Alternative Exciter Supply for use on Synchronous Alternators in Micro-Hydroelectric Applications

Thesis submitted to the University of Technology, Sydney
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Certificate of Authorship/Originality

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

Signature of Candidate

Acknowledgements

On 3rd September 1996 I arrived in the Solomon Island village of Manawai Harbour on the weather-coast of Malaita. Although it wasn't my first experience of life in a remote rural community, it was certainly the first time I had been welcomed with such rejoicing, and expectation. The community had worked for many years constructing and installing their 50kW micro-hydro system, but it had ceased operating within a week of it being switched on for the first time – two months prior to my arrival. It is the events of this and subsequent trips that underpin the intellectual journey of this study.

Adjunct Professor Paul Bryce (Institute for Sustainable Futures, UTS) was at the time, and continues to be, my guide, mentor, supervisor, colleague. His decades of experience and capacity to add clarity to, and address transdisciplinary issues has afforded me a unique opportunity to learn. Paul's approach for technology transfer into developing communities is reflected in this study, and is as clear as his editorial lilt. Thank you chief!

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In conjunction with this study, I have offered project topics in, and engaged a number of final year undergraduate capstone project (thesis) students. The response from each student has been gratifying from an engineering educator's viewpoint, and from a researchers viewpoint; each contributing to the improved understanding of micro-hydroelectric systems. Joe Kohari demonstrated a proof-of-concept ballast load frequency controller using an off-the-shelf PLC; Raul Paradeza addressed the constraints of the PLC power supply; Nick Farriguia migrated the existing controller algorithm onto an alternative microcontroller hardware design.

Two projects stand apart in their direct contribution to this study: Cameron Dorrington commenced with my design and simulation results for the novel machine winding drying circuit, and went on to implement a working proof-of-concept circuit. Aaron Russell commenced with my design, simulation results, and working proof-of-concept (lab bench) circuit and went on to improve its operation and implement the stand-alone prototype circuit. Aaron's contribution in completing this hardware laid the groundwork for the results which followed; verifying my predicted performance of the alternative exciter supply.

Thanks to Dr Douglas Henderson (Napier University) and Mr Ian Robb for an enjoyable visit to his micro-hydro system near Edinburgh, Scotland. Dr Henderson provided valuable insight into his PhD topic on micro-hydro systems completed in 1992. Aspects of this study follow on from Douglas' work.

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To all of my family, friends and workplace colleagues (Vicki, Tim, David, Gerard, Ben, Robin, Keith, Prasanthi, and Elizabeth) – I'm sure you're all relieved to hear that the *magnum opus* has made it to this point. Thank you for the encouragement; even when you'd ask 'are you still doing that', you were still willing to hear the progress to-date. You know I can't say it's over, but I may take a short break. To my parents who are undoubtedly proud of all their sons, we've achieved because of the opportunities you afforded us.

To Brodie, Nicky, and Luke; you have had to endure my journey and tolerate much more than my absence when you could have reasonably expected me to be there. It's probably a good thing to have a parent indebted to you... enjoy spending it.

To Paula; without you this could not have been possible, which must be a little frustrating given that after all of your support, much of it might as well be written in a different language. Although it may have my name on it, this work is handed on to others not by me alone – but from both of us.

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List of abbreviations

AC	Alternating current
APACE	Appropriate Technology for Community and Environment Inc.
APACE VFEG	APACE – Village First Electrification Group
ANT	Actor network theory
AVR	Automatic voltage regulator
DC	Direct current
EES	Economic and environmental sustainability
MOV	Metal oxide varistor
NRSE	New and renewable sources of energy
OVI	Objectively verified indicators
PIC	Pacific Island Country
PID	Proportional Integral Derivative
PSCAD	Power Systems Computer Aided Design
RAPS	Remote area power system
RESCO	Renewable Energy Service Company
RET	Renewable energy technologies
RPM	Revolutions per minute
SCR	Silicon controlled rectifier
SIVEC	Solomon Islands Village Electrification Council
STEEP	Social, Technical, Economic, Environmental, Political
TRL	Technology readiness level
UFRO	Under frequency roll-off

List of symbols

t	Time [sec]
m	Metres [m]
V	Voltage [V]
I	Electrical current [A]
R	Resistance [Ω]
P	Power [W]
F	Force [N]
T	Torque [Nm]
J	Moment of inertia [kgm^{-2}]
ω	Angular velocity [rad sec^{-1}]
f	Frequency [Hz]
λ	Total flux linkage [Wb-turns]
ϕ	Magnetic flux [Wb]
E	Alternator induced voltage [V]
s	Laplace complex frequency variable
α	SCR firing or conduction angle (deg)
δ	Phase angle of induced voltage with respect to V_a [deg]
ψ	Phase angle of armature current with respect to V_a [deg]
N	Number of turns of the conductor (in making a winding)
I_{ref}	Reference current [A]
I_{field}	Exciter field winding current [A]
L_f	Inductance of the exciter field winding [H]
R_f	Resistance of the exciter field winding [Ω]
R_a	Resistance of the armature winding [Ω]
V_a	Alternator (armature) terminal voltage [V]
V_{ref}	Reference voltage [V]
ω_e	Electrical frequency [rad sec^{-1}]
ω_m	Angular velocity of mechanical components [rad sec^{-1}]
X_S	Alternator synchronous reactance [Ω]

List of Relevant Publications and Awards

- P.Bryce and R.Jarman, "Rural electrification as exemplifying myths and legends of appropriate technology", *XIX Pacific Science Congress*, UNSW Australia, July 1999
- P. Bryce and R. Jarman, "Manawai Harbour Micro Hydroelectic Scheme: A case study in Appropriate Technology Transfer", *International Small Islands Studies Association (ISISA) Conference*, Isle of Skye, October 2000
- R. Jarman and P.Bryce, "Investigation of the behaviour of an AVR in a ballast load frequency controlled stand alone micro-hydroelectric system", *Australasian Universities Power Electronics Conference (AUPEC'04),* Brisbane, September 2004
- R. Jarman, "Alternative Exciter Supply for use on Synchronous Alternators in Micro-Hydroelectric Applications", *UTS:Engineering Postgraduate Research Showcase*, Sydney, May 2004. [Runner-up – best presentation]
- R. Jarman, "Energy in remote rural communities – addressing a known technical problem in micro-hydroelectric power systems", *Australian Institute of Energy*, NSW Branch Postgraduate Awards, Sydney, November 2004. [Winner of Gold Award - Excellence in Engineering Science and Innovation]
- R.Jarman and P.Bryce, "Serving Solomon", *International Water Power and Dam Construction*, United Kingdom, August 2005 [Feature - cover story]
- R.Jarman and P.Bryce, "Experimental investigation and modelling of the interaction between an AVR and ballast load frequency controller in a stand alone micro-hydroelectric system", *International Journal of Renewable Energy* [accepted for publication – August 2006]

Abstract

This thesis develops an understanding of the context, and operating nexus linking synchronous machine excitation requirements and ballast load frequency controllers in remote area power supplies in developing communities in the Pacific. A framework has been developed to serve as a guide for this study as well as future technology transfer projects. Remaining chapters in the thesis coalesce to offer confidence in the hardware solutions presented: an alternative, simpler exciter supply circuit; and a novel method for drying alternator windings.

The thesis stems from an ongoing need for the APACE-VFEG technical team to develop dedicated systems and hardware solutions for micro-hydroelectric systems. The close relationship between system designer and rural community users has afforded a wealth of valuable 'technical' experience and knowledge. Much of this 'intellectual property' remains in-house. We have evidence to show there is merit in the models and community partnership approach adopted; this study affords an appropriate vehicle to research this 'contextual' material with more rigour.

A void between two standpoints is apparent: one where researchers identify barriers to technology transfer at a systems or sociology level – and lack depth in technical design aspects; the other standpoint where electronic systems designers typically remain focussed on component level analysis of their equipment – and hence fail to consider the broader contextual issues. The study promotes the thesis that, beyond the barriers to technological diffusion at institutional, social, and political level (which appear to dominate the issues normally considered), problems remain in providing sustainable *technical* solutions for this small Pacific island context.

The framework is developed to provide guidance for this study and for future technology transfer projects. Soft Systems Methodology, STEEP analysis, the concepts of Actor Network Theory, and technology compatibility, readiness, and maturity afford pertinent insights to the framework at the institutional, actor, and technical levels.

A review of literature pertinent to this study has been completed and gaps identified in the general body of knowledge associated with micro-hydroelectric systems for consideration in this study. Focus areas include the assumption that an Automatic Voltage Regulator (AVR) is the only solution, the requirements for flywheels, and the

various explanations for what causes the unsatisfactory operation of (AVR excited) ballast load controlled micro-hydroelectric systems.

This thesis shows that despite the complexity of interconnections and time constants involved, a complete and verified control systems model developed from first principles is achievable. Relationships between the system steady state operating points and the equations describing the system parameters (accelerating torque, moment of inertia, armature current, alternator rotor speed) are modelled, simulated, and verified with measured responses on a full scale micro-hydroelectric test rig. Further system testing shows an alternative solution to the AVR exists, flywheels may not be a necessity, and the cause of the unsatisfactory operation (with AVR excitation) stems from the similar time constants of the two feedback control systems (the frequency controller and voltage regulator) as well as the Under Frequency Roll-Off characteristic of the AVR.

Two hardware solutions are specified, designed, simulated, implemented, and verified: the alternative exciter field supply; and a novel method for drying alternator windings. The specifications prepared have sufficient detail to afford confidence in the hardware solutions developed – they address the technical requirements and broader contextual requirements of a technology to be transferred into a developing community.

Two feedback control circuits have been completed: one to replicate the constant field current design of the existing APACE constant current exciter supply; the other to incorporate voltage regulation attributes (which address the constraints of the existing APACE solution). Experiments have been conducted to verify the predicted (simulated) operating characteristics. Although designed for the Renewable Energy Laboratory alternator, the alternative exciter supply is based on the specifications for a range of AVRs and hence the solution is expected to be transferable to a broad range of machines, as well as applications beyond those described in this study. A review of the new technology developed has been completed, with a view to verifying the designs against the specifications as well as the framework guidelines.

Moisture is the prime cause of machine winding insulation deterioration and corrosion of metallic parts, and this is certainly the case in humid or rainy conditions, such as those prevalent in the wet tropics. Moreover, moisture can demonstrably have catastrophic impacts if it is allowed to expand in the confined space of the windings during start-up. Given that the mechanism for moisture ingress (and egress) is not perceptible to users in this context, the existing remedy has been counter-intuitive and difficult to transfer. A novel method for drying machine windings has been developed and implemented to address this essential requirement. The method is safer and more intuitive for the system operators and reduces risks of damage to equipment.

Finally, this study is considered an incremental step towards improved system sustainability. That is, rather than being seen as an exit point, the outcomes from this study have proven the concept at component level. The recommendation is therefore to commence planning on the next phase, which may be to consider combining all the various control system components together into a single package. Consideration of such a design integration will benefit from the contextual framework suggested here.