An Efficient Scheduling Algorithm for Multiple Charge Migration Tasks in Hybrid Electrical Energy Storage Systems

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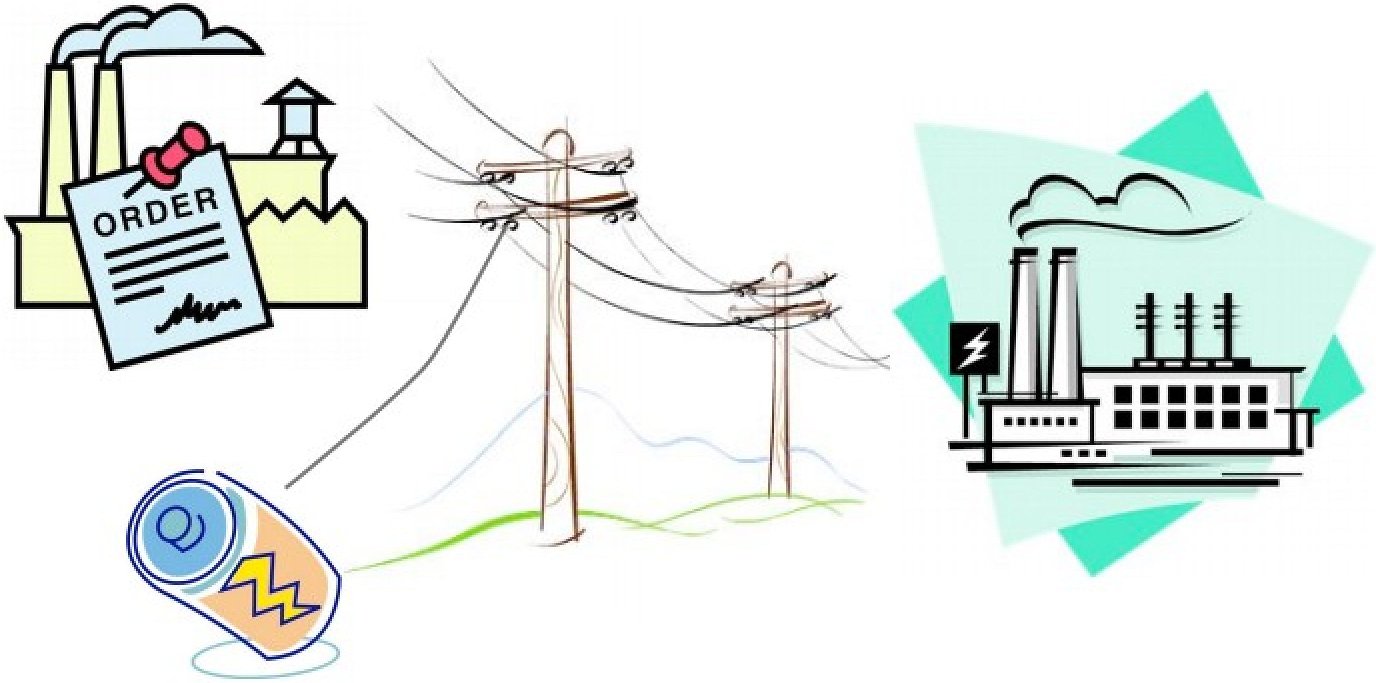
Outline

- Electrical Energy Storage System (EES)
- Hybrid Electrical Energy Storage System (HEES)
  - Architecture
  - Components
- HEES System Charge Management
- Charge Migration Scheduling
  - Motivation
  - Problem Statement
  - Solution Method
  - Simulation Results
- Conclusion

Electrical Energy Storage System

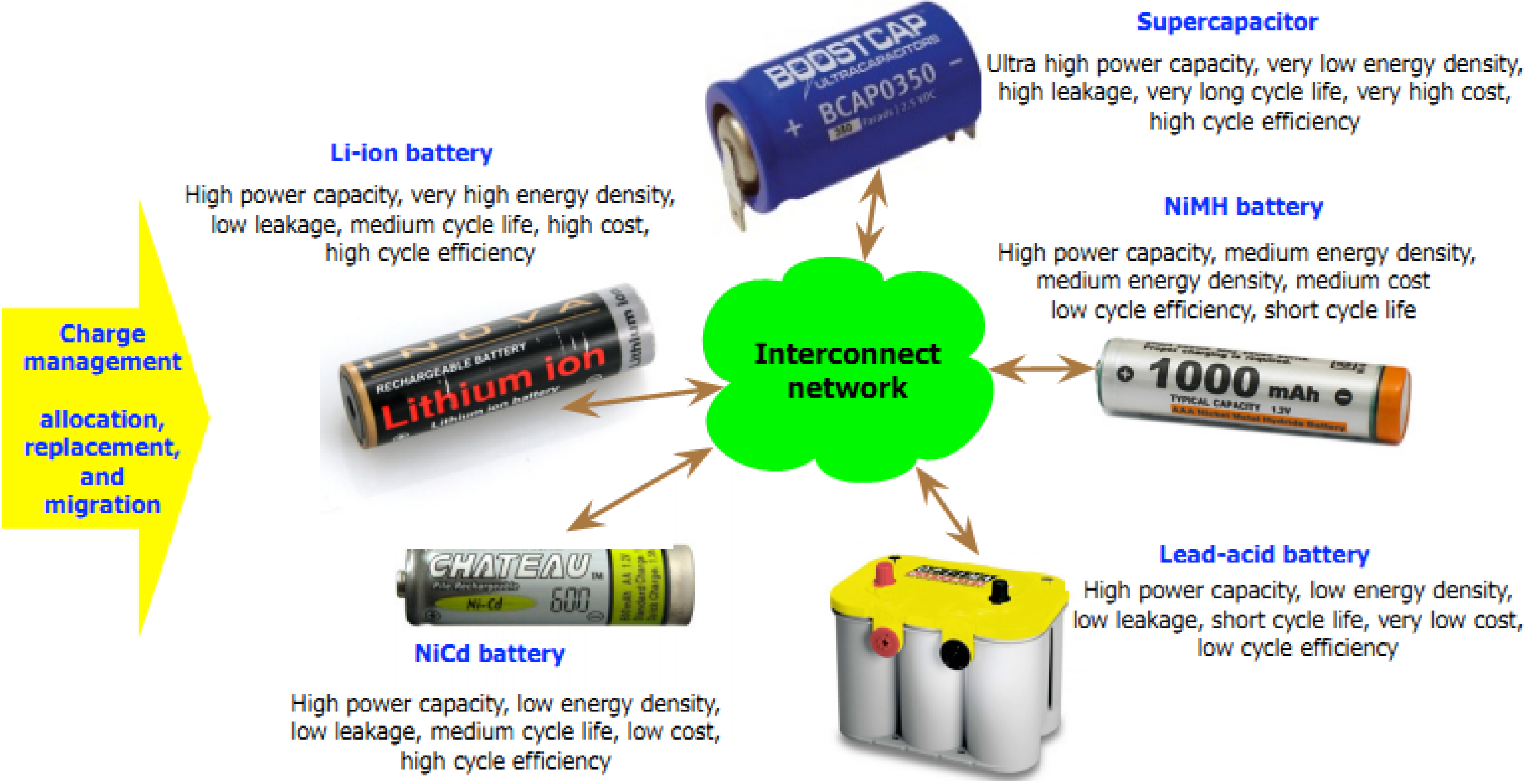
- Electrical energy storage (EES) systems store energy in various forms
- Chemical, kinetic, or potential energy to store energy that will later be converted to electricity



Electrical energy storage system

Hybrid Electrical Energy Storage System

- **Concept of HEES system**
  - **No single type of EES elements can simultaneously fulfill all the desired characteristics**
  - **Exploit the advantages of each EES element and hide its disadvantages by appropriate charge management policies**



Supercapacitor

Ultra high power capacity, very low energy density, high leakage, very long cycle life, very high cost, high cycle efficiency

Li-ion battery

High power capacity, very high energy density, low leakage, medium cycle life, high cost, high cycle efficiency

NiMH battery

High power capacity, medium energy density, medium energy density, medium cost low cycle efficiency, short cycle life

Interconnect network

Charge management

allocation, replacement, and migration

Lead-acid battery

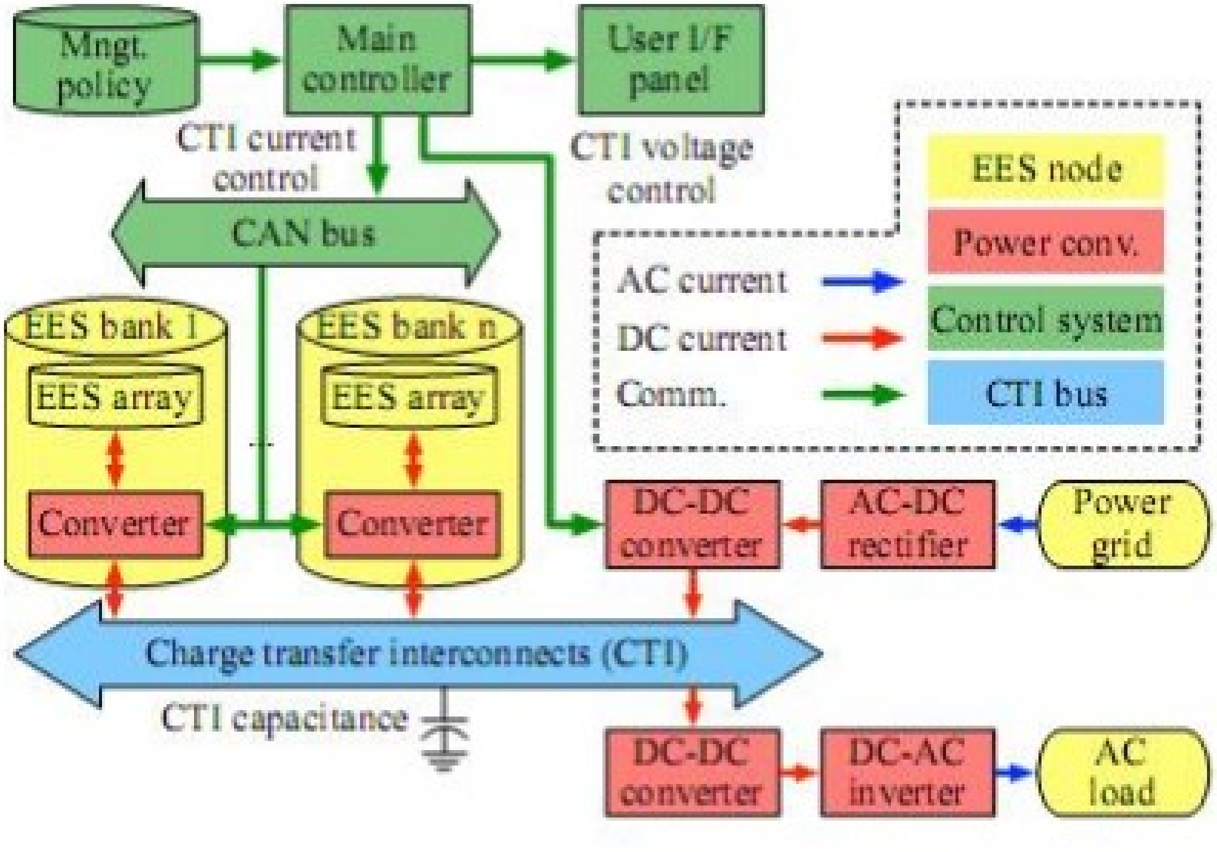
High power capacity, low energy density, low leakage, short cycle life, very low cost, low cycle efficiency

NiCd battery

High power capacity, low energy density, low leakage, medium cycle life, low cost, high cycle efficiency

Hybrid Electrical Energy Storage System

- General HEES system architecture
  - EES banks, composed of multiple, homogeneous EES elements
  - DC charge transfer interconnect (CTI)
  - Energy converters (voltage converters and chargers)

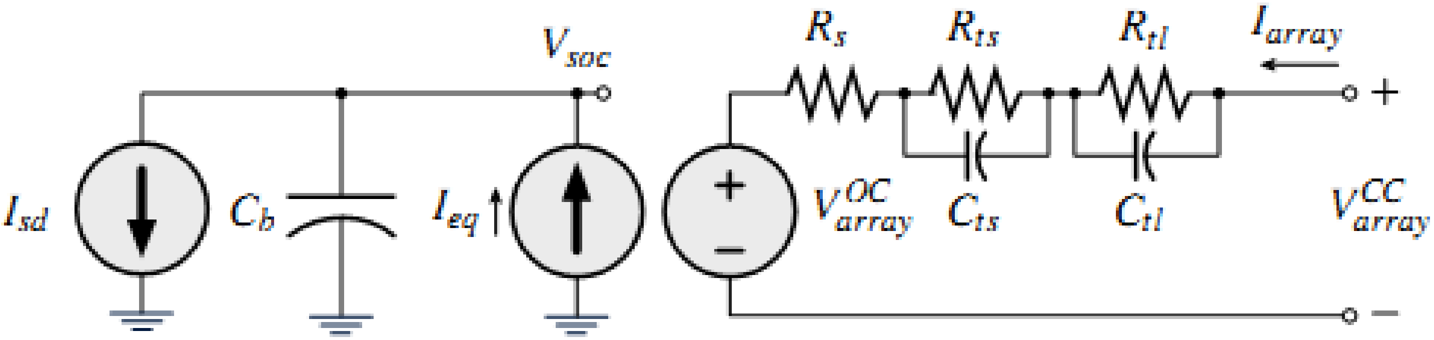


System Components and Properties

- Storage elements
  - Batteries
    - *Rate capacity effect*
    - *Internal resistance power loss*
  - Supercapacitor
    - *Self-discharge*
- Power converters
  - Voltage regulators
    - *DC-AC*
    - *DC-DC*
    - *AC-DC*
  - Current regulators (chargers)
    - *Conversion power loss*

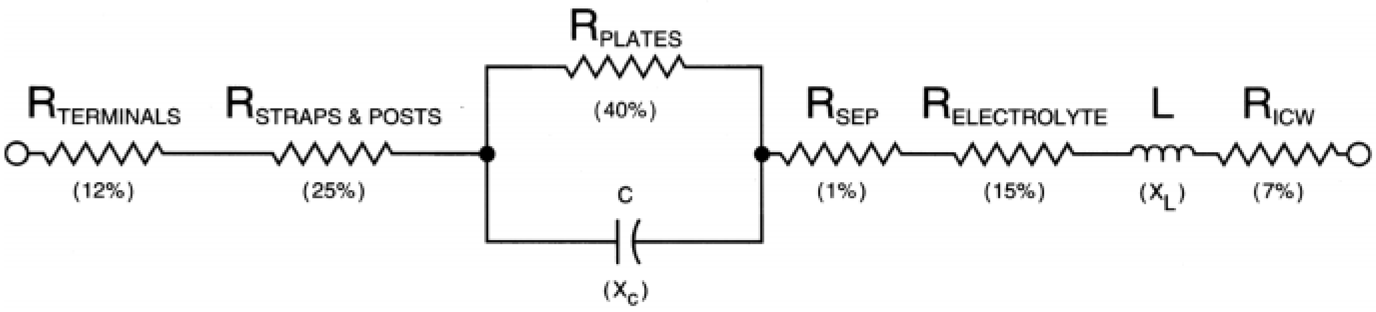
System Components and Properties

- **Rate capacity effect**
  - **Peukert's Law**
    - ***Discharging: remaining capacity of battery decreases proportional to the (discharging current)$^{\alpha 1}$, ($\alpha 1>1$)***
    - ***Charging: remaining capacity of battery increases proportional to the (charging current)$^{1/\alpha 2}$, ($\alpha 2>1$)***
    - ***Typical α value is 1.1 ~ 1.3***
  - **Avoid high charging/discharging currents, which leads to low charging/discharging efficiency**



System Components and Properties

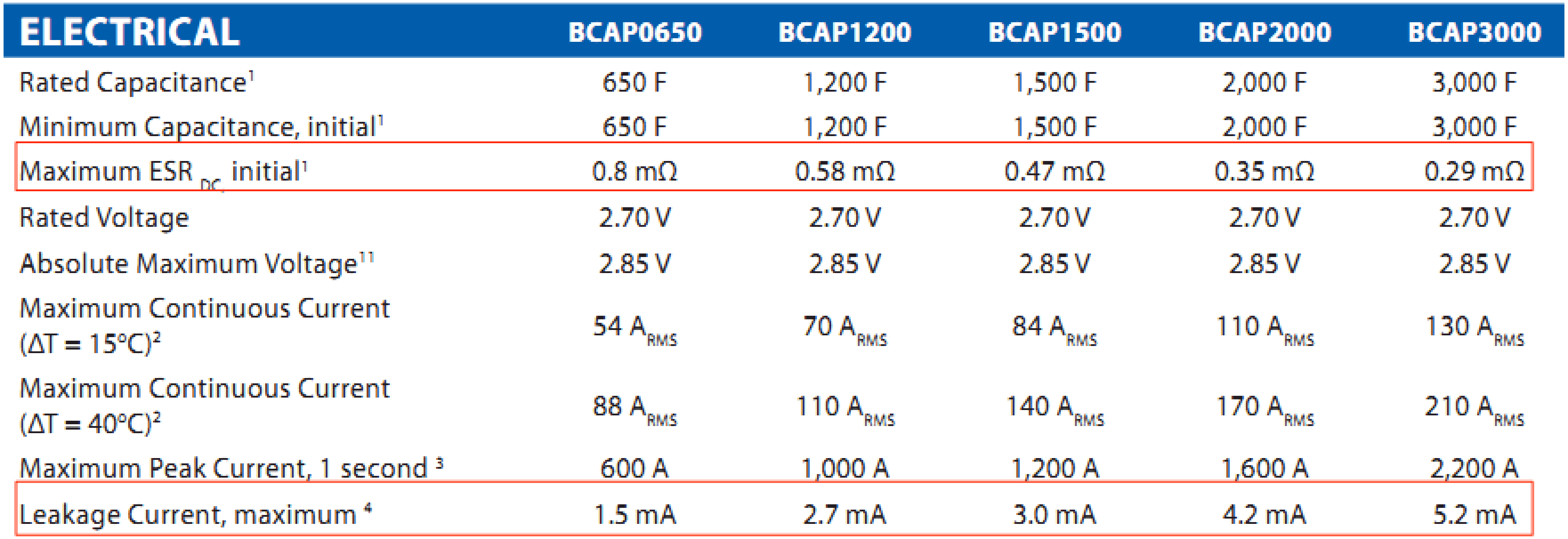
- Internal resistance power loss
  - 18650 Li-ion battery cell has less than 100 mΩ impedance at 1 KHz
  - 200 Ah Lead-acid batteries have around 1 mΩ impedance at 1 KHz
  - An FC-1 Alkaline battery has 2.9 Ω impedance at 1 KHz (www.omicron-lab.com)
  - Internal resistance depends on battery aging, temperature
- Proportional to the charging/discharging current



Battery equivalent circuit

System Components and Properties

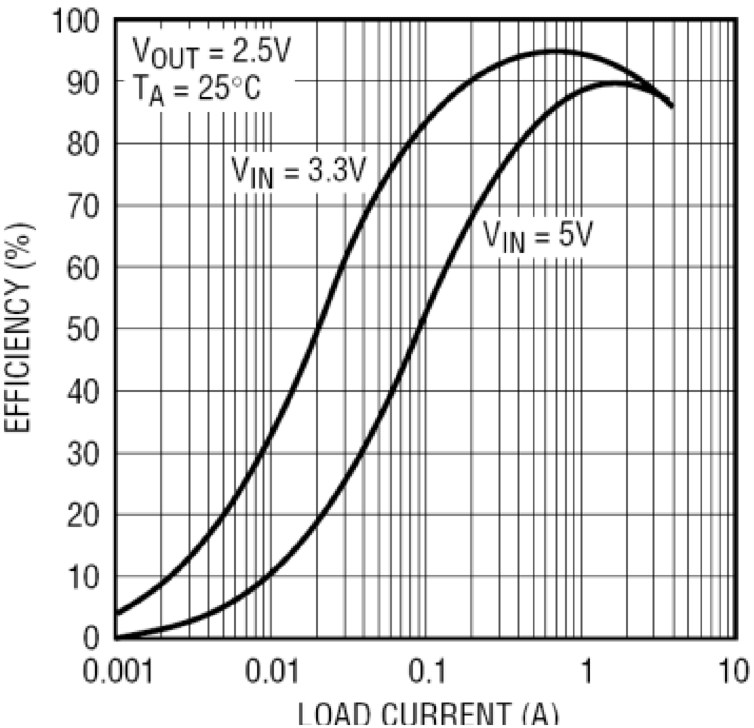
- Self-discharge
  - Supercapacitor self-discharge rate is proportional to the state of charge (SoC)
  - Avoid keeping the Supercapacitor having high SoC

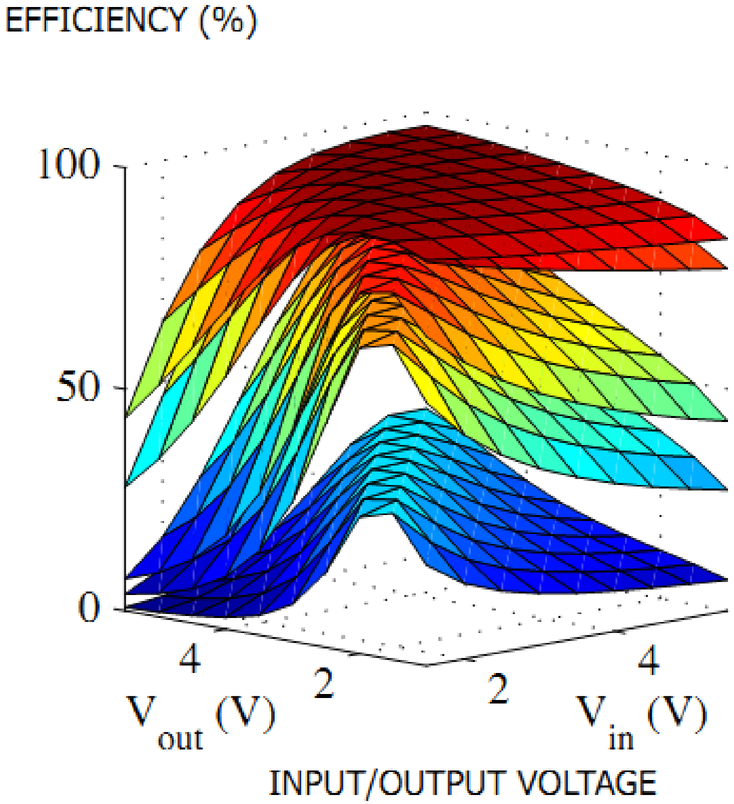


ELECTRICAL	BCAP0650	BCAP1200	BCAP1500	BCAP2000	BCAP3000
Rated Capacitance[1]	650 F	1,200 F	1,500 F	2,000 F	3,000 F
Minimum Capacitance, initial[1]	650 F	1,200 F	1,500 F	2,000 F	3,000 F
Maximum ESR_{DC} initial[1]	0.8 mΩ	0.58 mΩ	0.47 mΩ	0.35 mΩ	0.29 mΩ
Rated Voltage	2.70 V	2.70 V	2.70 V	2.70 V	2.70 V
Absolute Maximum Voltage[11]	2.85 V	2.85 V	2.85 V	2.85 V	2.85 V
Maximum Continuous Current (ΔT = 15°C)[2]	$54\ A_{RMS}$	$70\ A_{RMS}$	$84\ A_{RMS}$	$110\ A_{RMS}$	$130\ A_{RMS}$
Maximum Continuous Current (ΔT = 40°C)[2]	$88\ A_{RMS}$	$110\ A_{RMS}$	$140\ A_{RMS}$	$170\ A_{RMS}$	$210\ A_{RMS}$
Maximum Peak Current, 1 second [3]	600 A	1,000 A	1,200 A	1,600 A	2,200 A
Leakage Current, maximum [4]	1.5 mA	2.7 mA	3.0 mA	4.2 mA	5.2 mA

System Components and Properties

- Conversion power loss
  - Depends on the load current, input voltage and output voltage
  - Achieves maximum efficiency when $V_{in} \approx V_{out}$





HEES System Charge Management

- Charge Allocation
  - Maximize the total energy pushed into the HEES system for a given energy generation profile.
- Charge Replacement
  - Minimize the total energy drawn from the HEES system for a given load demand profile
- Charge Migration (CM)
  - Move energy between multiple EES banks
  - Motivation:
    - *Alleviate the self-discharge in supercapacitor*
    - *Ensure the energy availability of HEES system*
    - *Improve the efficiency of subsequent operations: such as allocation or replacement*

Charge Migration Scheduling

- Definition of a Charge Migration Task
  - Source bank(s)
  - Destination bank(s)
  - Target energy to push into all destination bank(s)
  - Starting time
  - Deadline T_D
- Perform a Charge Migration Task
  - The HEES controller needs to determine three sets of parameters:
    - *CTI voltage level setting – the voltage level that is maintained in CTI during the CM process;*
    - *Charging/discharging currents of all bank(s) involved;*
    - *CTI usage time – the amount of time that is assigned to finish this CM task.*

CM Scheduling vs. CPU Scheduling

Starting time, deadline	**Starting time, deadline**
Target energy	**Workload of a request**
CTI voltage and operation currents	**CPU voltage**
CTI usage time (occupying one CTI during CM process)	**CPU time** (occupying a CPU thread when processed)
Minimize total energy drawn from source bank(s)	**Minimize the total energy consumption**

CM Scheduling vs. CPU Scheduling cont'd

- **CM scheduling:** how to set the operating currents, CTI voltages and assign tasks to CTI to finish all charge migration tasks with limited number of CTIs, in order to minimize the total energy drawn from the source EES banks, under a deadline constraint.
- Differences due to HEES characteristics:
  - Power consumption is *no longer* a simple polynomial function of the CPU voltage;
  - Self-discharge and rate capacity effect in EES banks;
  - Power loss in converters;
  - Charge migration tasks can be merged.
- New solution method needs to be developed accordingly.

CM Scheduling vs. CPU Scheduling cont’d

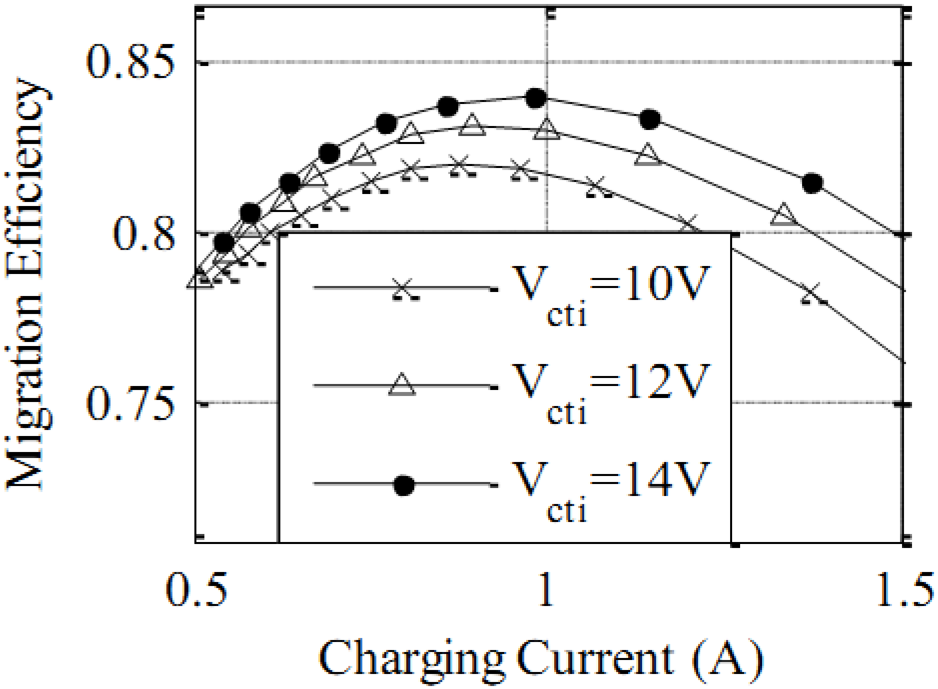
- Problem Statement
  - Given: a set of CM tasks, and specifications of the HEES system.
  - Find:
    - *updated set of CM tasks (after merging);*
    - *CTI usage time of each CM task;*
    - *operating currents: charging currents of destination bank(s), and discharging currents of source bank(s);*
    - *voltage settings of all CTIs during the CM process.*
  - Minimize: total energy drawn from all source bank(s).
  - Subject to:
    - *Finish all charge migration task:*
      - *push target amount of energy into corresponding destination banks;*
    - *The deadline constraint is met.*

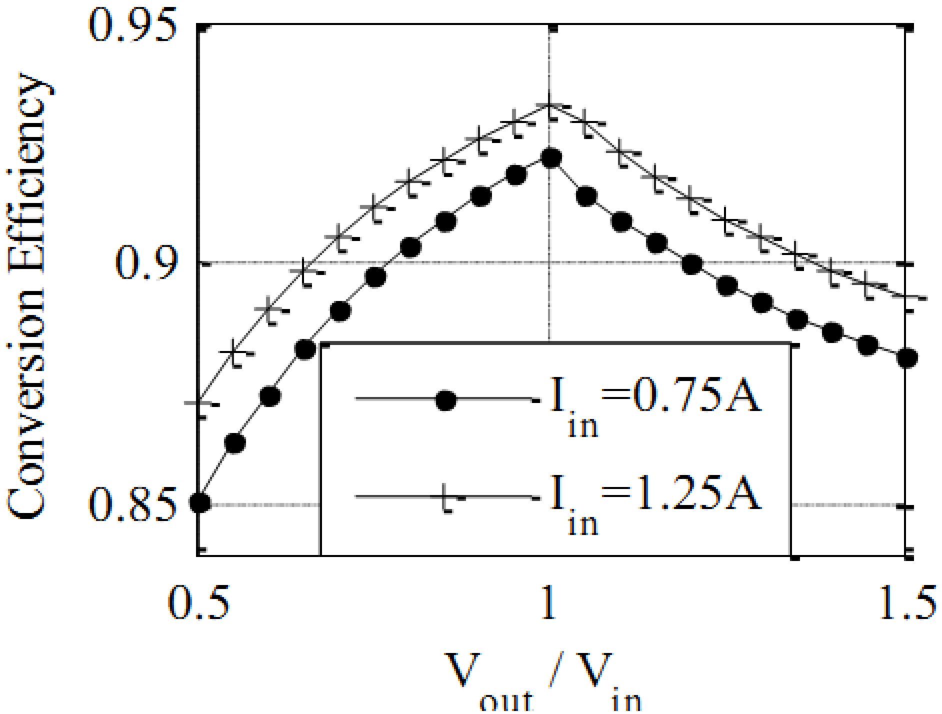
Solution Method – Two Facts

- **Define charge migration efficiency**

$$\eta = \frac{\text{target energy pushed into all destination bank(s)}}{\text{energy drawn from all source bank(s)}}$$

- **The efficiency depends on**
- **1) operating current** **2) CTI voltage**





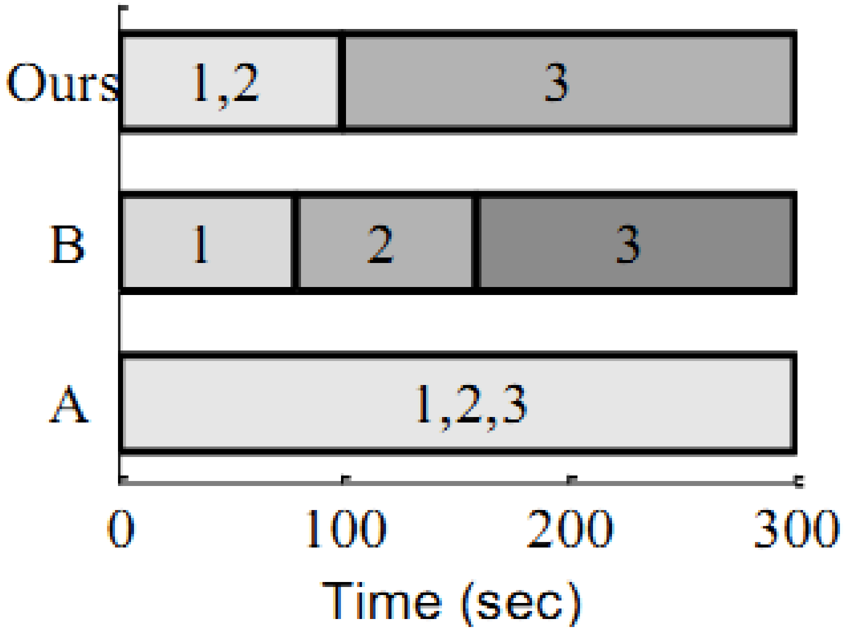
Solution Method – Two Facts cont'd

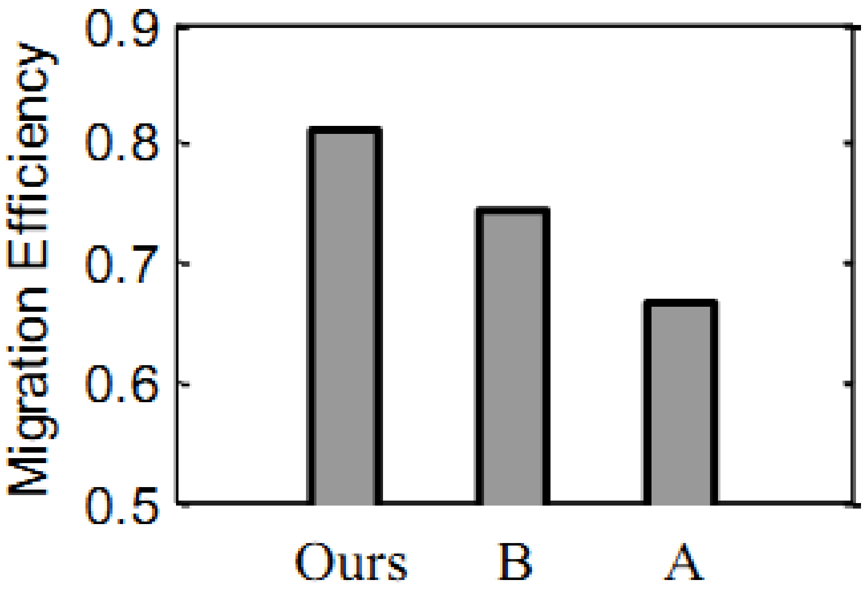
- Fact 1: there exists an optimal setting of the operating currents.
  - The optimal operating currents results in the *optimal CTI usage time*, t^*_{CTI}
  - We focus on the case that, $t^*_{CTI} > T_D$
  - Merging two CM tasks allows each have longer CTI usage time

- Fact 2: CTI voltage affects migration efficiency.
  - High conversion efficiency is achieved when input voltage is closed to output voltage
  - Merging two tasks that have different CTI voltages may degrade the migration efficiency
- We propose the algorithm based on these two facts.

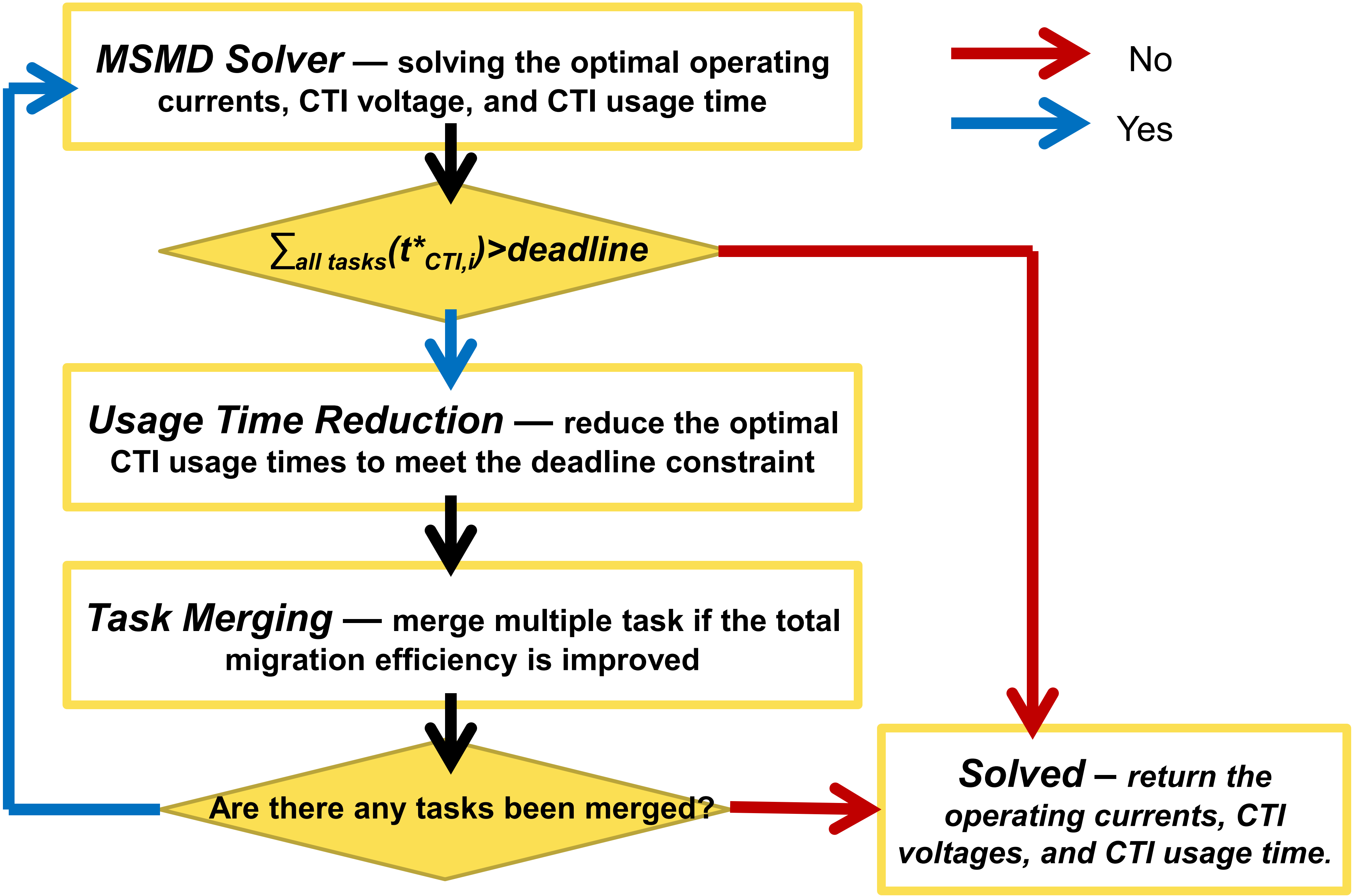
Solution Method – An example

- **Three migration tasks:**
  - **Target energies = (1000 *J*, 1000 *J*, 750 *J*).**
  - **Source bank OCVs = (15 *V*, 15 *V*, 6 *V*).**
  - **Destination bank OCVs = (12 *V*, 12 *V*, 6 *V*).**
  - **Stating time = 0; Deadline = 300 *sec.***
- **Schedule:**
- **(A) all merged; (B) all separated; and the (Proposed).**





Solution Method – Proposed Algorithm



MSMD Solver **— solving the optimal operating currents, CTI voltage, and CTI usage time**

$\sum_{\text{all tasks}}(t^*_{CTI,i})>deadline$

Usage Time Reduction **— reduce the optimal CTI usage times to meet the deadline constraint**

Task Merging **— merge multiple task if the total migration efficiency is improved**

Are there any tasks been merged?

Solved ***– return the operating currents, CTI voltages, and CTI usage time.***

Solution Method – Proposed Algorithm

- **MSMD Solver[†], for each task**
  - **Solve the multiple-source multiple destination charge migration problem <u>without</u> considering the deadline constraint**
  - **It finds the optimal migration efficiency**
  - **Return optimal operating currents, CTI voltages $V_{CTI,i}$, and CTI usage times $t^*_{CTI,i}$, i is the task index.**
- **If Deadline constraint is met, i.e., $\sum_{all\ tasks}(t^*_{CTI,i}) < deadline$**
  - **Assign $t^*_{CTI,I}$ time for each task**
  - **Problem is solved**
- **Else**
  - **perform *Usage Time Reduction (UTR)* algorithm**

[†] Y. Wan, Q. Xie, X. Lin, Y. Kim, N. Chang, and M. Pedram, DATE 2012.

Solution Method – Proposed Algorithm

- **Usage Time Reduction**
  - Set a small time step, Δt
  - For each task, compute the total energy drawn:
    - *With CTI usage time* $t_{CTI,i}$, *denoted by* $E_{drawn,i}(t_{CTI,i})$
    - *With reduced CTI usage time* $t_{CTI,i} - \Delta t$, *denoted by* $E_{drawn,i}(t_{CTI,i} - \Delta t)$
    - *Compute the energy increase* $\Delta E_{drawn,i} = E_{drawn,i}(t_{CTI,i} - \Delta t) - E_{drawn,i}(t_{CTI,i})$
  - Find the task that causes the minimum energy increase, and reduce the CTI usage time of that task by Δt
  - Repeat this process until the deadline constraint is met
- **Algorithm converges after** $\dfrac{\sum_{\text{all tasks}} t^*_{CTI,i} - \text{deadline}}{\Delta t}$ **steps**
- **Adaptive time step** Δt**, from 10sec ~ 100 sec**

Solution Method – Proposed Algorithm

- **Merged *N* tasks**
  - **start the migration process simultaneously**
  - **use the same CTI**
  - $t_{CTI} = t_{CTI,1} + t_{CTI,2} + \ldots + t_{CTI,n}$
- **Larger efficiency degradation if we merge multiple tasks having very different CTI voltages**
- **Task Merging**
  - **Check all tasks, find *K* pairs of tasks have similar CTI voltages**
  - **Merge the tasks, calculate the migration efficiency**
  - **If the migration efficiency improved**
    - ***Commit the merging***
  - **Else**
    - ***Undo the merging***
  - **Terminated after checking *K* pairs**
    - ***K is set as 5, considering the solution quality and run time***

Simulation Results

- **Migration improves total replacement efficiency**
  - **High efficiency bank efficiency, e.g., supercapacitor, >95%†**
  - **Low efficiency bank efficiency, e.g., battery, ~70%†**
  - **Typical migration efficiency: 80% ~ 85%††**
- **Electricity consumption profile of typical American household**
- **Simulation setup:**
  - **Setup A:**
    - ***Average daily power consumption 0.17 Kw***
    - ***Powered by a 20-bank EES system, 2 CTIs***
    - ***Migrate 0.3 Kwh energy during off-peak period to high efficiency bank for peak period usage***
  - **Setup B:**
    - ***Average daily power consumption 0.33 Kw***
    - ***Powered by a 40-bank EES system, 4 CTIs***
    - ***Migrate 0.6 Kwh energy during off-peak period to high efficiency bank for peak period usage***

†M Pedra, N. Chang, Y. Kim, and Y. Wang, ISLPED 2010.

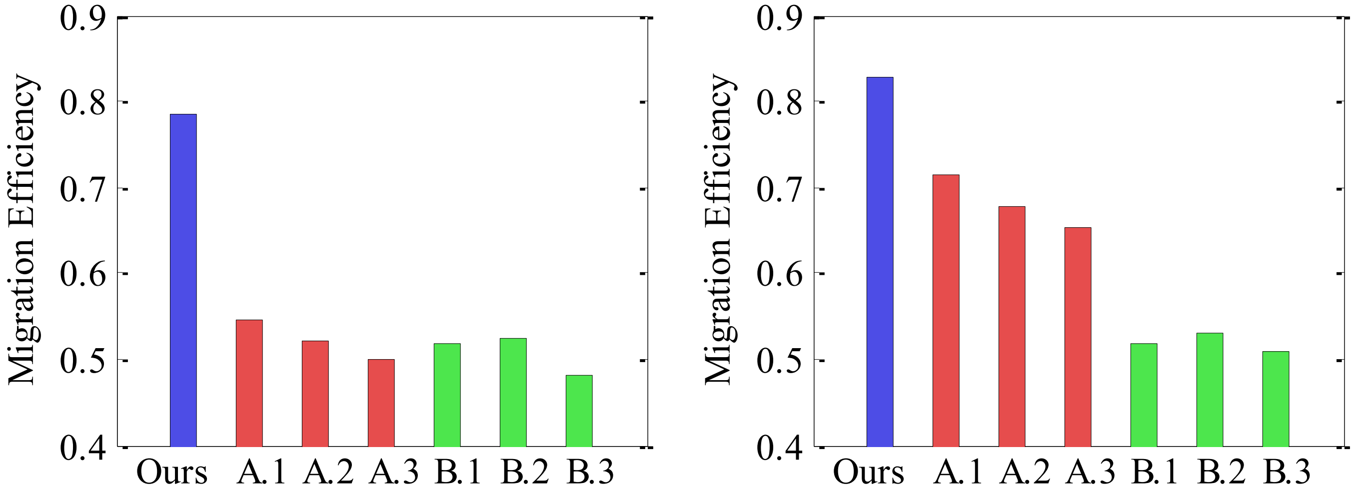
†† Y. Wan, Q. Xie, X. Lin, Y. Kim, N. Chang, and M. Pedram, DATE 2012.

Simulation Results

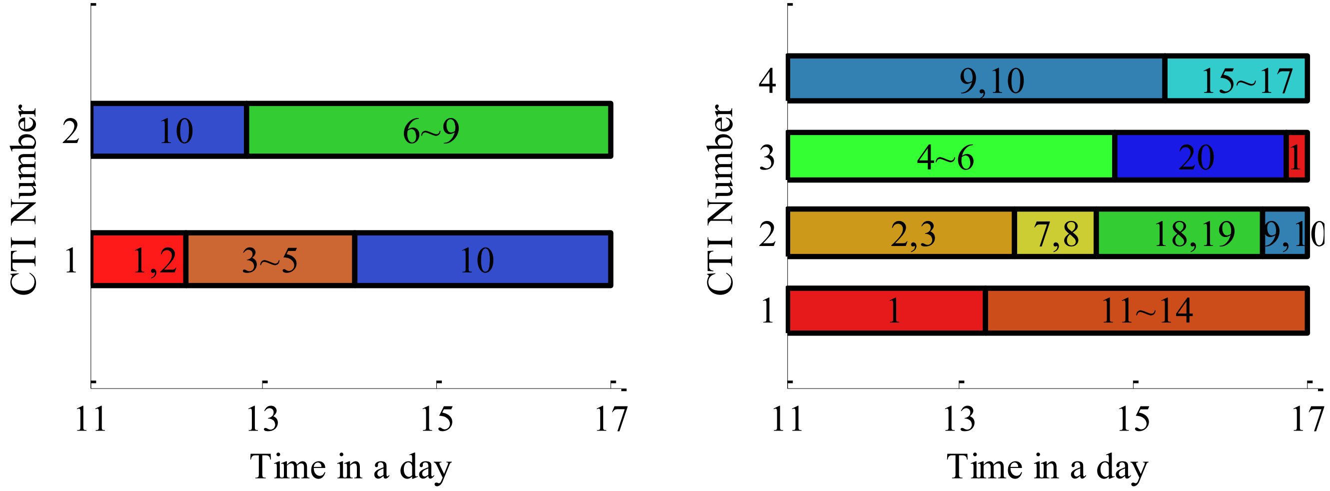
- **Baseline:**
  - **A – merging based method: merge initial tasks to form CTI numbers of merged tasks:**
    - ***1. according to OCVs***
    - ***2. according to target energy***
    - ***3. random pick***
  - **B – clustering based method: cluster initial tasks to CTI numbers of groups, assign each group to a CTI, and perform task one by one in a group**
    - ***1. according to the OCVs***
    - ***2. according to the target energy***
    - ***3. random pick***

Simulation Results

- **Simulation results demonstrated 11.4 ~ 32.2% improvements on charge migration efficiency**



- **Schedule obtained using proposed algorithm**



Conclusion

- HEES is a promising approach to leverage EES systems efficiency
- First paper to introduce charge migration scheduling (CSM) problem for a HEES system
- CSM problem is similar to CPU scheduling problem, but has it own special characteristics
- We divide the CSM problem into several sub-problem: MSMD migration problem, usage time reduction problem, and task merging problem
- Propose an effective and algorithm heuristic to solve each sub-problem individually and combine them together
- The proposed algorithm outperforms the baseline setups by 11.4 ~ 32.2%.