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Energy Management System for the future Distributed Grid

Kerk See Gim, PHD

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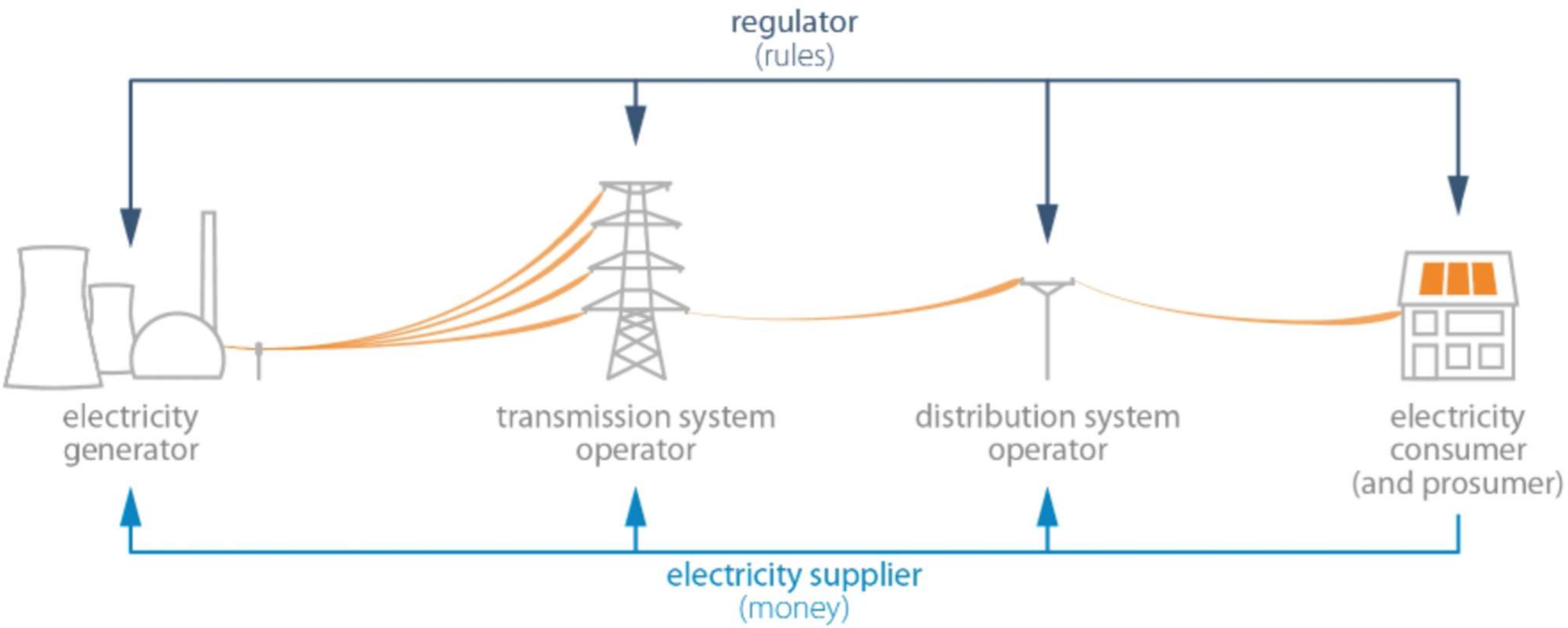
Foundation Technologies for A Smart City

Contents

- **Motivation and Background**
  - The traditional grid
  - The future grid
  - The future distributed grid
  - Approach and tasks of the research
  - The smart energy management system
- **Managing the Micro-grid**
  - Component modeling/Problem formulation/Results/Conclusion
- **Reliability Index for the Micro-grid**
  - Component modeling/Problem formulation/Results/Conclusion
- **Demand Management for End User distributed load**
  - DRM Methodologies/Problem formulation/Results/Conclusion
- **Home Appliance based Demand Management**
  - System modeling/NILM/Home energy storage system/Results/Conclusion
- **Publications**
- **Overall Conclusion and Future Work**
- **Q&A**

The Traditional Grid

+ The traditional power system control system -- Energy Management System (EMS)
  - Generation, transmission and distribution
  - Load dispatching, Balance of System and fault location
  - Focus on reliability of supply and more recently, Quality of Supply (QoS)
  - System Average Interruption Duration Index (SAIDI)
  - System Average Interruption Frequency Index (SAIFI)



CURRENT LIMITATIONS AND RISKS

For national grid to achieve network stability or balance of systems, these are the few strategies

Utility Side Strategies

1. Match load increase with increase in generation
2. Load Shedding at the substation level due to supply loss
3. Increase spinning reserve or standby capacity
4. More recently, large energy storage systems

Load Side Strategies

1. Demand Management for customer voluntary turning off load (Interruptible load scheme) started in 2006 but limited to industrial customers
2. End home users participation of interruptible loads (IL)

Risks and Challenges

1. Growth of renewables and impacts to the grid. -> NEGATIVE DEMAND !!
2. Increased customer expectations

THE FUTURE GRID – FROM A SINGAPORE UTILITY'S VIEW

- Government action on climate change is pushing growth of renewables and energy optimization to reduce carbon footprint.
- Solar leasing contracts are expanding exponentially. E.g SolarNova 1-7.. Target to install at HDB and govt estates amounting to around 3000 MW peak
- Cost of renewables are dropping and with government incentives (building grants) and penalties (EUI* and Carbon Tax) are driving huge investments into distributed generation.
- Impact to the grid could be negative as our peak usage is around 6,600 MW with installed capacity of 13,000 MW and with no requirements on the Quality of Supply (QoS)

SGD Carbon Tax Per tonne CO2 emission	$5	$25	$45	$50 -$80
	Current	2024 & 2025	2026 & 2027	2030
% Electricity Cost Increase	-%	2-3%	4-7%	8-12%

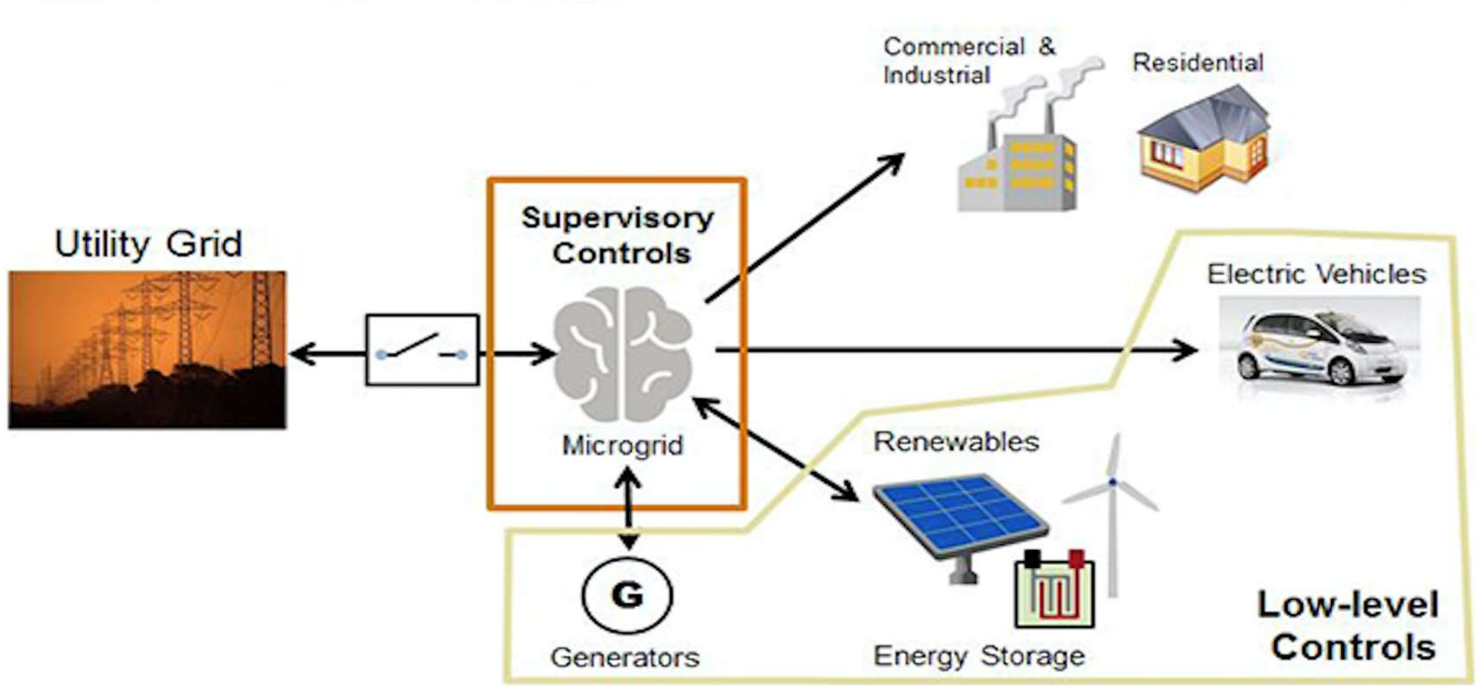
* Grid Emission Factor (GEF @ 0.4080 kg CO_2/kWh) Dependent on efficiency of power generation plants

Applicable to building emitting >25,000 tons of carbon (> SGD$2,000,000 tax annually by 2030)

*EUI – Energy Utilization Index – Total energy consumers/Total Area of buildings

WHAT IS A MICRO-GRID ?

- The grid connects homes, businesses and other buildings to central power sources
- A micro-grid generally operates while connected to the grid, but importantly, it can break off and operate on its own using local energy generation in times of crisis like storms or power outages, or for other reasons.
- Large buildings and clusters of buildings are now becoming micro-grids where they generate power (1-3 MW) with energy/thermal storage and can interrupt their loads.

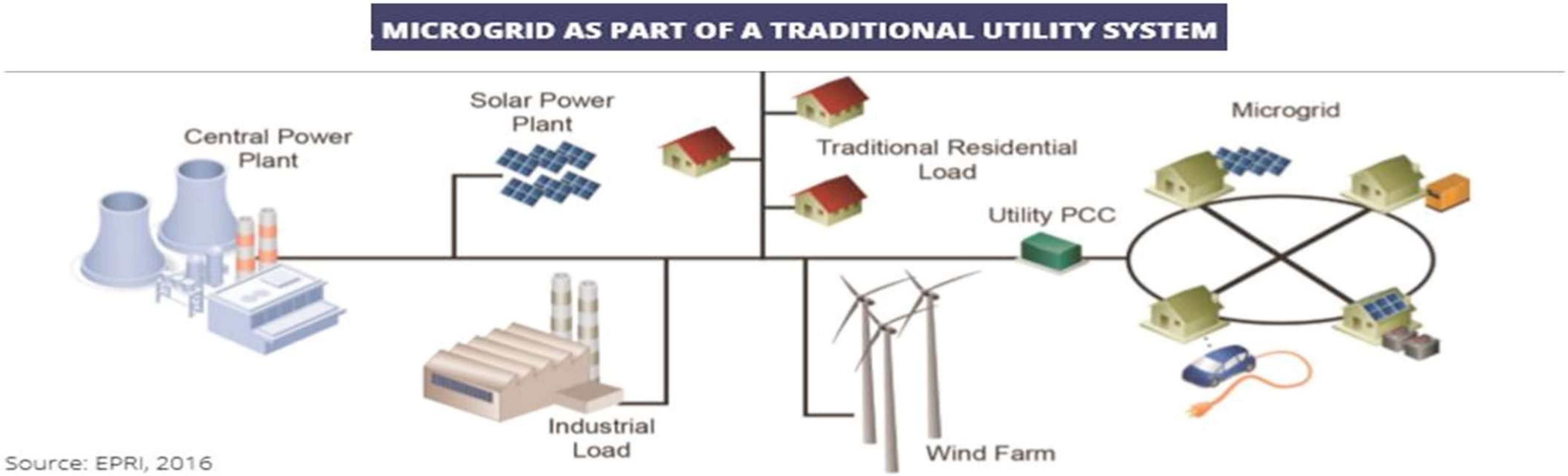


THE FUTURE DISTRIBUTED GRID

- The future distributed grid will have many micro-grids (home level to building level)
- These micro-grids can support the growth of renewables reliably with energy storage and manage their demand/usage as they adopt local optimization, while reducing impacts to the grid

Sustainable microgrids are the future of clean energy

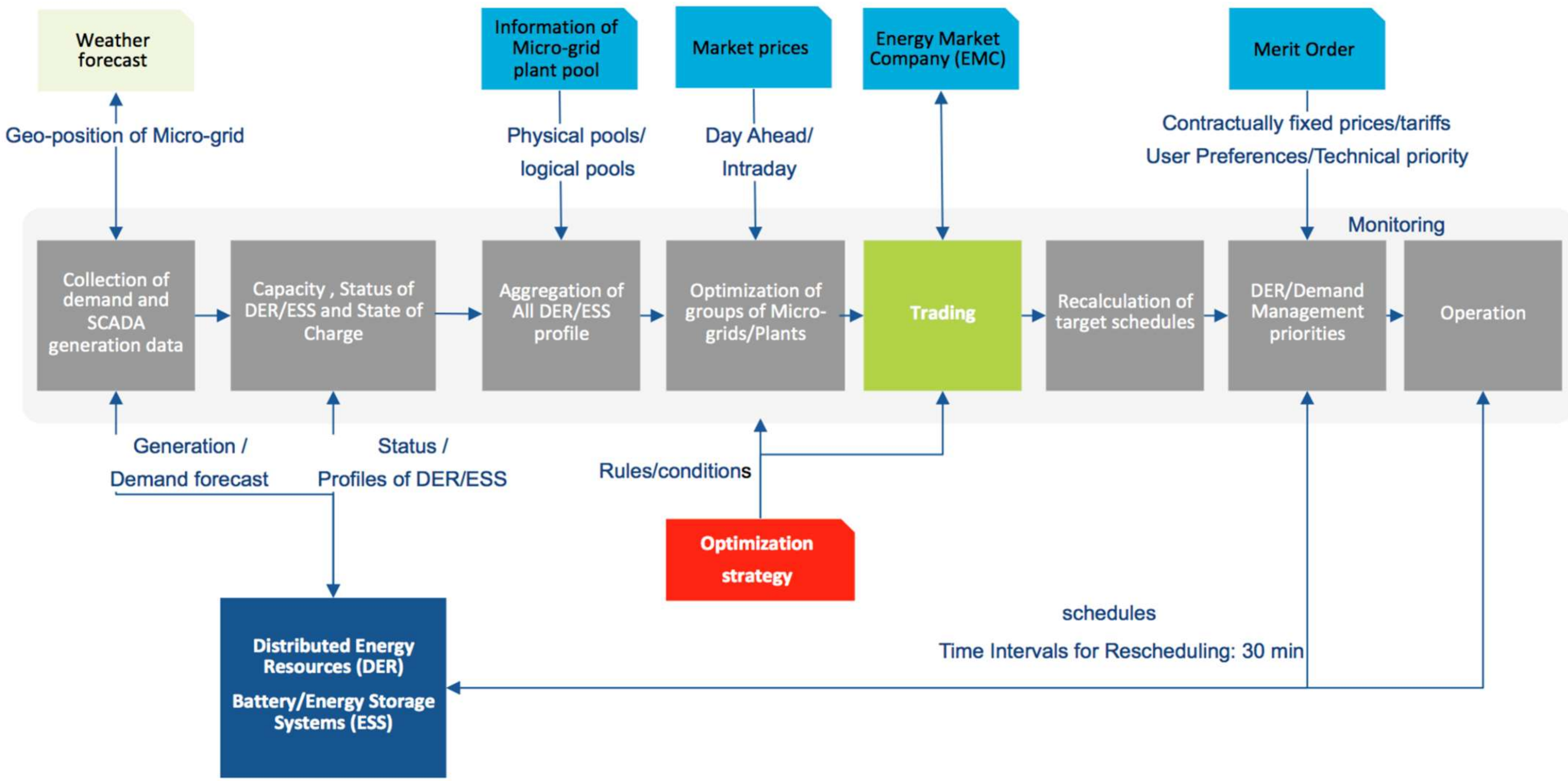
Alex Behrens @Watch_Crypto / 5:41 am +08 • March 5, 2020 Comment



THE NEW EMS

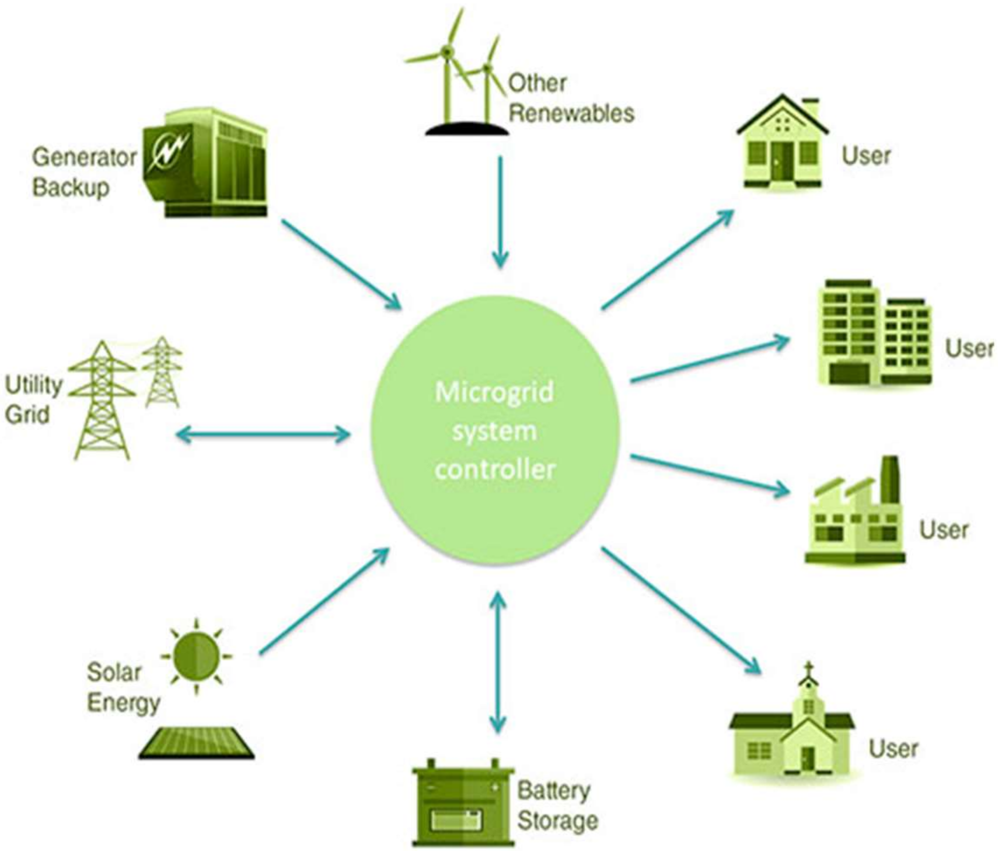
- The Energy Management System (EMS) must evolve to cater to these interconnected micro-grids to ensure that the system overall reliability and priorities
- Micro-grids are expected to “share the responsibility” in ensuring a high quality of supply (QoS) to their users and reduce disturbances (reliability indices) to the main grid.
- With that, the new EMS must support the following tasks
  - Task 1 - Direct management of Micro-grid
  - Task 2 – Measure and enforce the reliability index for micro-grid to allow inter-connection
  - Task 3 - Supports Demand Management via User participations (Interruptible Loads)
  - Task 4 – Supports smart homes to perform Appliance level demand management

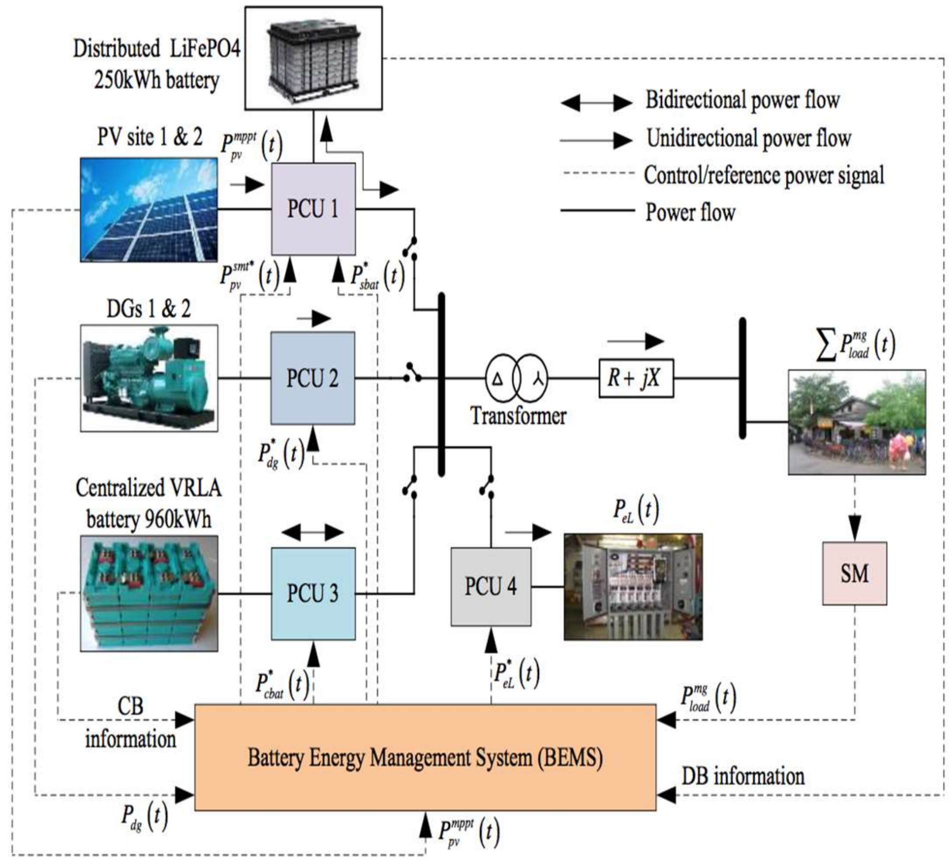
THE NEW EMS SYSTEM PROCESS FLOW



TASK 1 – MANAGING THE MICRO-GRID

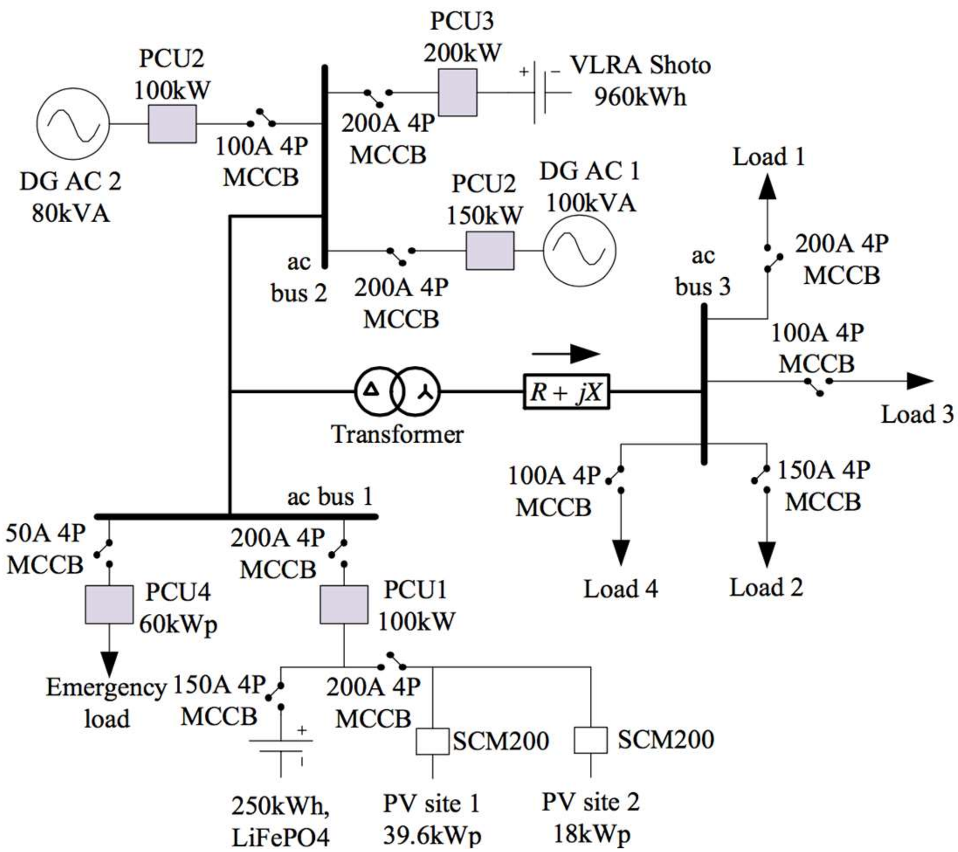
+ Developing the micro-grid control strategy to ensure
  - Stability
  - Reducing the use of diesel and imports from the grid





Our typical model micro-grid

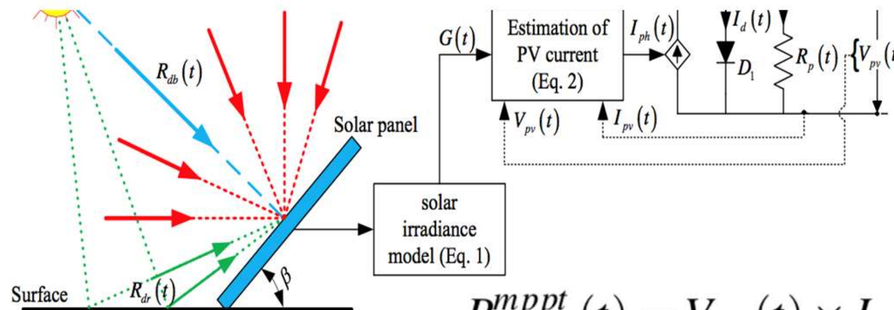
COMPONENT MODELING



1. Minimize Diesel Usage
2. Reduce PSOC battery cycling

PV Modeling

$$I_{pv}(t) = C_{np} I_{ph}(t) - C_{np} I_o(t)\left(e^{\frac{qV_{pv}(t)}{C_{ns}NKT_c}} - 1\right) - \frac{V_{pv}(t) + I_{pv}(t) R_s}{R_p}$$



$$P_{pv}^{mppt}(t) = V_{pv}(t) \times I_{pv}(t)$$

Battery Model

3000 – 5000 life cycles

$$V_{bat}(t) = V_o(t) - k\frac{Q_{bat}(t)}{Q_{bat}(t) - \int I_{batt}(t)\,dt} + A.\exp\left(-B\int I_{batt}(t)\,dt\right)$$

Diesel Model

$$E_{dg}(t) = \sum_{d=1}^{n} P_{dg}(t)\Delta t_d, \quad \forall \quad n = 1, 2, 3, \ldots$$

$$FC_{dg} = DG_{rfc} \times E_{dg}(t)$$

TASK 2 - RELIABILITY INDEX

+ To develop the overall reliability, index we need to consider each components operational considerations
+ Compute based on the number and duration of each interruptions per year

Diesel Indices

$$DGTR = \frac{No.\ of\ \ times\ DGs\ turned\ “on”}{Total\ operation\ hours}$$

$$DGTR = \frac{DGs\ turned\ “on”\ hours, D_{dg,ijm}^{on}}{Number\ of\ \ times\ DGs\ turned\ “on”}$$

PV and Battery Indices

$$RGSR = \frac{No.\ of\ \ times, t_{rgs}^{on}}{Total\ operation\ hours}$$

$$RGSH = \frac{\sum\left(D_{ba,ijn}^{on}(t) + D_{pv,ijo}^{on}(t)\right)}{No\ of\ \ times\ DGS, t_{rgs}^{on}}$$

Load Indices

$$LPSH = \frac{Load\ demand\ satisfied\ hours}{Total\ operation\ hours}, \forall P_{dem,i,j}(t) = P_{sup}(t)$$

$$NCI = \frac{NCI_{ini} + 1}{Total\ operation\ hours}$$

Number of consumers interrupted

$$CIH = NCI \sum_{i=1}^{N_{sf}} \sum_{j=1}^{N_{ogb}} \sum_{k=1}^{L_t} (\Delta T_{off,\,ijk})$$

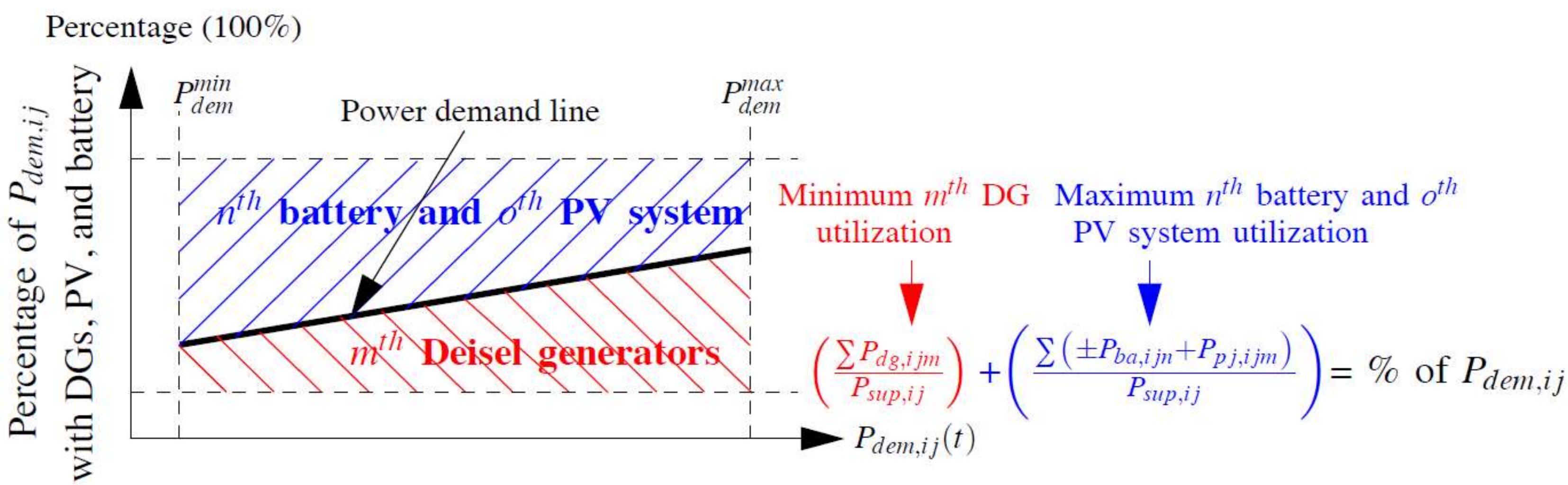
Consumer interrupted hours

$$QoS = 1 - \frac{\text{Total number of interruption x Duration}}{\text{Total operation hours}}$$

$$SAIFI = 1 - \frac{\text{Total number of consumer interruptions}}{\text{Total number if consumer serves}}$$

$$\text{SAIDI} = \frac{Customer\ interruption\ durations}{\text{Total number of consumer served}}$$

RELIABILITY INDICES PROBLEM FORMULATION



Reliability Index

$$\underset{\left(\partial, U_f, P_{in,ijk}^{mg}\right)}{Solve} R_{in} = \left(1 - \sum_{i=1}^{Nsf} \sum_{j=1}^{Nogb} \frac{P_{dem,ij}(t) - P_{\sup,ij}(t)}{P_{dem,ij}(t)}\right), R_{in}^{lw} \le R_{in} \le R_{in}^{up}$$

$$\partial = f\left(k_{dg,ijm}, t_{dg,ijm}^{on}, C_{ba,ijn}^{r}(t), D_{ba,ijn}^{r}(t)\right)$$

battery charge/discharge rate control,

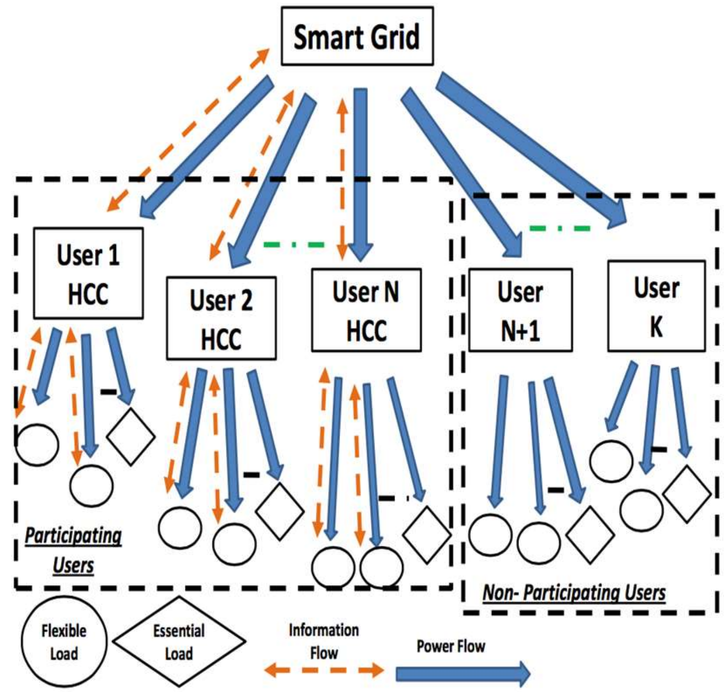
$$U_f = DGUF + RGSUF, \forall 0 \le U_f \le 1$$

DGs and RGS utilization factor

Cost of un-served power is not the same as the main grid

TASK 3 – DEMAND MANAGEMENT FOR END USER LOADS

- An EMS that consider an energy framework to
  - Achieve Demand Response Management (DRM) with min number of users using a **power limit index** and an **inconvenience limit**
  - **A Power limit** reduce their non-essentials load in response to a utility trigger power limit signal
  - **An inconvenience limit** reduce more load than what their non-essential loads can offer and creates an inconvenience
  - A dynamic mechanism to identify the level of inconvenience for each types of loads to manage users
  - Loads with "inconvenience levels" from HVAC, water heater (WH), dryer, optional lighting loads (OLL) and so on. In essence, a priority list.
    - Essential loads (non- trippable loads)
    - Flexible loads
      - Shiftable loads (SL) – clothes dryer (CD)
      - Breakable loads (BL)



$$BL = \{HVAC, WH, OLL\}, \quad SL = \{CD\}$$

AVOID LOAD SHEDDING

DRM METHODOLOGIES

- **Power limit method –** power reduction allocation problem among N participating users

$$D_l(t) = \frac{\widehat{D}(t)}{N}$$

- **Inconvenience limit method – User set inconvenience limit and preferences for each load. E.g**

$$U^n(t) = \sum_i \Omega_i U_i^n(t)$$

The net inconvenience severity

$$U_i^n(t) = \left(\frac{T_i^n(t) - \widehat{T}_i^n}{\widetilde{T}(t) - \widehat{T}_i^n} \right) W_i^n(t)(1 - C_i^n(t));$$

$\widetilde{T}(t)$ Outside temperatures

$\widetilde{W}_i^n$ denote the demand status duration of flexible load i of user n in time slot t i.e.,

$$T_{AC}^n(t) \in unif(64^o F, 67^o F), \forall n$$
$$T_{WH}^n(t) \in unif(110^o F, 120^o F), \forall n$$

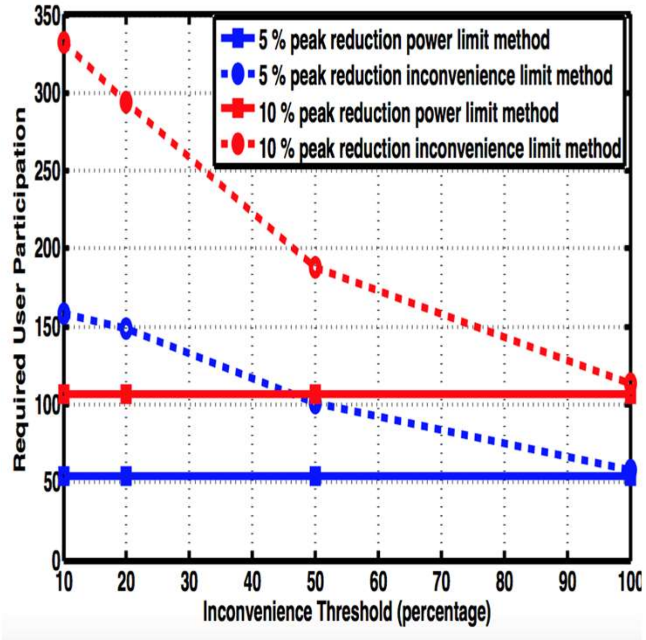
Aircon and water heater thermostat set points of users

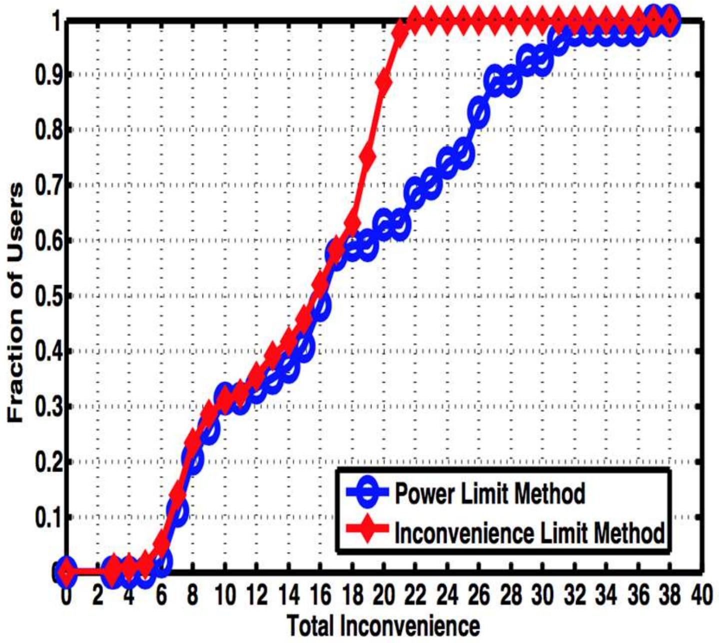
Power rating and usage patterns of flexible.

Flexible load	Power rating (kW)	Operation duration (h)	Usage pattern
AC	3	4	Consecutive operation
WH	2.5	3–6	Two or three separate instances of 1–2 h
CD	3.1	2	Consecutive operation
OLL	0.5	3–6	Two or three separate instances of 1–3 h

SAMPLE RESULTS FOR TASK 3

Peak Load Reduction (β)	Inconvenience Threshold (γ)	User Participation (N)	
		Power Limit Method	Inconvenience Limit Method
5 %	10 %	54	158
	20 %	54	149
	50 %	54	101
	100 %	54	58
10 %	10 %	107	332
	20 %	107	294
	50 %	107	188
	100 %	107	113



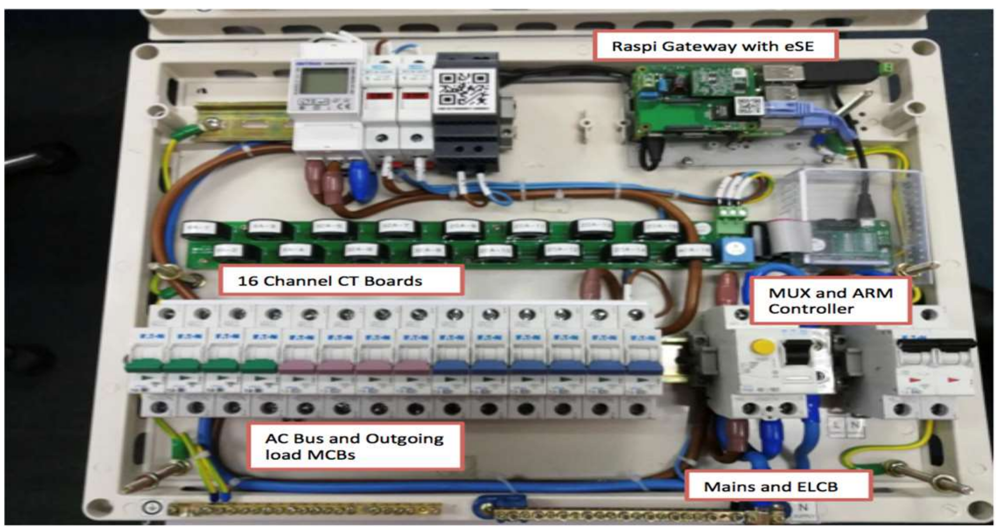


From this table we can see that for 5% peak load reduction and 10% inconvenience threshold, the power limit method requires 54 users while the inconvenience limit method requires 158 users.

Task 4- Appliance Level Demand Management

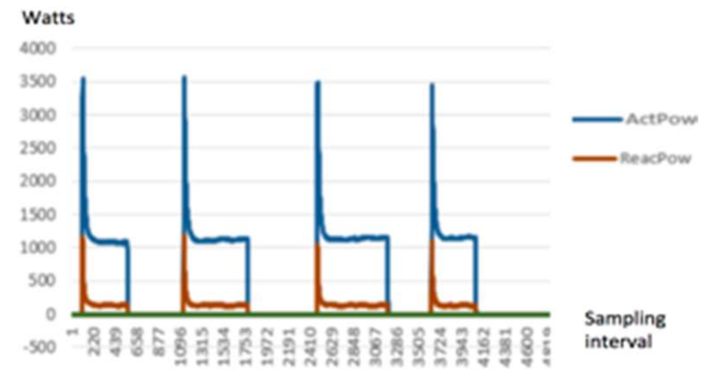
+ Demand management in the form of IL, allows user participation to balance the grid to avoid load shedding, which is highly disruptive to quality of life to end consumers.

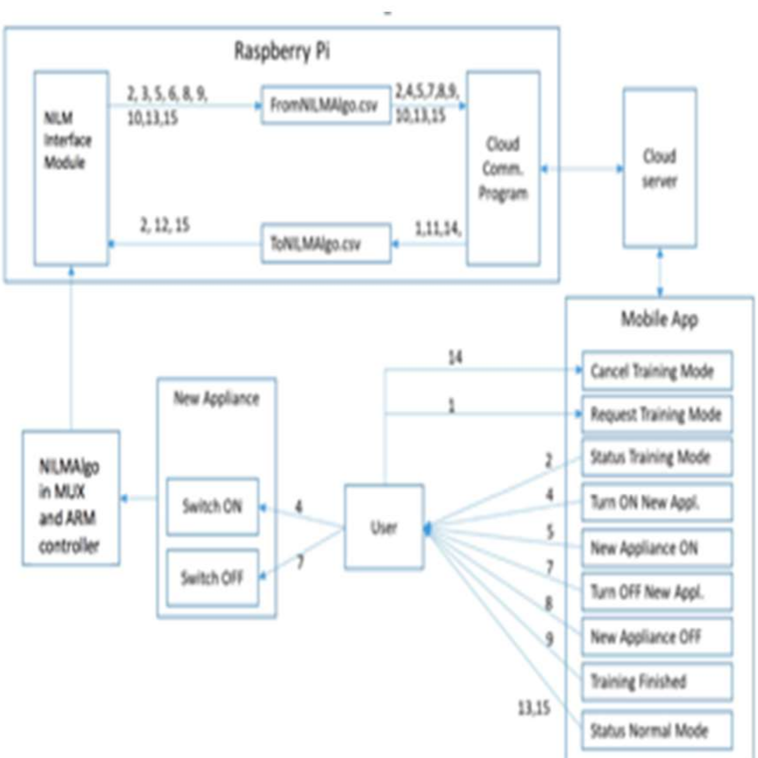
+ To achieve the Demand Response Management (DRM), the research focused on developing a new infrastructure and approach with supporting applications
  - Developing a smart Distribution Box (Smart DB)
  - Implementing a Non-Intrusive Load Monitoring (NILM) system
  - Developing a smart socket (wall in socket) with built in breakers
  - Providing usage profile based on individual appliance usage to suggest and encourage a higher level of user participation for interruptible load, while taking into their preferences



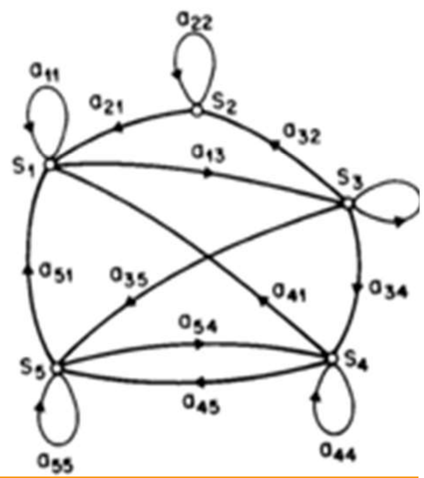
NON-INTRUSIVE LOAD MONITORING

- To develop a library of load signatures by capturing 1 sec of high speed profile (6 kHz) of kW, Kvar, V, I and pf
- Translate them into Markov models





$$\hat{x}_t = \sum_{n}^{N} \hat{x}_{n,t} = \sum_{n=1}^{N} \sum_{k=1}^{K_n} z_{t,k}^{n} \mu_k^n$$



3	15:25:43	Learning New Appliance Signature with Average Power : 800.811279
4	15:25:57	Learning Appliance Signature
5	15:26:12	Learning Appliance Signature
6	15:26:21	Learning Appliance Signature
7	15:26:48	Learning New Appliance Signature with Average Power : 2335.960205
8	15:27:01	Learning Appliance Signature
9	15:27:11	Learning Appliance Signature
10	15:27:20	Learning Appliance Signature
11	15:27:36	Learning Appliance Signature
12	15:27:36	Fetching Appliance Id from Central Database
13	15:27:51	Learning Appliance Signature
14	15:29:24	Learning Appliance Signature
15	15:29:42	Learning Appliance Signature
16	15:30:31	Updated LocalDB row 1 with response ApplID 666
17	15:30:31	Updated LocalDB row 1 with response ApplID 666
18	15:30:59	ApplId 666 Switched On
19	15:31:13	ApplId 666 Switched Off
20	15:32:04	ApplId 666 Switched On
21	15:32:21	ApplId 666 Switched Off

POC – 1200 Homes at HDB PUNGGOL NEW TOWN

OVERALL CONCLUSIONS AND FUTURE WORK

- The provides a foundation for a faster implementation of the micro-grids and their integration to the main grids,
- The control schemes provided will allow different types of micro-grids to join the main grid, allowing the formation of a larger EMS system
- The developmemt of the reliability indexes provides a way to qualify the performances of a micro-grid, providing a reasonable benchmark for inter-connections
- We create a shared responsibility in an evolved grid that will allow growth of renewables, while ensuring a sustainable national grid that provide a high quality of supply
- By deploying a framework for user to participate for IL, we have an innovative way to balance the grid, taking considerations for user preferences, minimizing their inconvenience while balancing the grid