Electric Vehicle Charging Demand Using Support Vector Machines .....</b>	<b>503</b>
<i>E. Xydias, C. Marmaras, L. Cipcigan, A. Hassan, N. Jenkins</i>	
<b>Assessment Of Domestic Load Suitable For Smart Consumer Load Participation .....</b>	<b>509</b>
<i>M. Almenta, J. Morrow, R. Best, B. Fox</i>	
<b>A Switch Capacitor KVAR And Selective Harmonic Current Compensator.....</b>	<b>515</b>
<i>C. Marouchos, M. Darwish, M. Evdokimou</i>	
<b>HVPL Conductor Sag Influence On Induced Voltage Evaluation In Nearby Metallic Structures.....</b>	<b>521</b>
<i>L. Czumbil, D. Micu, D. Stet, G. Christoforidis, L. Ancas</i>	
<b>Inter-Area Power Oscillation Frequency Mode With Wind Turbine Generator In Irish Power System Using PMU Data .....</b>	<b>527</b>
<i>H. Iswadi, R. Best, D. Morrow</i>	
<b>Assessing The Viability Of Electric Vehicle Technologies For UK Fleet Operators.....</b>	<b>532</b>
<i>K. Davis, P. Rowley, S. Carroll</i>	
<b>A New Concept For A Multilevel Switched Capacitor Sinusoidal Grid Connected Inverter.....</b>	<b>538</b>
<i>C. Marouchos, M. Darwish, L. Diomidou</i>	
<b>A Smart Grid Information System For Demand Side Participation: Remote Control Of Domestic Appliances To Balance Demand .....</b>	<b>544</b>
<i>J. Hastings, D. Laverty, D. Morrow</i>	
<b>A Comparison Of Two Hydro Scheduling Algorithms, SDDP And LpSim .....</b>	<b>549</b>
<i>G. Petursson, K. Jonasson, E. Hreinsson, U. Linnet</i>	
<b>Common-Mode Choke Design Considerations Applied To Domestic Induction Heating .....</b>	<b>554</b>
<i>I. Lope, W. Hurley, J. Zhang</i>	
<b>Python PSS/E Simulation To Test Efficacy Of Proposed PMU Based WAMS And Potential WAMPAC Applications .....</b>	<b>559</b>
<i>P. Brogan, J. Morrow, R. Best, D. Laverty</i>	

<b>An Empirical Approach To Calculate Short And Long Term Energy Storage Needs Of An Electricity System</b> .....	564
<i>T. Weiss, A. Lucken, D. Schulz</i>	
<b>Comparison Of Wind Turbine/Generator Configurations For Future Offshore Wind Farms</b> .....	570
<i>R. Meere, T. O'Donnell, A. Keane</i>	
<b>Oscillation Processes Of DC Electric Arcs At Different Setups Of Electrodes And Variable Parallel Capacitance</b> .....	576
<i>M. Streck, O. Eppler, F. Nothnagel, F. Berger</i>	
<b>Detection Of Fault Location, Monitoring And Control In Underwater Power System</b> .....	582
<i>M. Forjani, Z. Hashem</i>	
<b>Application Of Competitive Learning Clustering In The Load Time Series Segmentation</b> .....	588
<i>I. Panapakidis, M. Alexiadis, G. Papagiannis</i>	
<b>PSO Based Transmission Network Expansion</b> .....	594
<i>D. Cristian, A. Simo, C. Barbulescu, S. Kilyeni</i>	
<b>An On-Demand Generation Regulation Control For Small Independent Power Grids With Effective EV Charging Control</b> .....	600
<i>Y. Zoka, Y. Mashima, Y. Kuwada, Y. Sasaki, N. Yorino</i>	
<b>Operational Security At High Penetrations Of Stochastic, Non-Synchronous Generation</b> .....	606
<i>P. Daly, M. Power, A. Keane, D. Flynn</i>	
<b>Future Electricity Highways For Pan-European Transmission Systems: A GB Transmission System Perspective</b> .....	612
<i>A. Alikhanzadeh, G. Taylor, A. Zobaa</i>	
<b>Mitigating Imbalances From Wind Power By Using An Agent-Based Matching Mechanism</b> .....	618
<i>B. Ahmed, M. Ampatzis, P. Nguyen, H. Ferreira, W. Kling</i>	
<b>An Auto Tuning Substation Peak Shaving Controller For Congestion Management Using Flexible Demand</b> .....	624
<i>F. Sossan, M. Marinelli</i>	
<b>Distribution Network Power Loss By Using Artificial Bee Colony</b> .....	629
<i>M. Muhtazaruddin, G. Fujita</i>	
<b>Model-Based Condition Monitoring Of A Double-Fed Induction Generator Slip Ring Component</b> .....	634
<i>P. Heerden, H. Vermeulen</i>	
<b>Risk Assessment Of Power Wheeling In Extra High Voltage Transmission Systems</b> .....	640
<i>M. Fleckenstein, A. Rhein</i>	
<b>Topologies Of The North Sea Supergrid</b> .....	646
<i>O. Adeuyi, N. Jenkins, J. Wu</i>	
<b>Conceptual Evaluation Of A Fuel-Cell-Hybrid Powered Bus</b> .....	652
<i>W. Wu, R. Bucknall</i>	
<b>Maximum Power Point Tracking Of Photovoltaic Water Pumping System Using Fuzzy Logic Controller</b> .....	657
<i>F. Aashoor, F. Robinson</i>	
<b>A New Method For Incorporating Load Pickup As A Control Means For Standing Phase Angle Reduction In Power System Restoration</b> .....	662
<i>L. Wang, H. Ye, Y. Liu, X. Liu</i>	
<b>Padé Approximation Based Method For Computation Of Eigenvalues For Time Delay Power System</b> .....	666
<i>X. Niu, H. Ye, Y. Liu, X. Liu</i>	
<b>Technical Impact Of Grid Integration Of Wind Power On Distribution Or Sub-Transmission Networks: A Case Study For Namibia</b> .....	670
<i>C. Muyunda, S. Chowdhury</i>	
<b>A Load Flow Calculation Method With Optimal Multipliers For Integrated AC/DC Power Systems</b> .....	675
<i>Z. Li, Z. Xu</i>	
<b>Study Of A Clinical Analysis Laboratory's Lighting System Design</b> .....	681
<i>F. Raminhos, M. Valdez, C. Ferreira</i>	
<b>Application Of Time Series And Artificial Neural Network Models In Short-Term Forecasting Of PV Power Generation</b> .....	686
<i>E. Kardakos, M. Alexiadis, S. Vagropoulos, C. Simoglou, P. Biskas, A. Bakirtzis</i>	
<b>Impact Of DFIG Wind Turbines On Short Circuit Levels In Distribution Networks Using ETAP</b> .....	692
<i>S. Afifi, H. Wang, G. Taylor, M. Irving</i>	
<b>Probabilistic Network Usage. Case Study For The Romanian Power System</b> .....	696
<i>O. Pop, F. Surianu, S. Kilyeni, C. Barbulescu</i>	
<b>Active Damping Techniques For Suppressing The LCL Filter Resonance In Distributed Generators</b> .....	702
<i>M. Hanif</i>	

<b>Synchronisation Control And Operation Of Microgrids For Rural/Island Applications</b> .....	707
<i>L. Gan, D. Macpherson, J. Shek</i>	
<b>10 ohm Neutral Grounding Resistance In 30kV Western Libyan Network And Effects</b> .....	713
<i>H. Al-Amari, A. Fadel</i>	
<b>Assessing Electrocution Risks In Transmission Substations Using Probabilistic Criteria</b> .....	719
<i>A. Amin, N. Harid, A. Dimopoulos, D. Guo, H. Griffiths, G. Mpoju, A. Haddad, D. Frame</i>	
<b>Control Design For PMM Starter-Generator Operated In Flux-Weakening Mode</b> .....	724
<i>F. Gao, S. Bozhko, Y. Shen, G. Asher</i>	
<b>A Reliability Forecasting Method For Distribution Systems Based On Support Vector Machine With Chaotic Particle Swarm Optimization Algorithm</b> .....	730
<i>Z. Li, Z. Xu, H. Ye, Z. Wang</i>	
<b>Optimized Harmonic Elimination For Cascaded Multilevel Inverter</b> .....	735
<i>R. Hossam, G. Hashem, M. Marei</i>	
<b>Impact Of Climate Change On Static Ratings Of Overhead Line In Edinburgh</b> .....	741
<i>X. Hu, I. Cotton</i>	
<b>Analysis Of Self-Compensating DFIG For Wind Energy Conversion Systems</b> .....	747
<i>D. Nguyen, G. Fujita</i>	
<b>The Effect Of Stranded Conductor Geometry On DC Corona In The Coaxial Cylindrical Electrode Arrangement In Air</b> .....	753
<i>P. Mikropoulos, V. Zagkanas</i>	
<b>Development Of Power System Differential Protection Based On Optical Current Measurement</b> .....	758
<i>M. Nasir, A. Dysko, P. Niewczas, C. Booth, P. Orr, G. Fusiek</i>	
<b>Binary Integer Programming Applied To Fault Section Estimation In Power Systems</b> .....	762
<i>A. Oliveira, J. Zauk, O. Araujo, G. Cardoso</i>	
<b>Evaluation Of The MPPT Performance In Small Wind Turbines By Estimating The Tip-Speed Ratio</b> .....	768
<i>L. Gevaert, J. Kooning, T. Vandoorn, J. Vyver, L. Vandeveldde</i>	
<b>Robustness Of Photovoltaic System Based Stabilizer To Mitigate Inter-Area Oscillation In A Multi-Machine Power System</b> .....	773
<i>Y. Ge, W. Du, H. Wang, T. Littler, J. Cao</i>	
<b>An Educational Approach To A Cost-Efficiency Analysis Between Lighting Solutions Using DIALux</b> .....	778
<i>P. Santos, C. Agreira, M. Perdigao</i>	
<b>The Success Of Active And Cooperative Learning In Summer School Courses</b> .....	784
<i>P. Santos, C. Agreira, M. Valdez</i>	
<b>Dynamic Control Of Inverter-Connected Generators For Intentionally Islanded MV Distribution Networks</b> .....	788
<i>R. Caldon, M. Coppo, A. Raciti, R. Turri</i>	
<b>A Comparative Study Of Two Different Stand-Alone Schemes Based On Landfill Gas Energy Projects</b> .....	794
<i>W. Mbav, S. Chowdhury</i>	
<b>Risk Of Unintentional Islanding In LV Distribution Networks With Inverter-Based DGs</b> .....	799
<i>R. Caldon, M. Coppo, R. Sgarbossa, L. Sgarbossa, R. Turri</i>	
<b>ANN-Based Classification System For Different Windows Of Voltage Dips In A Power Network</b> .....	805
<i>O. Ipinimo, S. Chowdhury</i>	
<b>Wireless Measurement System For A Large-Scale Grounding Electrode Test Facility</b> .....	811
<i>D. Clark, H. Griffiths, N. Harid, A. Haddad, D. Guo</i>	
<b>A New Volt/VAR Control For Distributed Generation</b> .....	815
<i>W. Shang, S. Zheng, L. Li, M. Redfern</i>	
<b>Measurement Of Magnetic Fields Within A 3-Phase Core-Type Transformer During The Positive- And Zero-Sequence Impedance Tests</b> .....	820
<i>E. Sorrentino, A. De Gouveia, J. Burgos, P. Hormazabal, J. Marquez</i>	
<b>An Approximate 2D Method For Computing The Magnetizing Zero-Sequence Impedances In 3-Phase Core-Type Transformers Without Tank</b> .....	826
<i>E. Sorrentino, J. Burgos</i>	
<b>Interference Analysis From Medium-Voltage Cables Of Photovoltaic Plants To Metallic Pipelines</b> .....	830
<i>G. Christoforidis, T. Papadopoulos, C. Parisses, D. Micu, L. Czumbil</i>	
<b>Advances In MV Voltage Regulators</b> .....	836
<i>A. McGrath</i>	
<b>Small-Scale Wind Turbines: An Appraisal</b> .....	840
<i>T. Kealy</i>	
<b>Electrical Engineering Teaching And Distance Learning Using A Desktop Virtual Reality System</b> .....	846
<i>M. Valdez, C. Ferreira, F. Barbosa</i>	

<b>Portable And Compact Grounding System</b> .....	850
<i>W. Hassan, M. Akmal, M. Kamran</i>	
<b>A New Placement And Integration Method Of UPQC To Improve The Power Quality In DG Network</b> .....	856
<i>S. Khadem, M. Basu, M. Conlon</i>	
<b>Control Of The Shunt Active Power Filter Under Non-Ideal Grid Voltage And Unbalanced Load Conditions</b> .....	862
<i>S. Biricik, S. Redif, O. Ozerdem, M. Basu</i>	
<b>Performance Of An Asymmetrical Six-Phase Induction Machine In Single-And Two-Neutral Point Configurations</b> .....	867
<i>F. Patkar, M. Jones</i>	
<b>Review Of Harmonics In Offshore Wind Farms</b> .....	873
<i>M. Chaves-Baez, O. Anaya-Lara, K. Lo, J. McDonald</i>	
<b>Harmonics And Power Loss Reduction In Multi-Technology Offshore Wind Farms Using Simplex Method</b> .....	878
<i>M. Chavez-Baez, O. Anaya-Lara, K. Lo, J. McDonald</i>	
<b>Efficient Modelling Of A Modular Multilevel Converter</b> .....	883
<i>W. El-Khatib, J. Holboell, T. Rasmussen</i>	
<b>Reduction Of Circulating Current Flow In Parallel Operation Of APF Based On Hysteresis Current Control</b> .....	889
<i>S. Khadem, M. Basu, M. Conlon</i>	
<b>Sustainability Of Grid-Tie Micro-Generation System</b> .....	895
<i>L. Mariam, M. Basu, M. Conlon</i>	
<b>Energy Management Systems</b> .....	901
<i>J. Amaral, C. Reis, R. Brandao</i>	
<b>Implementation Of An Economic System To Measure Solar Radiation</b> .....	907
<i>M. Darwish, O. Castro, R. Valenzuela, A. Ortega, G. Jimenez</i>	
<b>Community Microgrid Based On Micro-Wind Generation System</b> .....	912
<i>L. Mariam, M. Basu, M. Conlon</i>	
<b>Application Of A Correction Current Injection Power Flow Algorithm To An Unbalanced 4-Wire Distribution Network Incorporating Tn-C-S Earthing</b> .....	918
<i>K. Sunderland, M. Coppo, M. Conlon, R. Turri</i>	
<b>Fault Identification Of LCC HVDC Using Signal Processing Techniques</b> .....	924
<i>B. Paily, M. Basu, M. Conlon</i>	
<b>Impact Of Carbon Financing On The Development Of Small Scale Run Of River Hydropower Plants In Malaysia During The Period 2008-2012</b> .....	930
<i>K. O'Kane</i>	
<b>Islanding Feasibility Considering Reactive Power In The Subtransmission Systems</b> .....	934
<i>J. Allahdadian, A. Berizzi, C. Bovo, V. Ilea, M. Gholami</i>	
<b>Connection Design Without Accurate LV Feeder Load Data - An Argument For LV Monitoring</b> .....	940
<i>J. Crouch, P. Crouch, D. Strickland</i>	
<b>Day-Ahead Scheduling Of A Photovoltaic Plant By The Energy Management Of A Storage System</b> .....	946
<i>M. Marinelli, F. Sossan, F. Isleifsson, G. Costanzo, H. Bindner</i>	
<b>Impact Of Electric Vehicles On GM Electricity Demand And Associated Benefits For System Control</b> .....	952
<i>M. Coldwell, D. Strickland, L. Chittock</i>	
<b>Stability Analysis Of Aircraft Electrical Power System With Active Front Rectifier System In Generation Channel</b> .....	958
<i>Y. Shen, L. Xia, S. Bozhko, G. Asher</i>	
<b>Operation Analysis Of Stress Grading System In Inverter-Driven Medium Voltage Motors</b> .....	964
<i>N. Nam, S. Matsumoto</i>	
<b>Coordinated BESS Control For Improving Voltage Stability Of A PV-Supplied Microgrid</b> .....	970
<i>K. Dinh, Y. Hayashi</i>	
<b>Control Strategies For Reactive Shunts To Improve Long-Term Voltage Stability</b> .....	976
<i>M. Tirtashi, O. Samuelsson, J. Svensson</i>	
<b>Contribution Of HVDC Converters To The DC Short Circuit Current</b> .....	981
<i>A. Wasserrab, B. Just, G. Balzer</i>	
<b>Aspects Of Evaluating The Efficiency Of Introducing Innovative Method And Technology Demand Side Management In Smart Grid System</b> .....	987
<i>D. Klavsuts, I. Klavsuts, G. Rusin</i>	
<b>The Effect Of Cycling On The State Of Health Of The Electric Vehicle Battery</b> .....	992
<i>G. Lacey, G. Putrus, T. Jiang, R. Kotter</i>	
<b>Project SoLa BRISTOL And The "Ecohome"</b> .....	999
<i>S. Kaushik, R. Aggarwal, M. Redfern, P. Bale, M. Dale, A. Smyth</i>	



<b>Design Procedure For Inductors-On-Silicon In Power Supply On Chip Applications</b> .....	1004
<i>C. Feeney, M. Duffy, C. O'Mathuna</i>	
<b>Advantages Of A Dynamic Smart Grid Training Tool For DSO Control Centre Staff</b> .....	1009
<i>D. Metz, M. Conlon, D. Mengapche</i>	
<b>Sag-Tension Calculation Program For Wood Pole Overhead Lines</b> .....	1015
<i>C. Baker, J. Baker, H. Nouri</i>	
<b>A Novel Stator Earth Fault Protection For Large Generator Based On Fault Current</b> .....	1021
<i>Y. Wang, X. Yin, Z. Zhang, Z. Li</i>	
<b>A Study On The Power Quality Of DG Integrated Building Energy System In Virtual Environment</b> .....	1027
<i>S. Khadem, R. Kerrigan, M. Basu, B. Basu</i>	
<b>Economic Analysis Of Reactive Power Control And Availability On Power Losses In A Wind Farm Connected At 38KV</b> .....	1032
<i>C. Lally, M. Basu</i>	
<b>Grid-Tie Arrangements For Micro-Generation Under EN50438; An Irish Evaluation</b> .....	1038
<i>L. Murphy</i>	
<b>Measurements Of DC Arc Faults In Real Photovoltaic Systems</b> .....	1044
<i>F. Erhard, F. Berger</i>	
<b>Efficiency Plan For A Large Interconnected Urban Ring Main Network Under Contingency Conditions</b> .....	1050
<i>J. Iindombo, G. Atkinson-Hope</i>	
<b>Development And Evaluation Of A SCORPF Framework For The National Grid Control Centre</b> .....	1056
<i>P. Macfie, P. Hurlock, G. Taylor, M. Irving</i>	
<b>Investigating Scalable Computational Tools And Infrastructure To Enable Interoperable And Secure Control Of Large-Scale Power Systems</b> .....	1062
<i>A. Muttalib, G. Taylor, M. Bradley</i>	
<b>Magnetic Equivalent Circuit Modeling For Interior Permanent Magnet Synchronous Machine Under Eccentricity Fault</b> .....	1068
<i>M. Zhang, A. MacDonald, K. Tseng, G. Burt</i>	
<b>Wind Generation Assessment Proposal By Experimental Harmonic And Distortion Factor Analysis</b> .....	1074
<i>N. Golovanov, G. Lazaroiu, R. Porumb</i>	
<b>Solar Photovoltaic Water Pumping For Multiple Use Systems (MUS) In Nepal</b> .....	1078
<i>F. McLoughlin, A. Duffy, M. Conlon</i>	
<b>Author Index</b>	

# Inter-Area Power Oscillation Frequency Mode with Wind Turbine Generator in Irish Power System using PMU Data

Iswadi HR  
Queen's University Belfast  
iiswadihr01@qub.ac.uk

R.J. Best  
Queen's University Belfast  
r.best@qub.ac.uk

D.J. Morrow  
Queen's University Belfast  
dj.morrow@ee.qub.ac.uk

**Abstract**—Two case studies are presented in this paper to demonstrate the impact of different power system operation conditions on the power oscillation frequency modes in the Irish power system. A simplified 2 area equivalent of the Irish power system has been used in this paper, where area 1 represents the Republic of Ireland power system and area 2 represents the Northern Ireland power system.

The potential power oscillation frequency modes on the interconnector during different operation conditions have been analysed in this paper. The main objective of this paper is to analyse the influence of different operation conditions involving wind turbine generator (WTG) penetration on power oscillation frequency modes using phasor measurement unit (PMU) data.

Fast Fourier transform (FFT) analysis was performed to identify the frequency oscillation mode while correlation coefficient analysis was used to determine the source of the frequency oscillation. The results show that WTG, particularly fixed speed induction generation (FSIG), gives significant contribution to inter-area power oscillation frequency modes during high WTG operation.

**Index Terms**—correlation coefficient analysis, doubly fed induction generator, Fast Fourier transform, fixed speed induction generator, inter-area oscillation frequency, phasor measurement unit, power system oscillation, power system stability, wind turbine generator

## I. INTRODUCTION

The Irish power system is comprised the Republic of Ireland and the Northern Ireland power system. This system can be considered as a 2 area power system which is connected via a double circuit 275 kV North-South interconnector and two single circuit 110 kV [1].

European legislation has mandated that European Union countries have to provide at least 20% of final energy consumption supplied by renewable energy by 2020 [2]. In the Irish power system, due to the availability of renewable resources, both of Republic of Ireland and Northern Ireland government have targeted to have 40% of renewable energy in their system by 2020. WTG will become the main renewable energy contributor in the Irish power system [1].

With the increasing penetration level of WTG in the Irish power system, it is important to analyse their influence on power system operation, particularly inter-area power oscillation frequency modes. Previous work has shown how

fixed speed induction generator (FSIG) can produce power oscillation at certain characteristic frequencies [3].

Moreover, the penetration of WTG has no influence on the damping of electromechanical modes of the system. However, it can induce several oscillatory modes [4]. Authors in [5] also observed that the increasing penetration of WTG has negligible effect on frequency damping.

The purpose of this paper is to investigate the behaviour of inter-area power oscillation frequency modes during different operation conditions. The details of case studies are presented in section II of this paper.

## II. THE STUDY SYSTEM

### A. Description of the Study Network

Fig.1 describes the characteristics of the study network that is used in this paper. This study network is an equivalent model of Irish power system which is comprised of the Republic of Ireland (area 1) and Northern Ireland (area 2) power systems. The equivalent model is based upon the one described in [6] and whose structure has been chosen to be roughly representative of the Republic of Ireland and Northern Ireland power systems.

Although the two power systems are connected through three interconnectors, in this paper only a double circuit 275 kV interconnector was considered since only this interconnector is used for bulk power transfer between the two areas.

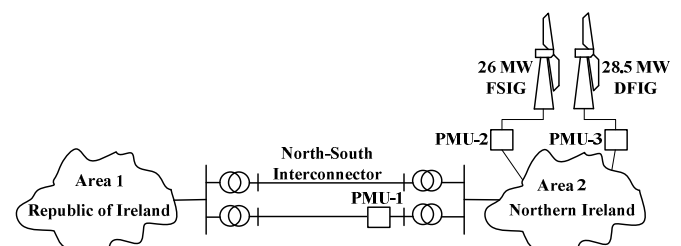


Fig. 1. Irish equivalent power system

Due to the limitation of data, only 10 conventional power plants and 2 WTGs are chosen in area 1 for this analysis while in area 2, there are 16 conventional power plants and 7 WTGs considered.

### B. Phasor Measurement Units Data

A number of Phasor Measurement Units (PMUs) have been installed on the Irish power system. In this paper, the recorded PMU data from the three different measurement locations of PMU-1, PMU-2 and PMU-3 have been used. PMU-1 measures voltage and current (both magnitude and phase angle) and frequency at the North-South interconnector on the North side, while PMU-2 and PMU-3 have been employed for measurement at wind farms in area 2 for measurement at a 26 MW fixed speed induction generator (FSIG) wind farm and a 28.5 MW doubly fed induction generation (DFIG) wind farm respectively.

The measurements are taken at a rate 50 samples per second and time synchronized to global positioning system (GPS). Data is stored 5 minutes long comma separate value (csv) files. Recorded PMU data are available for long periods of time. The data analysed in this paper was recorded during the period of November 2011 to May 2012.

A number of generation units' (conventional and WTGs) power output data at  $\frac{1}{2}$  hour resolution has been used in the analysis. These data can be publically accessed from the single electricity market operator [7]. In addition,  $\frac{1}{2}$  hour resolution data of total wind farm generation in Republic of Ireland and power demand in Republic of Ireland and Northern Ireland can be acquired from SONI and EirGrid online publication and data centre [8], [9].

### C. Case Studies

Two case studies have been analysed in this paper. Case study A is to analyse the inter-area oscillation frequency modes that occur in the interconnector during low wind and high demand operation condition. To achieve this condition, measurement data from the interconnector have been selected from the operation condition when WTG power output in the Republic of Ireland is less than 600-MW (36.5% of installed capacity) and the total Irish power demand from 4,500-MW to 6,300-MW (71.4%-100% of Peak Demand).

Conversely, case study B is to analyse the inter-area frequency oscillation mode during high wind and low demand condition when WTGs power output in the Republic of Ireland more than 800-MW (48.70% of installed capacity) while total Irish power demand is from 2500-MW to 4,500-MW (39.6%-71.4%).

Power oscillation frequency from 26-MW FSIG and 28.5-MW DFIG wind farms were analysed as well to observe whether these types of WTG give contribution to inter-area oscillation frequency by inducing its frequency to the power system.

### C. Fast Fourier Transform and Correlation Coefficient Analysis

A Fast Fourier transform (FFT) is performed using MATLAB by code written in m-files specifically for the task [10]. FFT amplitudes were calculated from 5 minutes length data during 6 month period. The number of FFT points from 5 minutes length of data is  $2^{13}$  points (equal to 2.73 minutes of data) and the frequency resolution between FFT points is  $50/2^{13}=0.006103$  Hz. The first 400 FFT amplitude points were analysed since this paper needs only to show the frequency amplitude spectrum from 0.2 Hz to 2.5 Hz.

Furthermore, correlation coefficient analysis is employed to identify a correlation between low resolution generator power outputs and certain frequencies in the interconnector. A positive correlation coefficient means that the increasing of generator power output would correspond to an increase in frequency spectrum amplitude while the negative coefficient means particular generator has an inverse relationship to the frequency spectrum amplitude. Furthermore, zero correlation coefficient means there is no association between generator power outputs to the oscillation frequency.

## IV. RESULTS AND ANALYSIS

### A. Case Study A: Inter-Area Power Oscillation Frequency during Low Wind and High Demand Operation Condition

Fig. 2 shows the power flow frequency spectrum in the North-South interconnector during low wind and high demand operation condition. From such conditions, it is possible to characterise the frequency oscillations on the interconnector when conventional thermal power plant is dominant.

It is noticeable from the fig. 2 that during case study A that several oscillation frequency modes occur on the interconnector in the range frequency from 0.2 Hz to 1.0 Hz.

The dominant oscillation frequencies are 0.268 Hz, 0.317 Hz, 0.336 Hz, 0.415 Hz, 0.446 Hz, 0.494 Hz, 0.653 Hz, 0.958 Hz and 0.995. Since during low wind and high demand operation condition some WTGs are still online so there is a possibility that these particular frequencies might be induced by excitation frequency from WTGs to the system. One of the sources of the frequency from WTG is the constant rotational turbine rotor speed, referred to as 1p (first excitation frequency). The second excitation frequency is the rotor blade passing frequency which is called as 2p and 3p excitation frequency for WTG with 2 and 3 blades respectively [11].

Some turbine manufactures have different gear ratios as describes in table I. It is shown from the table I that some of the excitation frequencies are close to the frequency on the interconnector during low wind and high demand operation condition. Frequency 0.653 Hz is probably from 2p excitation frequency while frequency 0.317 Hz and 0.336 are much closer to the 1p excitation frequency of fixed speed wind turbine with gear ratio 1:78. The peaks observed at 0.5 Hz and

1.0 Hz can be ignored as they are thought to be a function of the measurement process.

TABLE I  
FIXED SPEED WIND TURBINE GEAR RATIO AND EXCITATION FREQUENCY

No	Gear ratio	Induction Generator Speed (rpm)	1p (Hz)	2p (Hz)	3p (Hz)
1	1/78	1515	0.324	0.647	0.971
2	1/91	1515	0.277	0.555	0.832
3	1/50	1515	0.505	1.010	1.515
4	1/55	1515	0.459	0.918	1.377

Furthermore, to identify which synchronous generator gives contribution to other frequency modes, correlation coefficient analysis was performed on 26 synchronous generators' power output to the oscillation frequencies in both areas.

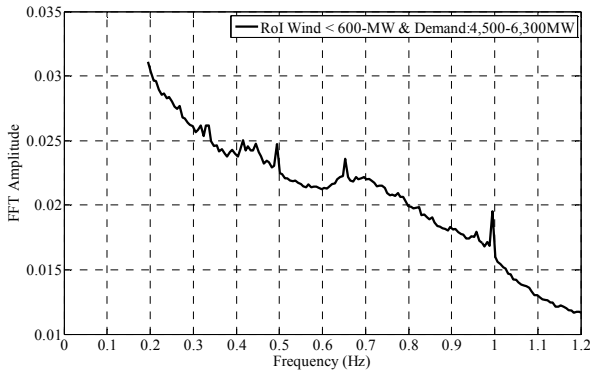


Fig. 2. Interconnector power flow frequency spectrum during high synchronous generation operation

The correlation coefficient of conventional power plants power output in area 1 and 2 to oscillation frequencies are given in fig. 3 and fig. 4 respectively. Among the 10 power plants in area 1, it has been found that 4 power plants (see fig. 3) have high positive and negative correlation coefficient to the inter-area frequency oscillations range while there are 7 power plants among 16 power plants in area 2 have been observed giving significant correlation coefficient in the inter-area oscillation frequency range.

It can be seen from the fig. 3 that these power plants give significant correlation on inter-area oscillation frequency at 0.446 Hz, 0.7-0.75 Hz and 0.958 Hz respectively. Power plant A1-3 and A1-1 give positive correlation coefficient on the frequency 0.446 Hz while power plant A1-2 and A1-4 give negative correlation coefficient. For the range of frequency 0.7-0.75 Hz, power plant A1-1 gives the highest positive correlation coefficient. Moreover, for the frequency 0.958 Hz, the highest positive correlation has given by power plant A1-3 then followed by generator A1-1 while the other two power plants have no significant correlation coefficient to the frequency 0.958 Hz.

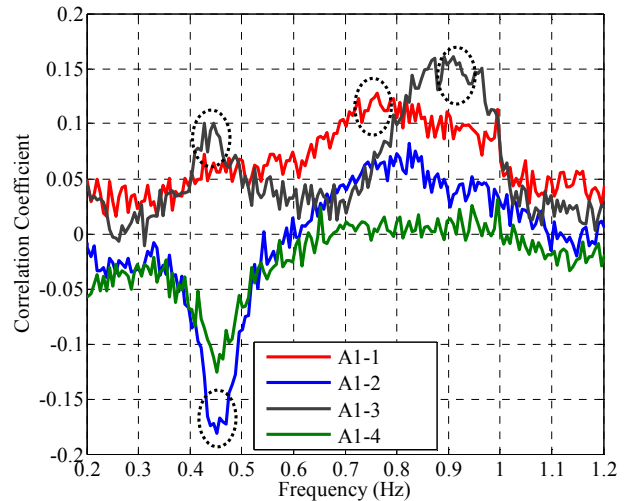


Fig. 3. Correlation of oscillation frequencies with the Republic of Ireland (area 1) synchronous generation power output during low wind and high demand operation.

Fig. 4 shows that 7 power plants in area 2 which contribute significantly to the oscillation frequency from 0.65 Hz to 1.0 Hz. Power plant A2-3, A2-7, A2-4 and A2-6 give positive correlation coefficient to the oscillation frequency 0.7-0.75 Hz while power plant A2-5 gives a small negative correlation coefficient. The highest negative correlation coefficient for the frequency 0.958 Hz is from power plant A2-2 and then followed by A2-5 while four others power plants namely: A2-7, A2-1, A2-6 and A2-4 give positive correlation coefficients.

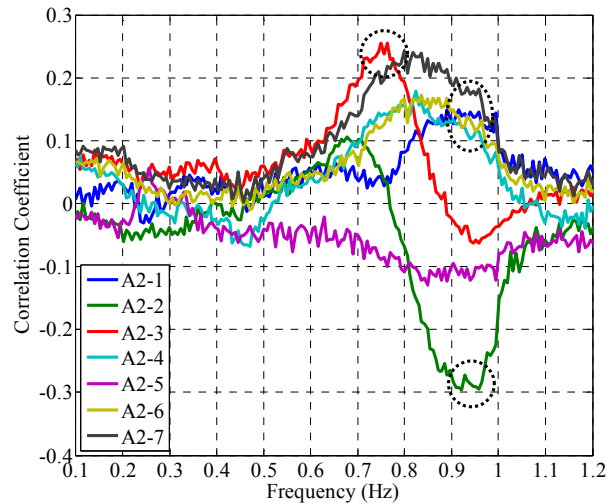


Fig. 4. Correlation of oscillation frequencies with Northern Ireland (area 2) synchronous generation power output during low wind and high demand operation.

Table II gives the summary of the correlation coefficients of different power plants from different areas on the certain oscillation frequencies during low wind and high demand condition.

TABLE II  
SUMMARY OF DOMINANT CORRELATIONS OF POWER PLANTS ON  
CERTAIN FREQUENCIES

No	Freq (Hz)	Area 1		Area 2	
		+	-	+	-
1	0.446	A1-1 A1-3	A1-2 A1-4		
2	0.7-0.75	A1-1		A2-3 A2-4 A2-6 A2-7	A2-5
3	0.958	A1-1 A1-3		A2-1 A2-4 A2-6 A2-7	A2-2 A2-5

*B. Case B: Inter-Area Power Oscillation Frequency during High Wind Low Demand Operation Condition.*

Fig. 5 shows the power flow spectrum frequency in the North-South interconnector during both high wind and low demand condition (black line), and low wind and high demand condition (blue line) on the interconnection. These two operating conditions give different oscillation frequency modes on the North-South interconnector. Fig. 6 describes the significant difference of the oscillation frequency modes during these two conditions.

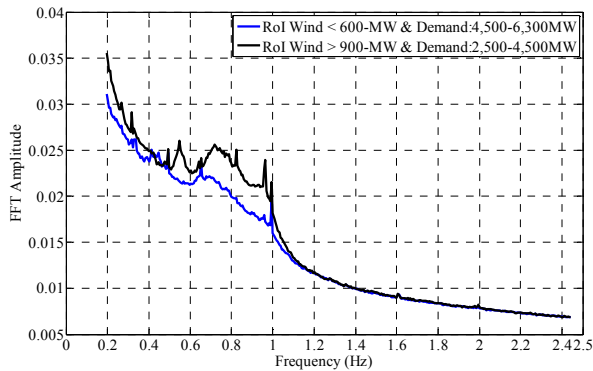


Fig. 5. Interconnector power flow frequency spectrum during high synchronous and high wind generation operation.

It can be observed from the fig. 6 that several peaks are present. Two frequencies 0.415 Hz and 0.446 Hz have negative peaks while the rest of frequencies (6 frequency modes), namely: 0.268 Hz, 0.317 Hz, 0.55 Hz, 0.64 Hz, 0.824 Hz and 0.964 Hz have a positive peak values. Negative peak values mean that these frequencies are dominant during case study A while the positive peak values mean it occurred during case study B.

Since these six frequencies are occurred during dominant wind generation in the power system, it might be useful to analyse the cause of these frequencies to look at it correlation to WTG power output.

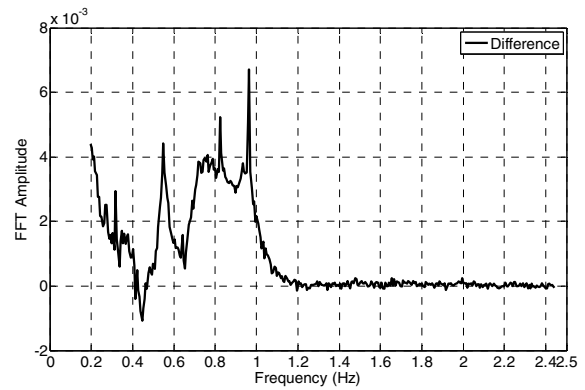


Fig. 6. Difference between Interconnector power flow frequency spectrum during high synchronous and high wind generation operation

Different types of WTGs are operated in the Irish power system, i.e. FSIG and DFIG WTGs. The recorded PMU data for these types of WTGs are available from measurement of PMU-2 and PMU-3. Using these data, the FFT analysis was performed to extract the potential power oscillation frequency from each of wind farm.

Fig. 7 shows the dominant power oscillation frequency from the 26-MW FSIG wind farm that consists of 20, 1.3 MW wind turbines. Dominant power oscillation frequency modes can be observed in the range of 0.2 Hz-1.0 Hz, namely: 0.273 Hz, 0.321 Hz, 0.55 Hz, 0.64 Hz, 0.79 Hz and 0.96 Hz. Three of these frequencies (i.e.: 0.55 Hz, 0.64 Hz and 0.96 Hz) have the same frequency as present on the interconnector. From the equality of frequency between FSIG wind farm and the frequency on the interconnector, it suggests that FSIG may contribute to certain frequencies that appear on the interconnector.

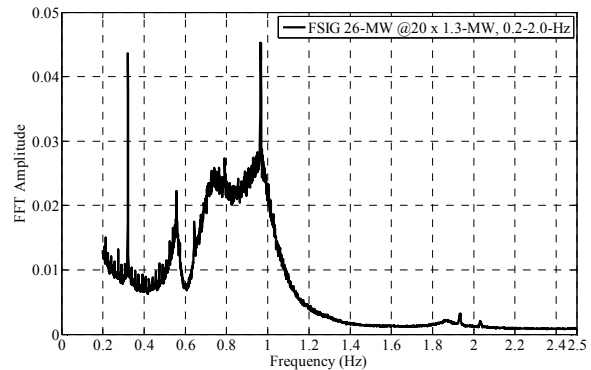


Fig. 7. Power output frequency spectrum for 26-MW FSIG wind farm of 1.3 MW turbines

Furthermore, the correlation coefficient analysis between 26-MW FSIG wind farm power outputs to oscillation frequencies on the interconnector has been performed. Fig. 8 shows the graph of correlation coefficient in the range frequency 0- 2.4 Hz. 6 frequencies can be observed from the fig. 8 that have peak values of correlation coefficients, namely: 0.268 Hz, 0.317 Hz, 0.55 Hz, 0.64 Hz, 0.824 Hz, and 0.964 Hz. These six frequency modes are also present on the North-South interconnector during high wind and low demand conditions.

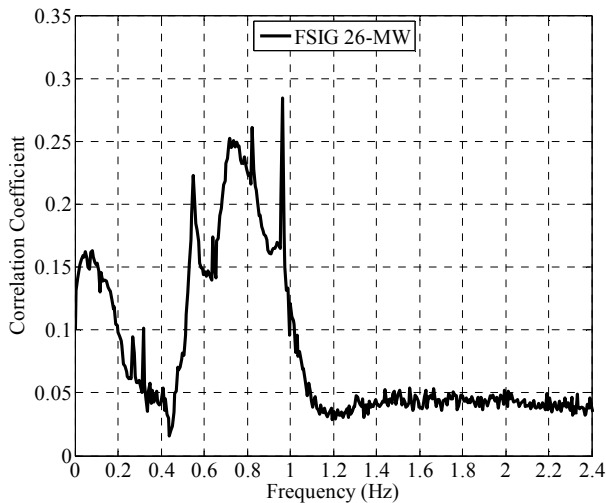


Fig. 8. Correlation of oscillation frequencies with 26-MW FSIG WTG power output

The PMU measurement data for DFIG wind farm was collected by PMU-3 and recorded data was analysed using FFT analysis as shown in Fig. 9. Dominant power oscillation frequencies from 28.5-MW DFIG in the range of 0.2-1.0 Hz can be observed as follows: 0.323 Hz, 0.64 Hz and 0.99 Hz. The frequency 0.64 Hz is also presence on the North-South interconnector during high wind and low demand condition.

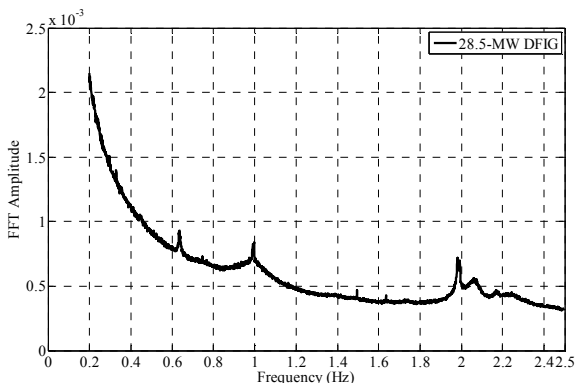


Fig. 9. Power output frequency spectrum for 28.5-MW DFIG wind farm

From the figures can be drawn a conclusion that FSIG power output give significant influence to the inter-area oscillation frequency modes that occur on the interconnector. However, further research is needed to observe whether power oscillation frequency modes from DFIG wind farm are induced to the system as inter-area oscillation frequency that exist in the interconnector.

## V. CONCLUSION

In this paper, two study cases to demonstrate the influence of WTG penetration on inter-area oscillation frequency modes have been presented. FFT analysis was performed to extract dominant oscillation frequency modes in the interconnector

and dominant frequency mode from both of FSIG and DFIG WTG using recorded PMU data.

Several oscillation frequency modes are observed and these oscillation frequency modes are influenced by the WTG penetration into the system.

Correlation coefficient analysis was performed for the two case studies so that the oscillation frequencies could be attributed to conventional thermal plant or WTGs. Power oscillation frequency from FSIG WTG can be observed on the interconnector as well. It suggests that frequency modes on the interconnector are influenced by FSIG WTG. Further research is needed to determine whether oscillation frequency modes from DFIG WTG are induced into the system as inter-area oscillation frequency modes on the North-South interconnector.

## ACKNOWLEDGEMENTS

The authors wish to thank the Directorate General of Higher Education, Ministry of Education and Culture, The Republic of Indonesia for providing a PhD scholarship to Iswadi HR to pursue his PhD at Energy Power and Intelligent Control (EPIC) research cluster, the School of Electronic, Electrical Engineering and Computer Science, Queen's University Belfast.

## REFERENCES

- [1] SONI; EirGrid, "All-Island Generation Capacity Statement 2013-2022," 2012.
- [2] European Parliament and The Council, "Directives 2009/28/EC," *Official Journal of the European Union*, vol. 52, pp. 16-62, 2009.
- [3] S. Brownlees, B. Fox, D. Flynn and T. Littler, "Wind Farm Induced Oscillations," in *41st International Universities Power Engineering Conference, UPEC 2006*.
- [4] M. H. Nguyen, T. K. Saha and M. Eghba, "Impact of high level of renewable energy penetration on inter-area oscillation," in *Universities Power Engineering Conference (AUPEC), 2011 21st Australasian*, 2011.
- [5] N. Modi, T. K. Saha and N. Mithulananthan, "Effect of Wind Farms with Doubly Fed Induction Generators on Small-Signal Stability- A Case Study on Australian Equivalent System," in *IEEE PES Innovative Smart Grid Technologies, ISGT Asia 2011*, 2011.
- [6] M. Kein, G. Rogers and P. Kundur, "A Fundamental Study of Inter-Area Oscillation in Power Systems," *Transaction on Power System*, vol. 6, no. 3, pp. 914-920, 1991.
- [7] Single Electricity Market Operator, "semo," 2013. [Online]. Available: <http://www.sem-o.com/Pages/default.aspx>. [Accessed 1 January 2013].
- [8] EirGrid, "EIRGRID," 2013. [Online]. Available: <http://www.eirgrid.com/>. [Accessed 01 January 2013].
- [9] SONI, "SONI," 2013. [Online]. Available: <http://www.soni.ltd.uk/>. [Accessed 1 January 2013].
- [10] Mathworks, "Mathworks," [Online]. Available: [www.mathworks.com](http://www.mathworks.com).
- [11] J. v. d. Tempel and D.-P. Molenaar, "Wind Turbine Structural Dynamic - A Review of the Principles for Modern Power Generation, Onshore and Offshore," *Wind Engineering*, vol. 26, no. 4, pp. 211-220, 2002.