Stability Analysis of Intelligent Home Energy Management System (HEMS)

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Home Network System (HNS)

A home automation system basically consists of household appliances linked via a communication network allowing interactions for control purposes.

Problem
As more and more home appliances and consumer electronics are deployed, power consumption in home area

- Tends to grow
- Increases risk of power blackout

Solution
We need Energy Management System for home to mitigate the energy crises and the environmental problems by using

Home Energy Management System (HEMS)

In order to adapt the consumption to the available energy, the HNS controls the appliances by determining the starting time of their services.
The home energy management system is a networked system that helps in managing the power supply to residences in order to reduce power consumption.

**Advantages**
- Low cost
- Safe and easily configurable
- Reduce power shortage
- Simple construction
- Security
- Efficiency
- Greater reliability
- Reduce carbon emissions

**Functionalities**
- Planning
- Repairing operations
- Auto configuration
- Easy monitoring
- Remote controlling
- Smart planning
- Provide information on the status of installed devices
- Gives dynamic information

**Load Management**
- Energy supply Management
- Energy demand Management
- Energy response management
- User comfort management
- Energy price variation management

A part of HEMS called Smart Meter can collect amount of electricity and accuracy for supplier and users of home.
Smart Meter

Smart Meter (SM)

“Smart Meter is an advanced energy meter that measures the energy consumption of home appliance and provide added information to regular meter”.

SM benefits

- Enhance reliability and outage detection
- Gives customers more control over their everyday energy usage
- Opportunity for lower bills
- Improves customer service and allows for a more proactive workforce
- Can read real-time energy consumption
- Can communicate remotely and locally
- Can communicate with other SM’s
- Diagnose information about home appliances

Need Implementation of SM to transform data into actionable commands to target DR events which is important for Stability Analysis.
Demand Response (DR) Event

“Electric power systems have encountered more frequent stress conditions due to ever increasing electricity demand, which are likely to occur during critical peak hours. Such events will cause a Demand Response Events.

Reasons to use

- DR deal with unexpected supply-limit by selecting system loads
- DR plays important role in load shifting
- Helps in increasing reliability and efficiency in operation
- Widely implemented by commercial energy markets
- Rarely use in Home systems

A demand event is defined as a period during which the user demand needs to be curtailed to alleviate a system stress condition.
2- Research Motivation

- Focus on balancing the energy usage for HEMS, and this work distinguished because this stability analysis work has not been studied yet by the community of Home Networks.

- The presence of DR is raising the question of stability of HEMS.

- It motivates us to study how we can propose a scheme to efficiently and effectively balance the energy demand with the limitation of energy supply.

Stability of HEMS is an important consideration while energy consumption is on peak hours.
3- Research Objective

- Promoting **Stability of energy** with SM create transparent real-time monitoring of power consumed, successful DR event implementation in frequent stress condition.

  System Stability Need System Model

- To setup mathematical formulation that makes optimized home energy management systems, able to determine the **best energy stabilization plan** according to given criteria.

  Link Stability Need Link Model

- The problem would be formulated as a muli-objective constraint problem and has been solved by **Lyapunov Stability**.

  ![LMI(Linear Matrix Inequality)](image) ![Lyapunov-based function](image)
4- Related Work

Reducing transient and steady state behavior
Anil et al. proposed Reducing Transient and Steady State Electricity Consumption in HVAC using Learning Based Model predictive Control

Tree Structure of Power Strip Type Smart Meter
Cho et al. proposed Determining Location of Appliances from Multi-hop Tree Structure of Power Strip Type Smart Meter

HEMS Stability

The effect of Stability in Power Market
Manisa et al. proposed an algorithm for Intelligent Home Energy Management and Demand Response Analysis
5- Proposed System Modeling

- Overall HEMS model with SM infrastructure.
- The existing equipment in home that we use in home is AC and Light.
- A SM that is attached on the transmission line measures the current consumption of the connected home appliance.
- HEMS receives energy signal (supply) which is limited (kilo watt per hour kwh).
- The energy consumption of appliances (demand) can vary every time.
- The total household consumption should remain below the specified supply limit during the DR event.
- Frequent DR events make HEMS unstable and malfunction system.

NOTE: In each room considering both Transient and Steady state energy consumption behaviors during DR event in more frequent stress conditions.


Energy Consumption Profile Model

\[ E = \sum_{k=0}^{N-1} r \cdot u[m+k] + \sum_{k=0}^{N-1} \rho \cdot u[m+k] \]

\[ u_m = (u[m] \ldots u[m+N-1]) \]

- **Average rate of steady state energy consumption**
- **Average rate of transient energy consumption**
- **Number of discrete time steps over which energy consumption is to be computed**

\[ t_{on}, t_{ss}, t_{off} \] indicate the time when the home appliance turns on, the time when the power reaches steady state, and the time when the home appliances turn off, respectively.
Proposed Strategy

**Inputs**
- Building Description
- Occupancy profile
- Appliances etc.

**Energy Demand**
- Consumed energy increased due to transient behavior $D_{tr}$
- Consumed actual Energy due to steady state behavior $D_{ss}$ (Appliance Side)

**Energy Supply**
- Available energy increased due to transient behavior $S_{tr}$
- Available actual Energy due to steady state behavior $S_{ss}$ (Energy Provider SM)

**Outputs**
- System Evaluation
- Reliability Assessment
- Stability plan
Energy Supply/Demand Model

**Energy Supply Model**

\[
E_s = \lambda - (\lambda_m) - kE \\
E_s = \lambda - (S_{tr} + S_{ss}) - kE \\
E_s = \lambda - S_{tr} - S_{ss} - kE
\]

- \( \lambda \) Maximum energy limit
- \( \lambda_m \) Marginal energy limit equals to \( S_{tr} + S_{ss} \)
- \( S_{tr} \) supply energy due to transient behavior
- \( S_{ss} \) supply energy due to steady state behavior
- \( E \) Energy Imbalance
- \( E_s \) Energy supply

**Energy Demand Model**

\[
E_d = D_{tr} + D_{ss} - \lambda
\]

- \( \lambda \) Maximum energy limit
- \( D_{tr} \) energy demand due to transient behavior
- \( D_{ss} \) energy demand due to steady state behavior
- \( E_d \) Energy demand
Energy Imbalance

- For Energy demand $E_d$ to represent demand, a constraint that $E_d > 0$ will need to be additionally imposed.
- The final condition required to characterize the Energy situation is the balance between supply and demand.
- If there is an **Energy balance** $E$, using the definition of $E_s$ and $E_d$, we can derive the differential equation.
- In HEMS, with several home appliances and unknown demand, energy imbalance must be reduced and *driven to zero* to satisfy consumption of all loads.
- A simple model of the energy dynamics is given by

$$\lambda(t) = -E$$

$\lambda(t)$ indicates the time constant of the energy update.
Energy Model

- We propose a realistic approach, which uses SM to measure $E_d$ which can measure with a time delay $\tau$,

- therefore, the energy imbalance $E$ is determined as

$$\dot{E} = E_s(t) - E_d(t - \tau)$$

$$\dot{E} = (E_s = \lambda - S_{tr} - S_{ss} - kE) - (D_{tr} + D_{ss} - \lambda)(t - \tau)$$

$$\dot{E} = (E_s = \lambda - S_{tr} - S_{ss} - kE) - \left(\sum_{k=0}^{N-1} \frac{r}{4} + \lambda\right) u[m + k](t - \tau)$$
Supply and demand models include constraints on energy supply or supply links and evaluate the effect of DR event on stability.

Now by considering Eqs. and including constraints.

\[
E_s = \lambda - S_{tr} - S_{ss} - kE
\]
\[
E_d = D_{tr} + D_{ss} - \lambda
\]
\[
\lambda(t) = -E
\]
\[
\dot{E} = E_s - \sum_{j=1}^{n} E_d(t - \tau)
\]

The model can be written compactly as

\[
\dot{x} = \overline{A_0}x(t) + \overline{A_1}x(t - \tau) + B
\]
7- Concluding Remarks

- The introduction and availability of Smart Meter infrastructure would introduce a paradigm shift in the analysis of home networks.
- The time delay feature would provide the maximum peak of transient energy consumption to analyze.
- Stability analysis is dependent on time delay feature $\tau$.
- The proposed scheme will cover two stability aspects.

- **Overall Stability**
  Overall Stability of a home will consider SM A, and apply Stability analysis for overall limited supply and demand event.

- **Link Stability**
  Link Stability would provide the stability of a specific link that it is stable or not.
Thank you very much for your kind attention
Lyapunov Stability

$$\bar{A}_0 = \begin{bmatrix} \frac{-E_{\text{act}_1}}{t_{s1}} & 0 & \ldots & 0 & 0 & \ldots & 0 & \frac{-k}{t_{s1}} & \frac{-1}{t_{s1}} \\ 0 & \frac{-E_{\text{act}}}{t_{s2}} & \ldots & 0 & 0 & \ldots & 0 & \frac{-k}{t_{s2}} & \frac{-1}{t_{s2}} \\ \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\ 0 & \ldots & 0 & \frac{-E_{\text{act}_m}}{t_{s_m}} & 0 & \ldots & 0 & \frac{-k}{t_{s_m}} & \frac{1}{t_{s_m}} \\ 0 & \ldots & 0 & 0 & \frac{-E_{\text{act}_1}}{t_{d1}} & \ldots & 0 & 0 & \frac{-1}{t_{d1}} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\ 0 & \ldots & 0 & 0 & 0 & \ldots & \frac{-E_{\text{act}_n}}{t_{d_n}} & 0 & \frac{-1}{t_{d_n}} \\ 1 & \ldots & 1 & 1 & 0 & \ldots & 0 & 0 & 0 \\ 0 & \ldots & 0 & 0 & 0 & \ldots & 0 & \frac{-1}{t_\lambda} & 0 \end{bmatrix}$$
Lyapunov Stability

\[
\overline{A}_1 = 
\begin{bmatrix}
0 & 0 & \ldots & 0 & 0 & \ldots & 0 & 0 & 0 \\
0 & 0 & \ldots & 0 & 0 & \ldots & 0 & 0 & 0 \\
\vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\
0 & \ldots & 0 & 0 & 0 & \ldots & 0 & 0 & 0 \\
0 & \ldots & 0 & 0 & 0 & \ldots & 0 & 0 & 0 \\
1 & \ldots & 1 & 1 & \frac{-1}{t_{d1}} & \ldots & \frac{-1}{t_{dn}} & 0 & 0 \\
0 & \ldots & 0 & 0 & 0 & \ldots & 0 & 0 & 0
\end{bmatrix}
\]
\[ \dot{x} = A_0 x(t) + A_1 x(t - \tau) + B \]

\[ x = [P_{s1} \ldots P_{sm} \quad P_{d1} \ldots P_{dn} \quad E \quad \lambda]^T \]

\[ B = \begin{bmatrix} -\frac{E_{inc1}}{t_{s1}} & \ldots & -\frac{E_{incm}}{t_{sm}} & \frac{E_{inc1}}{t_{d1}} & \ldots & \frac{E_{incn}}{t_{dn}} & 0 & 0 \end{bmatrix}^T \]
7- Analysis of Proposed Scheme

- Power market include a **variety of participants** including
  - Suppliers
  - consumers (users)
  - Electric Power Companies (EPCo.), which is responsible for pricing of the energy as well as the energy supply lines.

- In HEMS with real time pricing, suppliers and users continuously adjust their supply **power quantities and consumptions** respectively, Based on supply-demand energy as well as the price of electricity.

- The price in turn affects the available and consumed energy, and **overall energy imbalance**.

- The **time constraint of SM** to monitor energy consumption would provide the maximum peak of transient energy consumption to analyze and raises the question of stability of HEMS.

- By analyzing the dynamics of resulting energy, we study the effect of stability in the **presence of delay** $\tau$ which does not exceed a certain bound of energy supply.
Mathematical Model for SM Operation

- Mathematical model for SM operation
  - The links between the nodes are not communication links but power supply links.
  - Tree configuration is symmetric.
  - A is the parent of B and C.
  - B is the parent of D and E and vice versa.
  - L indicate Light
  - AC indicate Air conditioner

$$n(MAX_lS) = 2^l$$

Where \( l \) is the depth of the SM layer and the number of nodes are two. Thus, the maximum number of SM when the depth of the layer is \( L \) is

$$n(S_{TOTAL_L}) = \sum_{i=0}^{L} 2^i$$

From (2), we obtain the maximum number of SM with three hops: 15(1+2+4+8)