Enhanced
Power Frequency Droop Control for Microgrids

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B.E. (Elec.)(Hons. 1)

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A thesis submitted to embody the research carried out to fulfil the requirements for the degree of:

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Declaration

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. I give consent to this copy of my thesis, when deposited in the University Library, being made available for loan and photocopying subject to the provisions of the Copyright Act 1968.

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July 2013
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"Physics IS everything."

Dr Paul Dastoor
My first physics lecture.
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Abstract

This thesis develops enhancements to power frequency droop control for microgrids. Contemporary research fails to fully solve a number of problems with droop control. This thesis provides a conclusive argument that the control employed in microgrid inverters requires advancement, to address the specific problems of: imbalances in reactive power output; poor voltage regulation; increased voltage range; achieving frequency limiting and ensuring the stable operation of microgrid control algorithms.

This thesis provides enhancements to droop control that solve or circumvent the specific problems noted. The five contributions to primary level control in microgrids are: the utilisation of an arctan function for the power frequency droop profile; the enhancement of the virtual output impedance concept; a PCC voltage estimation technique; a parallel voltage and current control scheme and an adaptive sliding mode controller for microgrids. The thesis discusses the theoretical basis for each of these enhancements and justifies their advantages over contemporary state of the art control schemes.

Experimental and simulation results are presented from a three phase two inverter microgrid. The results confirm the performance improvements provided by each enhancement to power frequency droop control, on a case by case basis.
Nomenclature

3pPWM  Three phase pulse width modulation

\( \alpha[k, k + 1] \)  \( \alpha \)-axis duty cycle over the next control period in deadbeat current control

\( \rho \)  Arctan droop concavity co-efficient

\( A \)  Amperes, the base quantity of electrical current

\( A - SMC \)  Adaptive sliding mode control

\( a_p \)  Arctan droop bounding co-efficient

\( AC \)  Alternating current

\( B_{aa'} \)  Magnetic flux density of the a phase stator winding in a three phase AC machine

\( B_{bb'} \)  Magnetic flux density of the b phase stator winding in a three phase AC machine

\( B_{cc'} \)  Magnetic flux density of the c phase stator winding in a three phase AC machine

\( B_s \)  Resultant magnetic flux density space vector in a three phase AC machine

\( CSIRO \)  Commonwealth Scientific and Industrial Research Organisation, the national government body for scientific research in Australia

\( \delta_n \)  Power angle, the angle between \( V_n \) and \( V_{PCC} \), where \( n \) denotes the inverter number

\( D \)  Duty cycle
*DC*  Direct current

*DG*  Distributed generation

*DGU*  Distributed generation unit, singular

*DLL*  Dynamic link library

*e[k]*  Voltage at the present sample in deadbeat current control

*e_{avg}[k, k + 1]*  Average voltage over the next control period in deadbeat current control

*EV*  Electric vehicle

*f_c*  Cut off frequency of a specified filter

*f*  Frequency of the inverter AC output voltage *Hz*

*f_0*  Nominal frequency of inverter output voltage *Hz*

*GUI*  Graphical user interface

*GPS*  Global Positioning System

*HDL*  Hardware description language

 İ̇_{rated}  Peak rated output current of the inverter

 İ̇_n  Line current space vector

 İ̇̃_n  Line current phasor

*i_{cap}*  Current through the capacitor in the LCL filter

*I_{rated}*  RMS rated output current of the inverter

*i^{e+}_{x,qd}*  Positive sequence component SRF Current

*i^a_{x,qd}*  SRF Current

İ̇̃_n  Output current phasor for inverter n

*i[k]*  Current at the present sample in deadbeat current control

*I_n*  Inverter output current, where n denotes the inverter number
\( i_\alpha \) \( \alpha \)-axis SRF current

\( i_\beta \) \( \beta \)-axis SRF current

\( I_a \) A phase current

\( i_a \) Instantaneous A phase current

\( I_b \) B phase current

\( i_b \) Instantaneous B phase current

\( I_c \) C phase current

\( i_c \) Instantaneous C phase current

\( i_{\text{des}}[k+1] \) Desired current one control period in the future, in deadbeat current control

\( i_{\text{des}}[k, k+1] \) Desired current over the next control period in deadbeat current control

\( i_d \) \( d \)-axis RRF current

\( i_n(t) \) Instantaneous inverter output current as a function of time

\( i_q \) \( q \)-axis RRF current

\( ICE \) Internal combustion engine

\( k_{ii} \) Integral gain of the current controller in a nested control structure

\( k_{iv} \) Integral gain of the voltage controller in a nested control structure

\( k_{pi} \) Proportional gain of the current controller in a nested control structure

\( k_{pv} \) Proportional gain of the voltage controller in a nested control structure

\( k_{PWM} \) Maximum modulation index of a PWM scheme

\( KVL \) Kirchhoff’s voltage law

\( KPI \) Key performance indicator

\( LPF \) Low pass filter

\( LRT \) Linear rotational transform
\( M - SVM \) Modified space vector modulation

\( m_{dp} \) Differential droop co-efficient

\( m_{dq} \) Differential droop co-efficient

\( m_p \) Droop co-efficient or droop gradient of \( P - f \) or \( P' - f \) droop control

\( m_q \) Droop co-efficient or droop gradient of \( Q - V \) or \( Q' - V \) droop control

\( n \) Designates the inverter number

\( n_{SMC} \) Sliding mode control time step

\( n_T \) Total number of inverters in the system

\( PLL \) Phase locked loop

\( P \) Active power

\( P \) Proportional controller

\( P'_0 \) \( P' \) power set point

\( P - f \) Active power proportional to frequency

\( P - V \) Active power proportional to voltage

\( P_0 \) Nominal single phase active power set point

\( P_{1\phi} \) Single phase active power

\( P_{3\phi} \) Three phase active power

\( P_{avg} \) Average or Fryze real power

\( PC - PWM \) Pulse centred pulse width modulation

\( PCC \) Point of common coupling

\( PD \) Proportional derivative controller

\( PI \) Proportional integral controller

\( PID \) Proportional, integral and derivative controller
\[ PR \] Proportional resonant controller

\[ PV \] Photovoltaic

\[ PWM \] Pulse width modulation

\( P' \) or \( P_{dash} \) Apparent power quantity that is directly coupled to the frequency variation in \( P' - f \) droop control

\[ Q \] Reactive Power

\[ Q'_0 \] \( Q' \) power set point

\[ Q'_{average} \] Average of the \( Q' \) power of all inverters in the system

\[ Q'_{imbalance} \] Imbalance in \( Q' \) power

\[ Q'_n \] Apparent power quantity that is directly coupled to the voltage variation in \( Q' - V \) droop control for inverter \( n \)

\[ Q - f \] Reactive power proportional to frequency

\[ Q - V \] Reactive power proportional to voltage

\[ Q_0 \] Nominal single phase reactive power set point

\[ Q_{1\phi} \] Single phase reactive power

\[ Q_{3\phi} \] Three phase reactive power

\[ Q_{avg} \] Average or Fryze imaginary power

\( Q' \) or \( Q_{dash} \) Apparent power quantity that is directly coupled to the voltage variation in \( Q' - V \) droop control

\[ R_{en} \] Virtual output resistance for inverter \( n \)

\[ R_{ln} \] Line resistance, from inverter \( n \) to the PCC

\[ RMS \] Root mean squared

\[ RRF \] Rotating reference frame

\[ SMC \] Sliding mode control
SMPS Switch mode power supply
SRF Stationary reference frame
SVM Space vector modulation
$T_{SMC}$ Sliding mode control time step
$T$ Length of the control period in seconds.
$t_1$ Time before the output voltage is forced high in space vector PWM
$T_{PLL}$ Length of the control period in seconds.
u Number of samples per period in Fryze power theory
UPS Uninterruptible power supply
$\hat{V}_{PCC_{max}}$ Maximum, peak PCC connection voltage
$V_0$ Inverter voltage set point
$V_n$ Inverter output voltage, where $n$ denotes the inverter number
$v_{A(\text{control})}$ Sinesoidal control voltage used in three phase pulse width modulation
$v_{\text{cap}}$ Voltage across the capacitor in the LCL filter
$V_{DC\text{ Rated}}$ Rated DC voltage of the inverter DC bus
$v_{\text{dropn}}$ Voltage drop across the line impedance for inverter $n$
$V_{\text{err}}$ Input error of the voltage PI controller
$v^{out}_{k+1}$ Voltage output one control step in the future, at time $k + 1$
$v^{out}_{k}$ Voltage output at time $k$
$V_{PCC}$ RMS point of common coupling voltage
$v_{\text{step}x}$ Sliding mode control voltage step size for region $x$
$v_{\text{TRIANGLE}}$ Triangular wave voltage used in three phase pulse width modulation
$v_{\text{err}}^{+}$ Positive sequence component SRF Voltage
\( v_{x,qd} \)  
SRF Voltage

\( VOI \)  
Virtual output impedance

\( \dot{V} \) or \( V_{dot} \)  
V dot voltage

\( v_d \)  
d-axis RRF voltage

\( v_\alpha \)  
\( \alpha \)-axis SRF voltage

\( \vec{V}_{PCC} \)  
PCC voltage phasor

\( v_q \)  
q-axis RRF voltage

\( v_\beta \)  
\( \beta \)-axis SRF voltage

\( V \)  
Volts, the base quantity of electrical voltage

\( V_a \)  
A phase voltage

\( V_b \)  
B phase voltage

\( V_c \)  
C phase voltage

\( V_{dc} \)  
DC bus voltage

\( V_{fl} \)  
Full load receiving end voltage of a transmission line

\( v_L \)  
Voltage across an inductor

\( V_{nl} \)  
No load receiving end voltage of a transmission line

\( v_{PCC(t)} \)  
Instantaneous voltage at the PCC as a function of time

\( V_{rms} \)  
Voltage specified in RMS

\( V_R \)  
Receiving end voltage of a transmission line

\( V_S \)  
Sending end voltage of a transmission line

\( VA \)  
Volt-Amperes, the base quantity of apparent power

\( var \)  
Volt-Amperes Reactive, the base quantity of imaginary power

\( VR \)  
Voltage regulation
VSC  Voltage source converter

$\omega$  Angular frequency of inverter output voltage $\text{rads}^{-1}$

$\omega_0$  Nominal angular frequency of inverter output voltage $\text{rads}^{-1}$

$W$  Watts, the base quantity of real power

$\frac{X_{in}}{R_{in}}$  Inductive reactance to resistance ratio of the line

$X_{vn}$  Virtual output inductive reactance for inverter n

$X_{ln}$  Line reactance, from inverter n to the PCC

$Z_{ln}$  Line impedance, from inverter n to the PCC

$Z_{TC}$  Total coupling impedance; from the inverter terminal to the PCC, including the filter impedance

$Z_{vn}$  Virtual output impedance for inverter n

$\theta_{k+1}$  Angle specified one control period in the future, at time $k + 1$

$\varphi$  Angle of the coupling impedance of inverter n to the PCC

$\lambda$  Power factor in Fryze power theory