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

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Thesis submitted in fulfillment of the requirements
for the award of the degree of
Doctor of Philosophy

Faculty of Electrical & Electronics Engineering

UNIVERSITI MALAYSIA PAHANG

JANUARY 2019

ACKNOWLEDGEMENTS

First and foremost, all thanks and glory are due to "ALLAH" the Almighty, who gave me the power, the health and patience to accomplish this research.

It is my great fortune to have Ir. Dr. Ing. Muhamad Zahim Bin Sujod as the supervisor during my Ph.D. I would like to express my warmest appreciation, gratitude and sincere thanks to him for his guidance, encouragement, support, kind help and sound advice throughout the period of this research. Dr. Zahim's technical expertise, and energy have been invaluable during my study and I am truly honored to have worked with a world class researcher such as him.

I would like to acknowledge the Faculty of Electrical and Electronic Engineering, University Malaysia Pahang for providing the facilities to conduct this research. Also, I am very grateful to the Ministry of Higher Education Malaysia (MOHE) for their financial support of this research through the Fundamental Research Grant Scheme (RDU 150125). Also, I wish to acknowledge the support of UMP Post Graduate Research Grant Scheme (PGRS1703106).

Moreover, I am very grateful to University Malaysia Pahang for financial support through the Doctoral research Scheme (DRS) to cover my living cost in Malaysia during two years of my study.

Lastly, I would like to express my deepest gratitude and greatest appreciation to my parents, wife, children, brothers, and sisters for their enormous love, inspiration, and prayers. They always respect what I want to do and give me their full support. Encouragement over the years. I just want to say that I love you all very much and that dedicated this thesis to all of you. I am also forever grateful to my lovely wife for all her unconditional love, sacrifices and endless patience during the past three years, and all thanks to my sweet daughter Hadil and my son Laith for adding a sugary flavor to my life.

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 melangkaui gangguan elektrik dengan lancar. Selepas menjamin bahawa penyongsang terus disambungkan dan dilindungi, strategi kawalan ini juga boleh memastikan ciri yang sangat penting iaitu memberi sokongan kuasa reaktif melalui suntikan arus reaktif mengikut keperluan standard. Tambahan pula, untuk menjaga keseimbangan kuasa antara kedua-dua belah penyongsang, PV boleh menjana jumlah kuasa aktif yang diperlukan 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 pengesanan yang cepat dan tepat yang penting bagi sistem untuk beralih dari mod operasi normal ke mod operasi kawalan FRT. Untuk tujuan ini, kaedah pengesanan RMS telah digunakan. Dalam kajian ini, loji PV berskala besar yang disambungkan ke sisi MV grid utiliti, yang mengambil pematuhan peraturan teknikal 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 dengan keupayaan FRT telah dilbangunkan. Rekabentuk 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%, ketidakimbangan voltan kurang dari 1% , julat frekuensi dalam ± 0.1 Hz, dan factor kuasa lebih tinggi daripada 0.9. Di samping itu, hasil simulasi kawalan yang dibentangkan menunjukkan keberkesanan 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
$\tilde{\imath}_{dref}$	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)

N_{pvs}	Number of PV modules in series
N_{pvst}	Number of the parallel strings
P	Instantaneous active power
P_{inj}	Active power injected to the grid
P_{max}	The maximum available output power
P_{mpp}	Power of the PV array at the maximum power point
P_{pv}	Generated power by the PV array
Q	Instantaneous reactive power
Q_{inj}	Injected reactive power to the grid
R	Filter of the inverter
R_{ch}	Chopper resistance
R_P	Equivalent parallel resistance of the solar module
R_S	Equivalent series resistance of the solar module
T	The Temperature
t	Time in second
V^+	Positive sequence of the voltage
V^-	Negative sequence of the voltage
V_{abc}	Grid voltage
V_d	Active voltage in SRF
V_d^*	Active voltage reference in SRF
V_{dc}	Dc-link voltage
V_{gn}	Nominal grid voltage
V_{ia} V_{ib} V_{ic}	inverter voltage
V_{max}	Maximum voltage of the photovoltaic array
V_{mpp}	Voltage of the PV module/array at the maximum power point
V_{oc}	Open circuit voltage
V_{pg}	Present grid voltage before faults
V_q	Reactive voltage in synchronous reference frame.
V_q^*	Reactive voltage reference
V_T	The thermal voltage
V_{THD}	Voltage total harmonic distortion
ω	Angular frequency
ΔP	Change in the power of MPPT

α/β	Components of that variable in stationary frame
θ_{PLL}	Phase angle of the PLL
α_v	Temperature coefficients of open circuit voltage
α_i	Temperature coefficients of short circuit current

LIST OF ABBREVIATIONS

3-ph	Three phase
ac	Alternating current
AEMC	Australian Energy Market Commission
ANN	Artificial neural network
DCL	Adaptive dc-link
BDEW	German Association of Energy and Water Industries
CC	Constant current
CSI	Current Source Inverters
CV	Constant voltage
DB	Dead beat
dc	Direct current
DG	distribution generator
DPGS	Distributed power generation systems
DSO	Distribution system operators
DVR	Dynamic voltage restorer
DVS	Dynamic voltage support
ECM	Energy Commission Malaysia
FACTS	Flexible ac transmission system
FDP	Fuel diversification policy
FF	Fill factor
FFT	Fast Fourier transform
FiT	Feed-in-Traffic
FL	Fuzzy logic
FLC	Fuzzy logic control
FLS	Feedback linearization strategy
FL-GA	Fuzzy logic-genetic algorithm
FRT	Fault ride through
GA	Genetic algorithm
GB/T	Guobiao Standards/ recommended (Chinese national standards)
GC	Grid code
GCPPPs	Grid-connected photovoltaic power plants

GCPVS	Grid-connected photovoltaic system
GTO	Gate turn-off thyristor
GW	Giga watt
HC	Hill climbing
IEA	International Energy Agency
IEC	International Electro-technical Commission
IEEE	Institute of Electrical and Electronics Engineers
IGBT	Insulated-gate bipolar transistor
INC	Incremental conductance
IPP	Independent Power Producers
LL	Line to line
LLG	Line to line to ground
LV	Low voltage
LVRT	Low voltage ride-through
MDS	Main distribution substation
MOSFET	Metal oxide semiconductor field effect transistor
MPP	Maximum power point
MPPT	Maximum power point tracking
MV	Medium voltage
MVA	Mega volt-ampere
MW	Megawatt
P&O	Perturb and observe
p.u	Per unit
PCC	Point of common coupling
PI	Proportional integral
PID	Proportional integral derivative
PF	Power factor
PLL	Phase locked loop
PPU	Pencawang pembahagian utama-main distribution substation
PR	Proportional resonant
PSO	Power system operator
PV	Photovoltaic
PVPP	Photovoltaic power plants

PWM	Pulse width modulation
RC	Repetitive current
RE	Renewable energy
RM	Malaysian ringgit
RMS	Root mean square
SAPVS	Stand-alone photovoltaic system
SCESS	Supercapacitor energy storage system
SDBR	Series dynamic breaking resistor
SEDA	Sustainable energy development authority
SGCT	Symmetrical gate commutated thyristor
SLG	Single line to ground
sq km	Square kilometre
SRF-PLL	Synchronous reference frame phase-locked loop
STATCOM	Static compensator
STC	Standard test conditions
SVC	Static VAR compensator
THD	Total harmonic distortion
TNB	Tenaga Nasional Berhad
USANAERC	United States-north American electric Reliability Corporation
USAPREPA	United States-Puerto Rico Electric Power Authority
VAR	Volt-ampere reactive
VCO	Voltage controlled oscillator
VSI	Voltage source inverters
VUF	Voltage imbalance factor
WPP	Wind power plant
ZVRT	Zero voltage ride through

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