Power Fluctuation Minimization During Behavioral Synthesis using ILP-Based Datapath Scheduling

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Outline of the Talk

- Introduction
- Related Work
- Target Architecture
- Proposed Datapath Scheduling Scheme
- Experimental Results
- Conclusions

Why Transience / Fluctuation Minimization ?

- To reduce power supply noise
- To reduce cross-talk and electromagnetic noise
- To increase battery efficiency
- To increase reliability

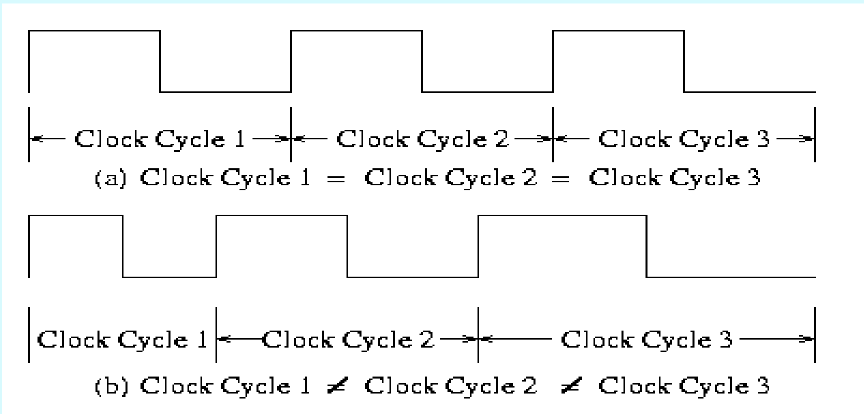
Related work
(Energy efficient scheduling using voltage reduction)

- Chang and Pedram 1997 – Dynamic programming
- Johnson and Roy 1997 – ILP based MOVER algorithm using multiple supply voltages
- Lin, Hwang and Wu 1997 – ILP and heuristic for variable voltages (VV) and multicycling (MC)
- Mohanty and Ranganathan 2003 – Heuristic based using multiple supply voltage and dynamic clocking

Related work
(Peak Power efficient scheduling)

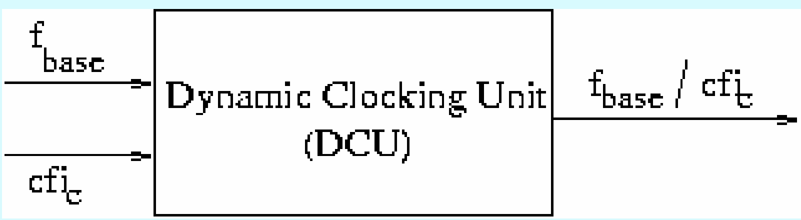
- Martin and Knight 1996 – Simultaneous assignment and scheduling
- Raghunathan, Ravi and Raghunathan 2001 – data monitor operations in VHDL
- Shiue 2000 – ILP based and modified force direct scheduling for peak power minimization
- Shiue and Chakrabarti 2000 - ILP model to minimize peak power and area for single voltage

Dynamic Frequency?



Single Frequency

Dynamic Frequency



DCU uses clock divider strategy

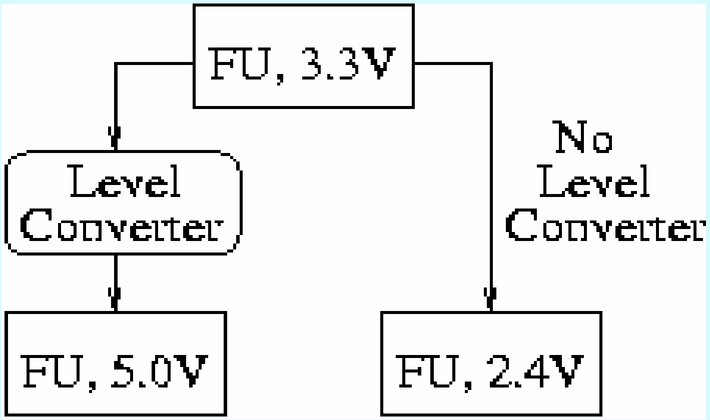
More details:

- Ranganathan, et.al.
- Byrnjolfson and Zilic

What is our approach?

Adjust the frequency and reduce the supply voltage in a coordinated manner to reduce various forms of dynamic power while maintaining performance, through datapath scheduling during behavioral synthesis.

Target Architecture



- Each functional unit has one register and one multiplexer.
- The register and the multiplexor operate at the same voltage level as that of the functional units.
- Level converters are used when a low-voltage functional unit is driving a high-voltage functional unit.
- Operational delay of a FU : $(d_{FU} + d_{Mux} + d_{Reg} + d_{Conv})$.

Assumption

- Time for voltage conversion is equal to time for frequency change.
- Controller has a storage unit to store the cycle frequency index (cfi_c).

Frequency Calculation from Delay Model

- Let d_c be the delay of a control step c. Then, the base frequency (f_{base}), the cycle frequency index (cfi_c), and the cycle frequency f_c are

$$cfi_c = \left\lceil \frac{\lfloor d_c / d_c^{min} \rfloor}{2^n} \right\rceil 2^n$$

$$f_c = \frac{f_{base}}{cfi_c}$$

$$f_{base} = \left\lfloor \frac{\lfloor 1 / d_c^{min} \rfloor}{2^{L_f}} \right\rfloor 2^{L_f}$$

- Where, d_c^{min} = minimum (d_c) for all c, L_f = number of allowable frequency levels, n is an integer chosen such that cfi_c is closest integer greater than or equal to $\lceil d_c / d_c^{min} \rceil$
- The scaled down operating frequency of a functional unit can also be calculated using the same formulae if d_c is replaced with the operational delay of a functional unit.

MPG Minimization

- Aim: to provide ILP-based model to minimize mean gradient of the power profile of the DFG over all control steps.
- Two different design options: MVDFC and MVMC
- The mean power gradient (MPG) is modeled as mean of the cycle-to-cycle power gradient.
- MPG serves as a measure of the total power fluctuation of the DFG over all the control steps.
- MPG is a *non-linear* function due to presence of absolute function.
- Non-linear programming may be more suitable, but will result in large space and time complexity.

MPG Minimization: Modeling

Background Material

- For a set of n observations, x_1, x_2, x_3, …..x_n, from a given distribution, the sample mean (which is an unbiased estimator for the population mean, μ) is $m = 1/n \Sigma_i x_i$.
- The observation-to-observation gradient is defined as $\Delta x_i = |x_i - x_{i-1}|$.
- The mean gradient of the observations is given by $MG = 1/n \Sigma_i |x_i - x_{i-1}|$.
- We model the power gradient for control step c, PG_c, as the absolute difference of cycle power P_c from the previous cycle power P_{c-1}.
- The mean power gradient MPG is the mean of the PG_c over all control steps.

MPG Minimization: Modeling …

- Power gradient for a cycle c, PG, defined as the absolute difference of cycle power from previous cycle power.

  $PG_c = |P_c - P_{c-1}|_{(\text{for all } c = 2 \text{ to } N)}$

- Peak of the power gradients PG_p: Maximum of power gradients of all control steps.

  $PG_p = \text{maximum}\ (PG_c) = |P_c - P_{c-1}|_{(\text{for all } c = 2 \text{ to } N)}$

- Mean power gradient MPG: Mean of the power gradients of all control steps.

$$\begin{aligned} MPG &= \frac{1}{N-1} \sum_{c=2}^{N} PG_c \\ &= \frac{1}{N-1} \sum_{c=2}^{N} |P_c - P_{c-1}| \end{aligned}$$

- NOTE: The complete description is obtained after inserting the capacitance, switching, etc. parameters as done in the previous chapters.

MPG Minimization: ILP Formulation

MVDFC Design Scenario

- Objective Function: Minimize the MPG for the whole DFG over all the control steps.

$$\text{Minimize}: \quad \frac{1}{N-1} \sum_{c=2}^{N} |P_c - P_{c-1}|$$

The absolute is replaced with sum and the appropriate constraints.

$$\text{Minimize}: \quad \frac{1}{N-1} \sum_{c=2}^{N} (P_c + P_{c-1})$$
$$\text{Subject to}: \quad \text{Power gradient constraints}$$

After simplification

$$\text{Minimize}: \quad \frac{2}{N-1} \sum_{c=2}^{N-1} P_c + P_1 + P_N$$
$$\text{Subject to}: \quad \text{Power gradient constraints}$$

$$\text{Minimize}: \left(\frac{2}{N-1}\right) \sum_{c=2}^{N-1} \sum_{i \in F_{k,v}} \sum_{v} \sum_{f} x_{i,c,v,f} P(C_{swi}, v, f) + \sum_{i \in F_{k,v}} \sum_{v} \sum_{f} x_{i,1,v,f} P(C_{swi}, v, f)$$
$$+ \sum_{i \in F_{k,v}} \sum_{v} \sum_{f} x_{i,N,v,f} P(C_{swi}, v, f)$$
$$\text{Subject to}: \quad \text{Power gradient constraints}$$

MPG Minimization: ILP Formulation …

- The Uniqueness Constraints, Precedence Constraints, Resource Constraints, and Frequency Constraints are also formulated.
- Power Gradient Constraints : To eliminate the non-linearity introduced due to the absolute function introduced as, for all c, 2<= c <= N,

$$\sum_{i \in F_{k,v}} \sum_{v} \sum_{f} x_{i,c,v,f} * P(C_{sw\,i}, v, f) - \sum_{i \in F_{k,v}} \sum_{v} \sum_{f} x_{i,c-1,v,f} * P(C_{sw\,i}, v, f) \leq PG_p$$

- NOTE: The unknown PG_p is added to the objective function and minimized alongwith it.

MPG Minimization: ILP Formulation …

MVMC Design Scenario

- Objective Function: Following the same steps as in the MVDFC case in terms of decision variables we write,

$$
\begin{aligned}
\text{Minimize :} \quad & \left(\frac{2}{N-1}\right) \sum_{l=2}^{N-1} \sum_{i \in F_{k,v}} \sum_{v} y_{i,v,l,(l+L_{i,v}-1)} P(C_{swi}, v, f) \\
& + \sum_{i \in F_{k,v}} \sum_{v} \sum_{f} y_{i,v,1,1} P(C_{swi}, v, f) \\
& + \sum_{i \in F_{k,v}} \sum_{v} \sum_{f} y_{i,v,N,N} P(C_{swi}, v, f) \\
\text{Subject to :} \quad & \text{Power gradient constraints}
\end{aligned}
$$

- The Uniqueness Constraints, Precedence Constraints, and Resource Constraints, and are the same as before.
- Power Gradient Constraints : To eliminate the non-linearity introduced due to the absolute function introduced as, for all l, 2<= l <= N,

$$
\begin{aligned}
& \sum_{i \in F_{k,v}} \sum_{v} y_{i,v,l,(l+L_{i,v}-1)} * P(C_{swi}, v, f_{clk}) \\
& - \sum_{i \in F_{k,v}} \sum_{v} y_{i,v,(l-1),(l+L_{i,v}-2)} * P(C_{swi}, v, f_{clk}) \quad \leq \quad PG_p
\end{aligned}
$$

MPG Minimization: Results

Notations used in describing the results

MPG_S	: the mean power gradient (in mW) for SVSF operation
MPG_D	: the mean power gradient (in mW) for MVDFC operation
MPG_M	: the mean power gradient (in mW) for MVMC operation
P_{pS}	: the peak power consumption (in mW) for SVSF operation
P_{pD}	: the peak power consumption (in mW) for MVDFC operation
P_{pM}	: the peak power consumption (in mW) for MVMC operation
P_{aS}	: the average power consumption (in mW) for SVSF operation
P_{aD}	: the average power consumption (in mW) for MVDFC operation
P_{aM}	: the average power consumption (in mW) for MVMC operation
T_S	: the critical path delay (in ns) for SVSF operation
T_D	: the critical path delay (in ns) for MVDFC operation
T_M	: the critical path delay (in ns) for MVMC operation
PDP_S	: the power delay product (in nJ) for SVSF operation
PDP_D	: the power delay product (in nJ) for MVDFC operation ($= P_{aD} * T_D$)
PDP_M	: the power delay product (in nJ) for MVMC operation ($= P_{aM} * T_M$)
ΔP_{pD}	: percentage peak power reduction for MVDFC operation ($= \frac{(P_{pS} - P_{pD})}{P_{pS}} * 100$)
ΔP_{pM}	: percentage peak power reduction for MVMC operation ($= \frac{(P_{pS} - P_{pM})}{P_{pS}} * 100$)
ΔPDP_D	: percentage PDP reduction for MVDFC operation ($= \frac{(PDP_S - PDP_D)}{PDP_S} * 100$)
ΔPDP_M	: percentage PDP reduction for MVMC operation ($= \frac{(PDP_S - PDP_M)}{PDP_S} * 100$)

Number of Voltage Levels = 2 (2.4V and 3.3V)
Number of Frequency Levels = 3

MPG Minimization: Results …

	MPG Estimates (mW)					Peak Power (%)		Average Power (%)		PDP (%)	
	MPG_S	MPG_D	ΔMPG_D	MPG_M	ΔMPG_M	ΔP_{p_D}	ΔP_{p_M}	ΔP_{a_D}	ΔP_{a_M}	ΔPDP_D	ΔPDP_M
1	2	3	4	5	6	7	8	9	10	11	12
e	8.42	2.11	74.94	5.96	29.22	73.61	0	72.80	22.91	54.58	0
x	8.42	2.11	74.94	5.97	29.10	73.61	20.83	72.80	21.56	54.58	0
p	8.42	2.06	75.53	2.17	74.23	73.61	47.22	72.12	36.68	53.56	0
f	4.26	1.11	73.94	3.53	17.14	73.61	0	73.47	15.65	52.24	0
i	6.42	1.72	73.21	4.54	29.28	73.61	47.22	73.47	12.93	52.24	0
r	4.26	1.08	74.65	3.00	29.58	73.61	45.90	72.9	24.72	51.22	0
i	8.56	2.92	65.89	4.41	48.48	65.74	31.48	68.33	18.78	52.24	0
i	8.56	2.24	73.83	2.71	68.34	73.61	47.22	72.96	30.13	59.60	0
r	4.26	1.08	74.65	1.27	70.19	73.61	47.22	72.34	34.13	55.71	0
h	8.49	2.85	66.43	3.53	58.42	65.74	31.48	69.26	32.55	46.09	0
a	8.56	2.19	74.42	4.52	47.20	73.60	47.20	73.18	30.14	53.06	0
l	4.26	1.06	75.12	1.63	61.74	73.33	45.35	72.71	24.64	50.85	0
a	5.66	1.46	74.20	2.92	48.41	73.59	0	74.00	22.00	59.40	0
r	5.66	1.46	74.20	3.00	47.00	73.59	0	74.00	20.44	59.40	0
f	5.66	1.40	75.27	2.97	47.53	73.02	0	71.33	18.89	57.20	0
Average Results			**73.42**		**47.10**	**72.50**	**27.41**	**72.38**	**24.41**	**54.13**	**0**

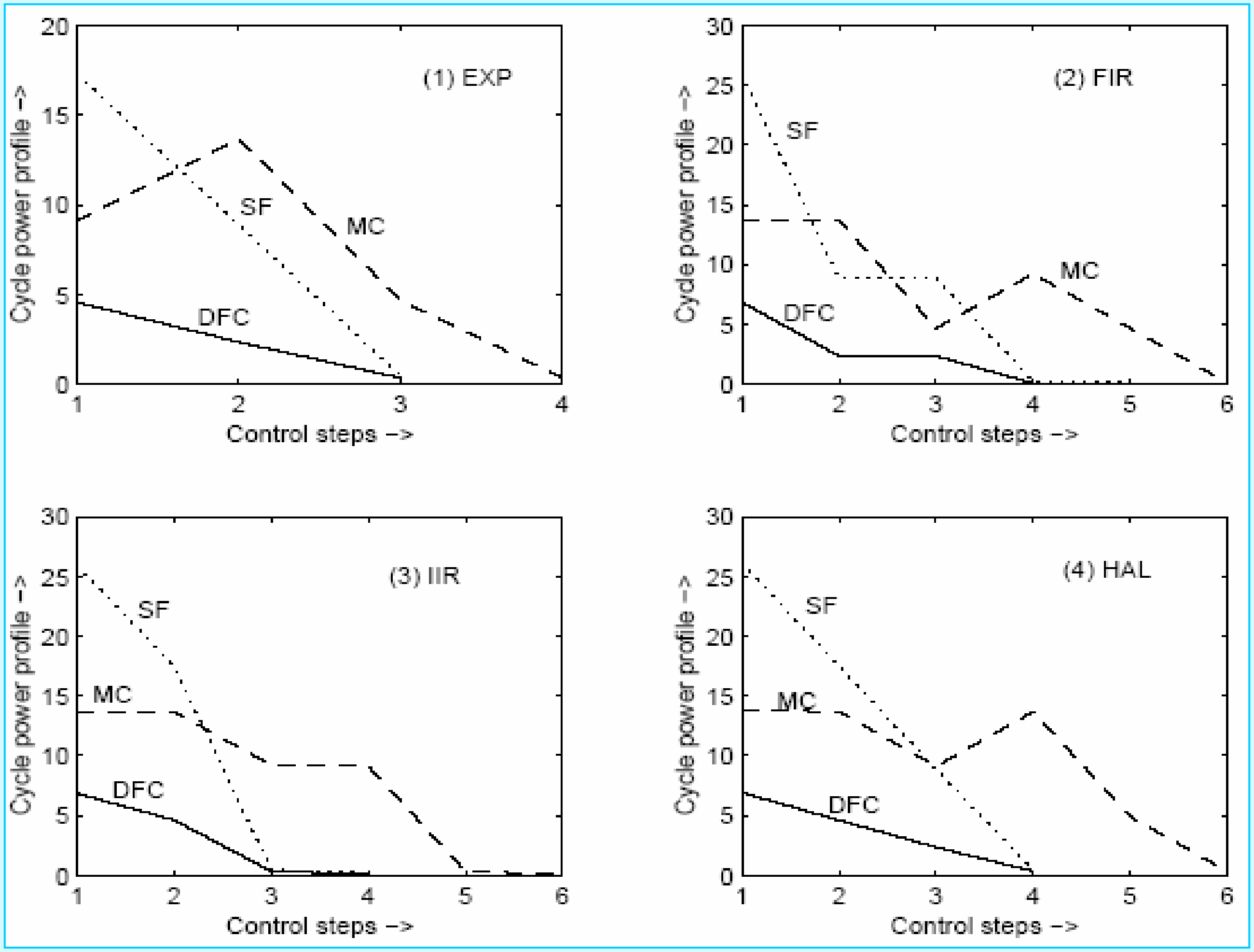
R1: Multipliers (2 at 2.4V and 1 at 3.3 V) ALUs (1 at 2.4V and 1 at 3.3V)
R2: Multipliers (3 at 2.4V) and ALUs (1 at 2.4V and 1 at 3.3V)
R3: Multipliers (2 at 2.4V) and ALUs (2 at 3.3V)

MPG Minimization: Results …

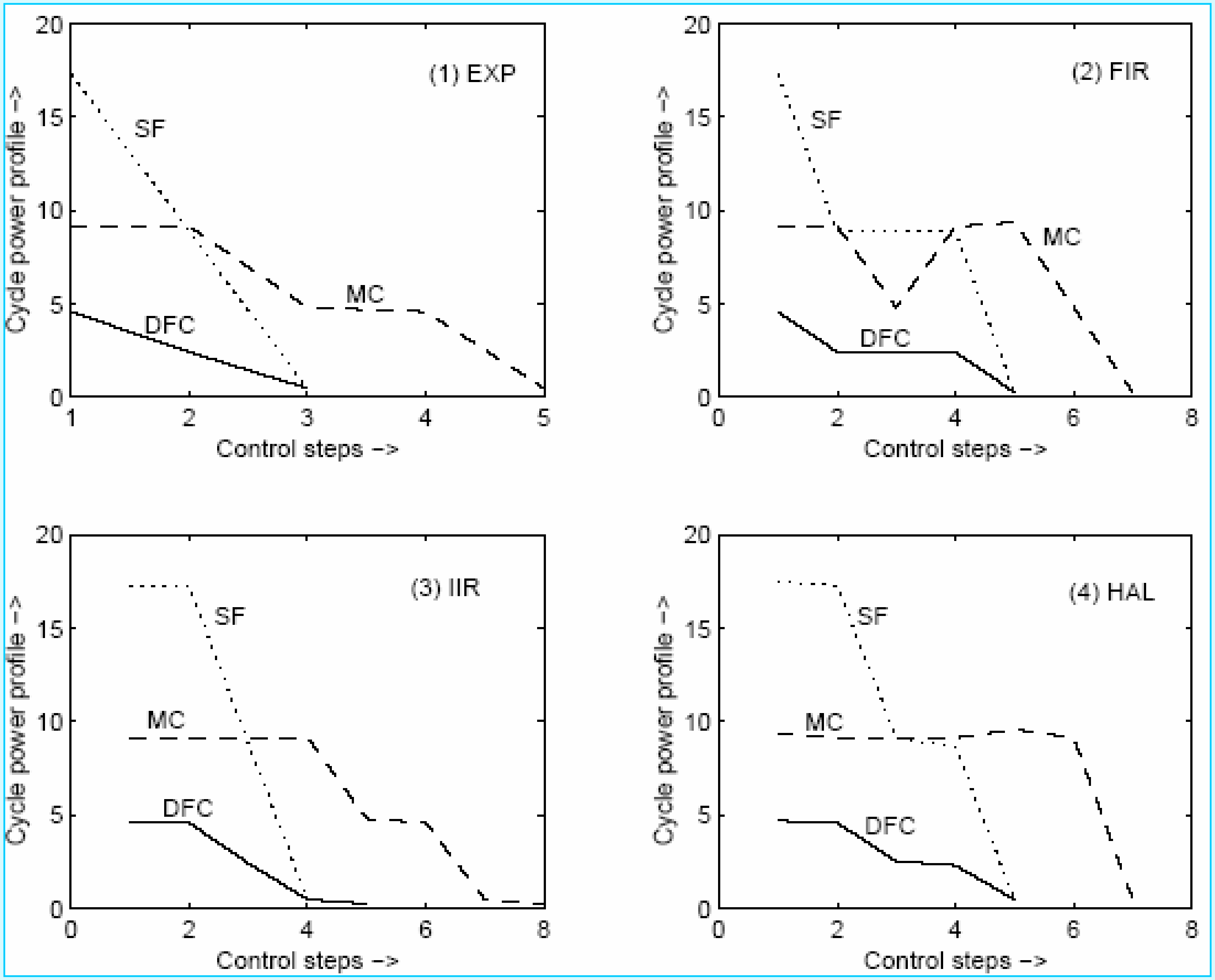
MVDFC Vs MVMC % Reduction

Power	MVDFC	MVMC
Peak Power	72.50	27.41
MPG	73.42	47.10
Average Power	72.38	24.41
Energy (PDP)	54.13	0.0

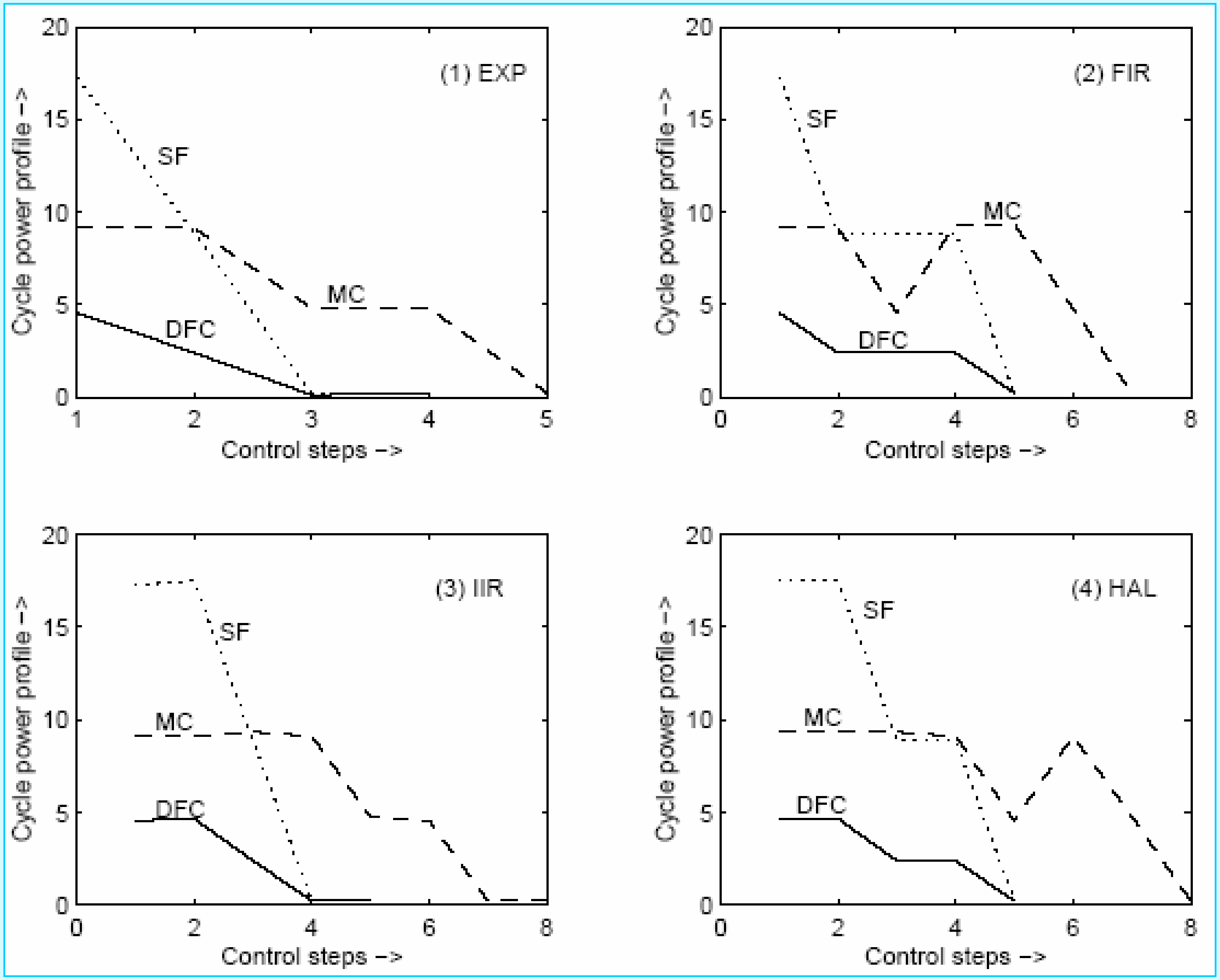
MPG Minimization: Power Profile for RC1



MPG Minimization: Power Profile for RC2



MPG Minimization: Power Profile for RC3



Conclusions

- Proposed an ILP formulations for scheduling for two scenarios:
  - MVDFC
  - MVMC
- Proposed approach optimizes power gradient, peak power, average power
- Dynamic Frequency Clocking is a better alternative to multi-cycling, for power optimization

THANK YOU!!