Distributed load management supporting power injection and reactive power balancing

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Thesis submitted for the degree of
Doctor of Philosophy (PhD)

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Co-supervisors: Prof. R. Shorten and Dr. J. H. Braslavsky

The University of Newcastle

June 2015
Statement of Originality

I hereby certify that 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 the final version of my thesis being made available worldwide when deposited in the University’s Digital Repository, subject to the provisions of the Copyright Act 1968.

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Statement of Collaboration

I hereby certify that the work embodied in this thesis has been done in collaboration with other researchers, or carried out in other institutions. I have included as part of the thesis a statement clearly outlining the extent of collaboration, with whom and under what auspices.

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Sonja Stüdli                  Date

Statement of Authorship

I hereby certify that the work embodied in this thesis contains published papers of which I am a joint author. I have included as part of the thesis a written statement, endorsed by my supervisor, attesting to my contribution to the joint publications.

__________________________     __________________________
Sonja Stüdli                  Date
I would like to use this opportunity to express my gratitude to the wonderful people and professionals who supported me throughout my PhD studies. Their guidance, friendly advice and constructive criticism were invaluable to me during the pursuit of this work.

First and foremost I would like to thank my supervisors R. Middleton, R. Shorten, and J. Braslavsky, who with a lot of patience helped me to achieve my goals. Without you I would have never been able to achieve this. I express my thanks to C. Kellett, who also took the role as my supervisor. Even though the time was short, he aid me to pursuit the thesis with his patience, valuable advice, and fruitful ideas and discussions. My special thanks go to the amazing people with whom I had the luck to collaborate. Thank you E. Crisostomi, W. Griggs, M. Liu, M. Corless, R. Khan, F. Wirth, and J. Yuan Yu for your guidance and help throughout our collaboration. Thank you for your patience and effort throughout the work.

I would like to thank S. & F. Knorn and F. Lopez-Caamal for your friendship. You made me feel home here in Australia when I first moved here. Further, to all the people I met at the University and at CSIRO, let me thank you all for your support and friendship. You made my life here in Australia richer.

This study was partly supported by Science Foundation Ireland under grant number 11/PI/1177.

Last but not least I would like to thank my parents S. & R. Stüdli and my partner E. Peters. Thank you for your endless love. There were countless occasions where your patience, support and understanding encouraged me to continue.
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Abstract

In recent years active control over selected electric loads has become increasingly important to reduce the peak demand and allow integration of intermittent renewable generation into the power grid. Two groups of loads are especially interesting in this regard due to their expected numbers and large freedom in scheduling: electric vehicles and so called thermostatically controlled loads, such as refrigerators, hot water heaters, or air conditioners. These electric loads allow their power consumption to be adapted depending on the needs of the distribution grid with a minimal impact on the customers. We consider two types of load power control abilities: binary and continuously controllable power.

In this project we propose a load management scheme to deal with such electric loads. The load management scheme allows the usage of two algorithms: one for binary and one for continuously controllable loads. The proposed load management scheme relies on broadcast signals that are sent by a central management unit to all the agents connected. This means that the communication load is low and that simultaneous management over different load types is possible, due to the identical set up. Further, as there is no data transmitted from the controllable loads to the central management unit, there are no data protection or privacy issues present.

For loads participating with binary controllable power consumption, we propose a binary automaton algorithm that uses stochastic decisions made by the agents to govern the power consumption. This algorithm’s behaviour is analysed and shows promising behaviour in simulations. The algorithm we propose for handling continuously controllable loads is the additive increase multiplicative decrease (AIMD) algorithm. This algorithm is commonly used for congestion control in communications networks and has shown to be very flexible and reliable. Its behaviour has been investigated in detail. While there are some adaptations needed to apply this algorithm in a load management case, we can apply many of the existing results found for the AIMD algorithm as it is applied in congestion control. We extend the analysis where necessary for our case.
Acronyms

AI  additive increase.
AIMD additive increase multiplicative decrease.
AINMD additive increase non-linear multiplicative decrease.

BA  binary automaton.

CCCV constant current constant voltage.
CE  capacity event.
CRF  Charge Rate Fairness.
CTF  Charge Time Fairness.

DAIMD  dual additive increase multiplicative decrease.

EV  electric vehicle.

FEV  full electric vehicle.

G2V  grid to vehicle.
GOF  Global Optimum Fairness.

HEV  hybrid electric vehicle.

IFS  iterated function system.

KKT  Karush-Kuhn-Tucker.

MD  multiplicative decrease.

NAIMD  non-linear additive increase multiplicative decrease.
### Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>OFF</td>
<td>turn off.</td>
</tr>
<tr>
<td>ON</td>
<td>turn on.</td>
</tr>
<tr>
<td>PHEV</td>
<td>plug-in hybrid electric vehicle.</td>
</tr>
<tr>
<td>PO</td>
<td>prioritised optimisation.</td>
</tr>
<tr>
<td>REF</td>
<td>Required Energy Fairness.</td>
</tr>
<tr>
<td>RET</td>
<td>Renewable Energy Target.</td>
</tr>
<tr>
<td>SWER</td>
<td>single-wire earth return.</td>
</tr>
<tr>
<td>TCL</td>
<td>thermostatically controlled load.</td>
</tr>
<tr>
<td>TCP</td>
<td>Transmission Control Protocol.</td>
</tr>
<tr>
<td>V2G</td>
<td>vehicle to grid.</td>
</tr>
</tbody>
</table>
### Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$\beta^{(1)}$</td>
<td>The first multiplicative factor used in the AIMD algorithm.</td>
</tr>
<tr>
<td>$\beta^{(2)}$</td>
<td>The second multiplicative factor used in the AIMD algorithm.</td>
</tr>
<tr>
<td>$E$</td>
<td>The energy that is required by an EV to fully charge its battery.</td>
</tr>
<tr>
<td>$L$</td>
<td>The number of priorities in the Charge Time Fairness scenario.</td>
</tr>
<tr>
<td>$N$</td>
<td>The number of controllable agents.</td>
</tr>
<tr>
<td>$T$</td>
<td>The time step at which an agent connects to the grid.</td>
</tr>
<tr>
<td>$\Psi$</td>
<td>The time duration an EV is connected to the grid.</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>The individual additive factor in the AIMD algorithm.</td>
</tr>
<tr>
<td>$\bar{P}$</td>
<td>The available power.</td>
</tr>
<tr>
<td>$\beta$</td>
<td>The actual multiplicative factor used in the AIMD algorithm.</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>The priority that is assigned to an EV in the Charge Time Fairness scenario.</td>
</tr>
<tr>
<td>$\hat{p}$</td>
<td>The desired active power consumption of a controllable agent.</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>The time an EV remains in the same priority group in the Charge Time Fairness scenario.</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>The probability to choose the first multiplicative factor during the AIMD algorithm.</td>
</tr>
<tr>
<td>$S$</td>
<td>The set in which the active power consumption of the controllable load can lie.</td>
</tr>
<tr>
<td>$\mu$</td>
<td>The probability to turn off when using the BA algorithm.</td>
</tr>
<tr>
<td>$\nu$</td>
<td>The probability to turn on when using the BA algorithm.</td>
</tr>
<tr>
<td>$\pi$</td>
<td>The global additive factor in the AIMD algorithm.</td>
</tr>
<tr>
<td>$\bar{\vartheta}$</td>
<td>The maximum inside temperature allowed of a controllable refrigerator.</td>
</tr>
<tr>
<td>$\pi$</td>
<td>The global additive factor for the reactive power AIMD.</td>
</tr>
<tr>
<td>$\bar{p}$</td>
<td>The maximum active power consumption a controllable agent can handle.</td>
</tr>
<tr>
<td>$\bar{\pi}$</td>
<td>The maximum apparent power a controllable agent can draw.</td>
</tr>
<tr>
<td>$\rho$</td>
<td>The average active power consumption of controllable loads, either it is a long term average since connection or a short term average over a period with predefined length.</td>
</tr>
<tr>
<td>$\tilde{E}$</td>
<td>The battery capacity of an EV.</td>
</tr>
<tr>
<td>$\bar{p}$</td>
<td>The aggregated active power consumption of uncontrollable agents.</td>
</tr>
<tr>
<td>$\bar{q}$</td>
<td>The aggregated reactive power consumption of uncontrollable agents.</td>
</tr>
<tr>
<td>$\beta$</td>
<td>The minimum decrease enforced during the MD phase.</td>
</tr>
</tbody>
</table>
Symbols

\( \vartheta \)  \hspace{1em} The minimum inside temperature allowed of a controllable refrigerator.

\( p \)  \hspace{1em} The minimum power consumption a controllable agent draws.

\( v \)  \hspace{1em} The indicator whether an agent is in G2V or V2G operation for the active power when applying the extended AIMD algorithm.

\( \theta \)  \hspace{1em} The temperature inside a controllable refrigerator.

\( \xi \)  \hspace{1em} The probability to choose the first multiplicative factor during the reactive power AIMD.

\( \zeta \)  \hspace{1em} The indicator whether an agent is in G2V or V2G operation for the reactive power when applying the DAIMD algorithm.

\( a \)  \hspace{1em} The individual additive factor for the reactive power AIMD.

\( b^{(1)} \)  \hspace{1em} The first multiplicative factor used in the reactive power AIMD algorithm.

\( b^{(2)} \)  \hspace{1em} The second multiplicative factor used in the reactive power AIMD algorithm.

\( b \)  \hspace{1em} The expected multiplicative factor in the AIMD algorithm.

\( g \)  \hspace{1em} The individual cost function of an EV in the Global Optimum Fairness scenario.

\( m \)  \hspace{1em} The number of steps used for the turn off probability during the BA algorithm.

\( n \)  \hspace{1em} The number of steps used for the turn on probability during the BA algorithm.

\( p \)  \hspace{1em} The active power consumption of controllable loads.

\( q \)  \hspace{1em} The reactive power consumption of controllable loads.
Math Notation

$A, B, \ldots$ Sets.
$\mathbb{R}$ The set of real numbers.
$\mathbb{R}_+$ The set of non-negative real numbers.
$\mathbb{N}$ The set of natural numbers.
$\text{conv } X$ The convex hull of a set $X$, it may be defined as the smallest convex set containing $X$.
$|x|$ The absolute value of $x \in \mathbb{R}$.
$\lfloor x \rfloor$ The integer part of $x \in \mathbb{R}$.
$(x \mod y)$ The modular operation of two integers $x$ and $y$, i.e. $x$ modulo $y$.
$x$ A column vector with elements in $\mathbb{R}$.
$x_i$ The $i$-th element of the vector $x$.
$e_i$ The $i$-th canonical basis vector.
$1$ The column vector of all ones.
$x \neq y$ There exists an index $i$ with $x_i \neq y_i$.
$A$ A matrix $A$ with elements in $\mathbb{R}$.
$I_n$ The identity matrix of dimension $n \times n$.
$||x||_1$ The $l_1$ norm of the vector $x$, i.e. $\sum_{i=1}^{n} |x_i|$.
$\text{dist}_{l_1}(x, X)$ The distance of a point $x$ to a set $X$ with respect to the $l_1$ norm, i.e. $\min_{z \in X} (||x - z||_1)$.
$B_1(x, \delta)$ The closed ball of radius $\delta$ around $x$ with respect to the $l_1$ norm.
$||x||_{H_T}$ The norm of a vector $x = [x_1^T \cdots x_T^T]^T$ defined by $\min_{i=1, \ldots, T} ||x_i||_{1}$.
$\text{dist}_{H}(x, y)$ The Hilbert metric between two vectors, i.e. $\max_i \log \frac{x_i}{y_i} - \min_j \log \frac{x_j}{y_j}$.
$e^{\mathcal{H}}(x, y)$ The Hilbert metric with the logarithm removed, i.e. $\max_i \frac{x_i}{y_i} - \min_j \frac{x_j}{y_j}$.
$A \otimes B$ The Kronecker product of the matrices $A$ and $B$.
$A \oplus B$ The Kronecker sum of two square matrices $A$ and $B$, i.e. $A \otimes I_n + I_n \otimes B$ if the dimensions of $A$ and $B$ are $n \times n$ and $m \times m$, respectively.
$A^T, x^T$ The transpose of the matrix $A$ or the vector $x$.
$A^{-1}$ The inverse of the matrix $A$.
$\Pr [A]$ The probability that event $A$ occurs.
$E [X]$ The expected value of a random variable $X$. 