DESIGN AND CONTROL OF LARGE-SCALE GRID-CONNECTED PHOTOVOLTAIC POWER PLANT WITH FAULT RIDE-THROUGH

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I hereby declare that I have checked this thesis and in my opinion, this thesis is adequate in terms of scope and quality for the award of the degree of Doctor of Philosophy.

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I hereby declare that the work in this thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at Universiti Malaysia Pahang or any other institutions.

__________________________________________
(Student’s Signature)

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Doctor of Philosophy

Faculty of Electrical & Electronics Engineering
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JANUARY 2019
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ABSTRACT

Over the recent years, the installation of photovoltaic (PV) system and integration with electrical grid has become more widespread worldwide. With the significant and rapid increase of photovoltaic power plants (PVPPs) penetration to the electric grid, the power system operation and stability issues become crucial and this leads to continuous evaluation of grid interconnection requirements. For this purpose, the modern grid codes (GCs) require a reliable PV generation system that achieves fault ride-through (FRT) requirements. Therefore, the FRT capability becomes the state of art as one of the challenges faced by the integration of large-scale PV power stations into electrical grid that has not been fully investigated. This research proposes FRT requirements for the connection of PVPPs into Malaysian grid as new requirements. In addition, presents a comprehensive control strategy of large-scale PVPPs to enhance the FRT capability based on modern GCs connection requirements. In order to meet these requirements, there are two major issues that should be addressed. The first one is the ac over-current and dc-link over-voltage that may cause disconnection or damage to the grid inverter. The second one is the injection of reactive current to assist the voltage recovery and support the grid to overcome the voltage sag problem. To address the first issue, the dc-chopper brake controller and current limiter are used to absorb the excessive dc-voltage and limits excessive ac current, respectively, and therefore protect the inverter and ride-through the faults smoothly. After guaranteeing that the inverter is kept connected and protected, this control strategy can also ensure a very important aspect which is the reactive power support through the injection of reactive current based on the standard requirements. Feed-forward decoupling strategy based-dq control is used for smooth voltage fluctuation and reactive current injection. Furthermore, to keep the power balance between both sides of the inverter, PV array can generate a possible amount of active power according to the rating of grid inverter and voltage sag depth by operating in two modes, which are normal and FRT modes. These two modes of operation require fast and precise sag detection strategy to switch the system from normal mode to a faulty mode of operation for an efficient FRT control. For this purpose, RMS detection method has been used. In this research, the large-scale PV plant connected to the MV side of the utility grid, taking the compliance of TNB technical regulations for PVPPs into consideration has been modelled using MATLAB/Simulink with nominal rated peak power of 1500 kW. Analyses of the dynamic response for the proposed PVPP under various types of symmetrical and asymmetrical grid faults also had been investigated. As a conclusion, the PVPP connected to the power grid provided with FRT capability has been developed. The sizing of the suggested PV array is achieved in which the simulation results matched the sizing calculation results. Moreover, the results at the point of common coupling show that the proposed PVPP is compatible with TNB requirements, including the PV-grid connection method, PV inverter type, nominal voltage operating range, total harmonic distortion less than 5%, voltage unbalance less than 1%, frequency fluctuation within ± 0.1 Hz, and power factor higher than 0.9. In addition, the control simulation results presented demonstrate the effectiveness of the overall presented FRT control strategy, which aims to improve the capability of ride-through during grid faults safely, to keep the inverter connected, to ensure the safety of the system equipment, to ensure all values return to pre-fault values as soon as the fault is cleared within almost zero second as compared to the strategy without FRT control which needs around 0.25s, and to provide grid support through active and reactive power control at different types of faults based on the FRT standard requirements.
ABSTRAK

Dalam tahun-tahun kebelakangan ini, pemasangan sistem fotovoltaik (PV) dan integrasi dengan grid elektrik telah menjadi semakin meluas di seluruh dunia. Dengan peningkatan ketara dan pesat penyambungan loji janakuasa fotovoltaik (PVPPs) ke grid elektrik, isu-isu berkaitan operasi sistem kuasa dan kestabilan menjadi lebih penting dan membawa kepada penilaian berterusan terhadap syarat penyambungan ke grid. Untuk tujuan ini, baru-baru ini, kod grid moden (GCs) memerlukan sistem penjanaan PV yang boleh dipercayai dengan mencapai keperluan melangkaui ganguan (FRT). Oleh itu, keupayaan FRT menjadi sebagai salah satu cabaran yang dihadapi oleh stesen kuasa PV berskala besar bagi penyambungan ke grid elektrik yang belum disiasat sepenuhnya. Kajian ini mencadangkan keperluan FRT untuk sambungan PVPP ke grid Malaysia sebagai keperluan baru. Di samping itu, membentangkan strategi kawalan komprehensif PVPP berskala besar untuk meningkatkan keupayaan FRT berdasarkan keperluan sambungan GC moden. Untuk memenuhi keperluan penyambungan ini, terdapat dua isu utama yang perlu ditangani. Yang pertama adalah arus ulang alik (ac) terlebih arus serta arus terus (dc) terlebih voltan yang boleh menyebabkan pemotongan atau kerosakan pada penyongsang grid. Yang kedua ialah suntikan arus reaktif untuk membantu pemulihan voltan dan menyokong grid mengatasi masalah sag voltan. Untuk menangani isu pertama, pengawal brek dc-chopper dan penghad arus digunakan untuk menyerap voltan dc yang berlebihan dan mengehadkan arus ac berlebihan, membolehkan melindungi penyongsang dan melangkau gangguan elektrik dengan lancar. Selepas menjamin bahawa penyongsang terus disambungan dan dilindungi, strategi kawalan ini juga boleh memastikan ciri yang sangat penting iaitu memastikan arus dan voltan yang diupayakan berdasarkan kepada penarafan grid penyongsang dan kedalaman voltan sag dengan dalam operasi dua mod iaitu mod biasa dan FRT. Kedua-dua mod operasi ini memerlukan strategi pengesahan yang cepat dan tepat yang penting bagi sistem untuk beralih dari mod operasi normal ke mod operasi kawalan FRT. Untuk tujuan ini, kaedah pengesahan RMS telah digunakan. Dalam kajian ini, loji PV berskala besar yang disambungkan ke sisi MV grid utiliti, yang mengambil pematuhan peraturan TNB mengenai penyambungan PVPP telah dimodelkan menggunakan MATLAB/Simulink dengan nominal kuasa puncak tertinggi 1500 kW. Analisa tindak balas dinamik untuk PVPP yang dicadangkan di bawah pelbagai jenis gangguan grid simetri dan bukan simetri juga telah dijalankan. Sebagai kesimpulan, reka bentuk lengkap PVPP yang disambungkan kepada grid kuasa yang disediakan di bawah pelbagai jenis gangguan grid simetri dan bukan simetri juga telah mendapat pelbagai jenis gangguan grid dinyatakan sebagai keperluan FRT telah dilakukan dengan keupayaan FRT telah dilaksanakan. Reka bentuk saiz PV yang dicadangkan berdasarkan pengiraan ukuran telah dicapai. Selain itu, keputusan di titik gandingan bersama menunjukkan bahawa PVPP yang dicadangkan adalah bersesuaian dengan syarat keperluan TNB termasuk kaedah sambungan PV-grid, jenis penyongsang PV, rangkaian operasi voltan nominal, jumlah harmonik gangguan kurang daripada 5%, ketidaklambangan voltan kurang dari 1%, jula frekuensi dalam ± 0.1 Hz, dan factor kuasa lembih tinggi daripada 0.9. Di samping itu, hasil simulasi kawalan yang dibentangkan menunjukkan keberkesan strategi kawalan yang dicadangkan secara keseluruhan, meningkatkan keupayaan melangkaui gangguan elektrik grid dengan selamat, memastikan penyongsang sentiasa terhubung, memastikan keselamatan peralatan sistem, semua nilai kembali kepada nilai pra-gangguan sebaik sahaja gangguan dibersihkan dalam masa hampir sifar saat berbanding tanpa kawalan yang memerlukan sekitar 0.25s, dan juga memberi sokongan kepada grid melalui kawalan kuasa aktif dan reaktif pada pelbagai jenis gangguan elektrik berdasarkan syarat keperluan FRT.
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LIST OF SYMBOLS

$C_{dc}$  DC-link capacitor  
$CO_2$  Carbon dioxide  
$d/q$  Components of that variable in SRF  
$f$  Grid frequency  
$f_c$  Switching frequency  
$f_{carrier}$  Carries frequency  
$G$  Sun irradiation  
$i_{abc}$  Grid currents  
$i_{ia} i_{ib} i_{ic}$  Inverter three-phase current  
$I_D$  Diode current of the PV cell  
$I_d$  Active current injected to the grid  
$I^*_d$  Active current reference  
$i_{dref}$  Active current reference of the inverter  
$i_{dref}$  Output active current reference of the current limiter  
$I_{max}$  Maximum current of the photovoltaic array  
$I_{mpp}$  Current of the PV module/array at the maximum power point  
$I_n$  Normal value of the inverter-rated current  
$I_P$  Shunt current of the solar module  
$I_{Ph}$  Photo current of the solar module  
$I_q$  Reactive current injected to the grid  
$I^*_q$  Reactive current reference  
$I_{qr}$  Ratio of injected reactive current to the nominal current  
$I_{sat}$  Reverse saturation current of the solar module  
$I_{sc}$  Short circuit current  
$I_{THD}$  Current total harmonic distortion  
$k_{p}, k_{i}$  PI parameter of current loop  
$k_{p}, k_{i}$  PI parameter of the voltage loop  
$L$  Filter of the inverter  
$m$  Modulation index  
$N_{cell}$  Numbers of cells per module  
$N_{pv}$  Total numbers of PV array modules (generators)
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{prs}$</td>
<td>Number of PV modules in series</td>
</tr>
<tr>
<td>$N_{pvest}$</td>
<td>Number of the parallel strings</td>
</tr>
<tr>
<td>$P$</td>
<td>Instantaneous active power</td>
</tr>
<tr>
<td>$P_{inj}$</td>
<td>Active power injected to the grid</td>
</tr>
<tr>
<td>$P_{max}$</td>
<td>The maximum available output power</td>
</tr>
<tr>
<td>$P_{mpp}$</td>
<td>Power of the PV array at the maximum power point</td>
</tr>
<tr>
<td>$P_{pv}$</td>
<td>Generated power by the PV array</td>
</tr>
<tr>
<td>$Q$</td>
<td>Instantaneous reactive power</td>
</tr>
<tr>
<td>$Q_{inj}$</td>
<td>Injected reactive power to the grid</td>
</tr>
<tr>
<td>$R$</td>
<td>Filter of the inverter</td>
</tr>
<tr>
<td>$R_{ch}$</td>
<td>Chopper resistance</td>
</tr>
<tr>
<td>$R_P$</td>
<td>Equivalent parallel resistance of the solar module</td>
</tr>
<tr>
<td>$R_S$</td>
<td>Equivalent series resistance of the solar module</td>
</tr>
<tr>
<td>$T$</td>
<td>The Temperature</td>
</tr>
<tr>
<td>$t$</td>
<td>Time in second</td>
</tr>
<tr>
<td>$V^+$</td>
<td>Positive sequence of the voltage</td>
</tr>
<tr>
<td>$V^-$</td>
<td>Negative sequence of the voltage</td>
</tr>
<tr>
<td>$V_{abc}$</td>
<td>Grid voltage</td>
</tr>
<tr>
<td>$V_d$</td>
<td>Active voltage in SRF</td>
</tr>
<tr>
<td>$V'_d$</td>
<td>Active voltage reference in SRF</td>
</tr>
<tr>
<td>$V_{dc}$</td>
<td>Dc-link voltage</td>
</tr>
<tr>
<td>$V_{gn}$</td>
<td>Nominal grid voltage</td>
</tr>
<tr>
<td>$V_{ia}, V_{ib}, V_{ic}$</td>
<td>inverter voltage</td>
</tr>
<tr>
<td>$V_{max}$</td>
<td>Maximum voltage of the photovoltaic array</td>
</tr>
<tr>
<td>$V_{mpp}$</td>
<td>Voltage of the PV module/array at the maximum power point</td>
</tr>
<tr>
<td>$V_{oc}$</td>
<td>Open circuit voltage</td>
</tr>
<tr>
<td>$V_{pg}$</td>
<td>Present grid voltage before faults</td>
</tr>
<tr>
<td>$V_q$</td>
<td>Reactive voltage in synchronous reference frame.</td>
</tr>
<tr>
<td>$V'_q$</td>
<td>Reactive voltage reference</td>
</tr>
<tr>
<td>$V_T$</td>
<td>The thermal voltage</td>
</tr>
<tr>
<td>$V_{THD}$</td>
<td>Voltage total harmonic distortion</td>
</tr>
<tr>
<td>$\omega$</td>
<td>Angular frequency</td>
</tr>
<tr>
<td>$\Delta P$</td>
<td>Change in the power of MPPT</td>
</tr>
</tbody>
</table>
\( \alpha/\beta \)  Components of that variable in stationary frame
\( \theta_{PLL} \)  Phase angle of the PLL
\( \alpha_v \)  Temperature coefficients of open circuit voltage
\( \alpha_i \)  Temperature coefficients of short circuit current
### LIST OF ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>3-ph</td>
<td>Three phase</td>
</tr>
<tr>
<td>ac</td>
<td>Alternating current</td>
</tr>
<tr>
<td>AEMC</td>
<td>Australian Energy Market Commission</td>
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<tr>
<td>ANN</td>
<td>Artificial neural network</td>
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<tr>
<td>DCL</td>
<td>Adaptive dc-link</td>
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<tr>
<td>BDEW</td>
<td>German Association of Energy and Water Industries</td>
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<tr>
<td>CC</td>
<td>Constant current</td>
</tr>
<tr>
<td>CSI</td>
<td>Current Source Inverters</td>
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<tr>
<td>CV</td>
<td>Constant voltage</td>
</tr>
<tr>
<td>DB</td>
<td>Dead beat</td>
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<tr>
<td>dc</td>
<td>Direct current</td>
</tr>
<tr>
<td>DG</td>
<td>distribution generator</td>
</tr>
<tr>
<td>DPGS</td>
<td>Distributed power generation systems</td>
</tr>
<tr>
<td>DSO</td>
<td>Distribution system operators</td>
</tr>
<tr>
<td>DVR</td>
<td>Dynamic voltage restorer</td>
</tr>
<tr>
<td>DVS</td>
<td>Dynamic voltage support</td>
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<tr>
<td>ECM</td>
<td>Energy Commission Malaysia</td>
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<td>FACTS</td>
<td>Flexible ac transmission system</td>
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<tr>
<td>FDP</td>
<td>Fuel diversification policy</td>
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<tr>
<td>FF</td>
<td>Fill factor</td>
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<tr>
<td>FFT</td>
<td>Fast Fourier transform</td>
</tr>
<tr>
<td>FiT</td>
<td>Feed-in-Traffic</td>
</tr>
<tr>
<td>FL</td>
<td>Fuzzy logic</td>
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<tr>
<td>FLC</td>
<td>Fuzzy logic control</td>
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<td>FLS</td>
<td>Feedback linearization strategy</td>
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<td>FL-GA</td>
<td>Fuzzy logic-genetic algorithm</td>
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<td>FRT</td>
<td>Fault ride through</td>
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<tr>
<td>GA</td>
<td>Genetic algorithm</td>
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<td>Guobiao Standards/ recommended (Chinese national standards)</td>
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<td>GCPPPs</td>
<td>Grid-connected photovoltaic power plants</td>
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<td>Acronym</td>
<td>Description</td>
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<td>GCPVS</td>
<td>Grid-connected photovoltaic system</td>
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<tr>
<td>GTO</td>
<td>Gate turn-off thyristor</td>
</tr>
<tr>
<td>GW</td>
<td>Giga watt</td>
</tr>
<tr>
<td>HC</td>
<td>Hill climbing</td>
</tr>
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<td>IEA</td>
<td>International Energy Agency</td>
</tr>
<tr>
<td>IEC</td>
<td>International Electro-technical Commission</td>
</tr>
<tr>
<td>IEEE</td>
<td>Institute of Electrical and Electronics Engineers</td>
</tr>
<tr>
<td>IGBT</td>
<td>Insulated-gate bipolar transistor</td>
</tr>
<tr>
<td>INC</td>
<td>Incremental conductance</td>
</tr>
<tr>
<td>IPP</td>
<td>Independent Power Producers</td>
</tr>
<tr>
<td>LL</td>
<td>Line to line</td>
</tr>
<tr>
<td>LLG</td>
<td>Line to line to ground</td>
</tr>
<tr>
<td>LV</td>
<td>Low voltage</td>
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<tr>
<td>LVVRT</td>
<td>Low voltage ride-through</td>
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<tr>
<td>MDS</td>
<td>Main distribution substation</td>
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<tr>
<td>MOSFET</td>
<td>Metal oxide semiconductor field effect transistor</td>
</tr>
<tr>
<td>MPP</td>
<td>Maximum power point</td>
</tr>
<tr>
<td>MPPT</td>
<td>Maximum power point tracking</td>
</tr>
<tr>
<td>MV</td>
<td>Medium voltage</td>
</tr>
<tr>
<td>MVA</td>
<td>Mega volt-ampere</td>
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<tr>
<td>MW</td>
<td>Megawatt</td>
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<tr>
<td>P&amp;O</td>
<td>Perturb and observe</td>
</tr>
<tr>
<td>p.u</td>
<td>Per unit</td>
</tr>
<tr>
<td>PCC</td>
<td>Point of common coupling</td>
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<tr>
<td>PI</td>
<td>Proportional integral</td>
</tr>
<tr>
<td>PID</td>
<td>Proportional integral derivative</td>
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<tr>
<td>PF</td>
<td>Power factor</td>
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<tr>
<td>PLL</td>
<td>Phase locked loop</td>
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<td>PPU</td>
<td>Pencawang pembahagian utama-main distribution substation</td>
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<tr>
<td>PR</td>
<td>Proportional resonant</td>
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<td>PSO</td>
<td>Power system operator</td>
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<tr>
<td>PV</td>
<td>Photovoltaic</td>
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<tr>
<td>PVPP</td>
<td>Photovoltaic power plants</td>
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<tr>
<td>Abbreviation</td>
<td>Definition</td>
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<td>--------------</td>
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<tr>
<td>PWM</td>
<td>Pulse width modulation</td>
</tr>
<tr>
<td>RC</td>
<td>Repetitive current</td>
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<tr>
<td>RE</td>
<td>Renewable energy</td>
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<tr>
<td>RM</td>
<td>Malaysian ringgit</td>
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<tr>
<td>RMS</td>
<td>Root mean square</td>
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<tr>
<td>SAPVS</td>
<td>Stand-alone photovoltaic system</td>
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<tr>
<td>SCESS</td>
<td>Supercapacitor energy storage system</td>
</tr>
<tr>
<td>SDBR</td>
<td>Series dynamic breaking resistor</td>
</tr>
<tr>
<td>SEDA</td>
<td>Sustainable energy development authority</td>
</tr>
<tr>
<td>SGCT</td>
<td>Symmetrical gate commutated thyristor</td>
</tr>
<tr>
<td>SLG</td>
<td>Single line to ground</td>
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<tr>
<td>sq km</td>
<td>Square kilometre</td>
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<tr>
<td>SRF-PLL</td>
<td>Synchronous reference frame phase-locked loop</td>
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<tr>
<td>STATCOM</td>
<td>Static compensator</td>
</tr>
<tr>
<td>STC</td>
<td>Standard test conditions</td>
</tr>
<tr>
<td>SVC</td>
<td>Static VAR compensator</td>
</tr>
<tr>
<td>THD</td>
<td>Total harmonic distortion</td>
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<tr>
<td>TNB</td>
<td>Tenaga Nasional Berhad</td>
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<tr>
<td>USANAERC</td>
<td>United States-north American electric Reliability Corporation</td>
</tr>
<tr>
<td>USAPREPA</td>
<td>United States-Puerto Rico Electric Power Authority</td>
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<tr>
<td>VAR</td>
<td>Volt-ampere reactive</td>
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<td>VCO</td>
<td>Voltage controlled oscillator</td>
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<td>VSI</td>
<td>Voltage source inverters</td>
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<td>VUF</td>
<td>Voltage imbalance factor</td>
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<td>WPP</td>
<td>Wind power plant</td>
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<td>ZVRT</td>
<td>Zero voltage ride through</td>
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</table>
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