On Transfer Function and Power Consumption Transient Response

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Abstract

This paper proposes to use time series analysis techniques to model both average and cycle-by-cycle moving average power consumption behavior of electronic systems. The power model is in the form of first and/or second order transfer functions that represent the mapping from primary input/output activities to power consumption profile over time. Such an approach has power estimation applications in both software simulation and hardware implementation of power monitor circuit.

I. Introduction

Power consumption is fundamentally a dynamic system problem – switching power varies with respect to switching events and leakage power fluctuates with state changes over time. When considering an electronic system or a functional unit (either combinational or sequential) within a system as a black box, its power consumption profile over time can be considered being stimulated by the activities of its primary inputs (and outputs if they represent states of an internal state machine) over time. In other words, *transient* power consumption modeling problem can be represented as a dynamic system modeling problem. The output of a dynamic system (Y_t) can be the power consumption profile over time, and the inputs of the dynamic system (X_{1t}, X_{2t}, …, X_{nt}) can be *certain representations* of the primary input/output activity profile over time. The correlation between Y_t and X_{1t}, X_{2t}, …, X_{nt} can be represented by transfer functions as shown in (1).

$$Y_t = \frac{\omega_{01} - \omega_{11}B - \cdots - \omega_{s_1}B^{s_1}}{1 - \delta_{11}B - \cdots \delta_{r_1}B^{r_1}} X_{1t-b_1} + \frac{\omega_{02} - \omega_{12}B - \cdots - \omega_{s_2}B^{s_2}}{1 - \delta_{12}B - \cdots \delta_{r_2}B^{r_2}} X_{2t-b_2} + \cdots + N_t \quad (1)$$

Here, b are constant time delay factors, and B is the delay operator defined as $B^n X_t = X_{t-n}$., ω, δ are coefficients of the transfer function in rational function format, s and r are integers equal or larger than 0, and N_t is the noise. This paper applies the statistical time series analysis techniques in [1] to power consumption modeling problem and shows that such transfer functions can be effectively used to represent power consumption transient response behavior, i.e. power value variation as a function of time.

II. Coherency based clustering

The cycle-by-cycle power consumption profile (Y_t) of an electronic system under study can be obtained by a cycle-accurate power estimation methodology using a representative set of test benches. The cycle-by-cycle logic transition profile of the primary inputs/outputs for the electronic system under study can be derived from logic simulation using the same set of test benches. In order to reduce dynamic system modeling complexity and improve modeling accuracy, only a limited few input time series in (1) should be used. These limited few input time series (X_{1t}, X_{2t}, …, X_{nt}) are derived from the much larger number of logic switching time series of primary inputs/outputs. For each test bench under consideration, this is achieved by performing frequency domain analysis [2] for both power time series Y_t and each of the primary input/output switching event time series, and further calculating a quantity called squared coherency [2] between them. Squared coherency measures the level of synchronization between two time series, and is used as the metric for clustering, in which multiple primary input/output time series of similar coherency with respect to Y_t are averaged to produce a single time series X_t. To consider multiple test benches at the same time, the coherency values for each test bench can be considered to be located in an independent dimension of a multi-dimensional space. And clustering is performed based on the proximity between PI/PO's in this multi-dimensional space. The averaged time series from each of the resulting clusters corresponds to a distinctive input of the dynamic system in (1).

III. Transfer function power model

After constructing dynamic system input/output time series as discussed in section II for a set of representative test benches, these input/output time series are then concatenated to form a single set of composite input/output time series. To focus on long-term trend, low-pass filters (e.g. moving-average filter) are applied to these input/output time series. After filtering, statistical methods discussed in [1] are then used to construct and validate transfer functions in the form of (1).

As a case study example, the subsystem (denoted as design X below) of a modern general-purpose microprocessor that handles instruction decode, scheduling, dispatch, and completion has been used to evaluate the robustness of transfer function power models. An in-house gate-level power analysis tool is used to produce cycle-by-cycle power consumption time series. Fig. 1 shows an example of the prediction accuracy of a 3-input transfer function power model constructed from 3 different test benches. Table 1 shows the validation results using the transfer function model constructed from test benches in Fig. 1 but tested against a set of test benches not used for transfer function model construction. Table 2 summarizes the prediction accuracy of transfer function power models for all major functional units within design X from 6 test benches. In table 1 and 2, "avg err%" denotes estimation error percentage of average power. "rms err%" denotes rms estimation error of cycle-by-cycle power as a percentage of average power.

IV. Power monitor circuit implication

Filter circuits with first and second order transfer functions are not difficult to construct. Building a filter circuit whose transfer function properties match those of the transfer function representing the correlation between primary input/output activities of a functional unit and its power consumption profile enables run-time power estimation of individual components of a system during system operation.

References

[1] G.E.P. Box, G.M. Jenkins, G.C. Reinsel, *Time Series Analysis – Forecasting and Control*, 3rd ed., Prentice-Hall, 1994.

[2] P. Bloomfield, *Fourier Analysis of Time Series*, 2nd ed., John Wiley & Sons, 2000

Table 1: Example transfer function power model validation results for design X. "TB no." denotes test bench identification number, "cycs" denotes total number of clock cycles of a test bench.

TB no.	cycs	avg err%	rms err%
1	13,460	-4.5	11.6
2	7,032	2.5	10.0
3	12,736	-0.5	11.9
4	8,138	0.4	15.0
5	11,984	-0.6	12.2

Table 2: Estimation errors of major functional blocks within design X using transfer function power models with 50-cycle moving average time series. D_1, D_2, D_3, D_4, D_5, D_6, D_7, D_8 denotes datapath functional units; C_1, C_2, C_3, C_4 denotes control functional units; "Rel%" denotes relative percentage of average power consumption within design X. "pars" denotes the number of fitting parameters used in transfer function power models.

	Rel %	avg err%	rms err%	pars
D_1	27.5	2	12	4
C_1	18.8	1	7	3
C_2	10.7	3	16	3
D_2	10.0	1	6	3
D_3	7.4	3	16	3
C_3	6.7	1	5	3
D_4	6.4	5	19	2
D_5	6.1	2	33	4
C_4	3.4	5	22	3
D_6	1.6	1	13	3
D_7	1.0	-4	43	2
D_8	0.2	1	7	2

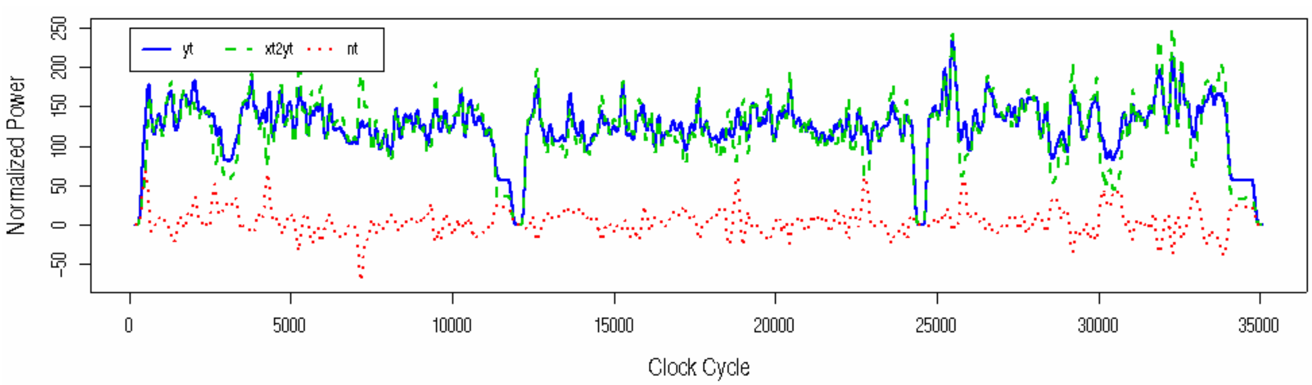

Fig. 1: Example of 100-cycle moving average power consumption time series predicted by a transfer function power model of 5 fitting parameters for design X. "yt" denotes the power consumption time series estimated from an in-house gate-level power estimation tool. "xt2yt" denotes the power consumption time series predicted by transfer function power models. "nt" denotes the non-linear optimization residue, which is the difference between "yt" and "xt2yt". Estimation error for average power is 3%. Root mean square estimation error of cycle-by-cycle power as a percentage of average power is 13%.