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Dynamic Voltage Scaling Based on Supply Current Tracking Using Fuzzy Logic Controller

Hamid Reza Pourshaghghi
Electronic Systems Group
Eindhoven University of Technology
Eindhoven, the Netherlands
h.r.pourshaghghi@tue.nl

José Pineda de Gyvez
Electronic Systems Group
Eindhoven University of Technology
Eindhoven, the Netherlands
J.Pineda.de.Gyvez@tue.nl

Abstract—It has been demonstrated that dynamic voltage and frequency scaling (DVFS) leads to a considerable saving in dynamic and static power of a processor. In this paper, we present an adaptive framework that can be used to dynamically adjust supply voltage and frequency of a processor under different application workloads. Voltage scaling decisions are made by a fuzzy Logic (FL) block based on variations of the processor's workload. By observing the supply-current of the processor and also its variation rate, the FL block can drive the processor to operate at the lowest possible voltage and also the corresponding minimum frequency, in which a specific application can meet all of its deadlines under time-constrained operation. As the voltage can change at the same time as the workload varies, significant savings in both dynamic and static power are achieved. Simulation results show that our approach outperforms a PID controller under distinct working loads.

I. INTRODUCTION

Reducing supply voltage and clock frequency of VLSI chips are important keys to save power and energy of a digital circuit. The power consumption of a clocked digital CMOS circuit (dynamic power consumption) is given by the well-known formula:

$$P_{dynamic} = \alpha \cdot C_{Tot} \cdot V_{DD}^2 \cdot F_c \quad (1)$$

where α C_{Tot} is the total switched capacitance, V_{DD} is the supply voltage and F_c is the clock frequency. By reducing the supply voltage and clock frequency, considerable power can be saved while α and C_{Tot} are generally fixed for a specific application. Over the years, researchers have proposed different hardware adaptive power management infrastructures to construct low power system-on-chip (SoC) integrated circuits [1-6]. Clock-gating, dynamic voltage scaling (DVS), dynamic frequency scaling (DFS), dynamic voltage and frequency scaling (DVFS) and power gating are some examples of the proposed approaches that today's SoCs use [1-6]. To dynamically adjust the supply voltage, we require three components: a circuit that can operate over a wide supply voltage range, a power manager that can intelligently vary the frequency of operation, and a power supply controller to set a minimum supply voltage for the desired operating frequency. In this paper, we focus on the designing of a closed loop power supply controller based on the main circuit's workload. A simplified block diagram of a dynamic supply scaled system is shown in Fig. 1.

In this block diagram there are three main components. The first component is a performance sensor that monitors the main specification of the circuit e.g. average of supply current, temperature and supply voltage variations. The second component is the controller. This block works based on an input data received from the sensors by comparing it with the reference performance received from the power management unit or software to decide the change in supply voltage when necessary. The third block is the supply voltage actuator that can be on-chip or off-chip, e.g. a DC-DC converter. It should be taken into account that in designing an adaptive voltage controller for this kind of closed-loop systems, the type of control required is fundamentally different from standard voltage regulators because in addition to voltage regulation for a given performance, it must also change the voltage when a new performance level is requested. Here, we present a closed loop configuration based on fuzzy logic (FL) controllers to adaptively adjust the supply voltage of the processor compatible with workload variations. FL controllers are well suited for low-cost implementations based on cheap sensors and low-resolution analog-to-digital converters. Such systems can be easily upgraded by adding new rules to improve performance or add new features. Furthermore, in closed loop adaptive voltage scaling most of the power is dissipated in the time interval between changing the workload and acting to change the supply voltage. Consequently predicting the processor's workload compensates this drawback. Also, FL controller can be used to enhance power savings in comparison to other traditional controller systems, especially when the rate of workload variations is high.

In the rest of the paper we first describe the state of the art related work. Next, we introduce an overview of FL system and its control model. After that we explain the closed loop adaptive voltage scaling configuration with more details. We finish with simulations of a sample processor and compare them with the traditional PID control method.

Figure 1. General block diagram of a dynamic supply scaled system

II. RELATED WORK

Here, we highlight the main approaches to enable the adaptive control of the power supply voltage. One such approach is to derive the supply voltage from the clock frequency as described in [1]. Researchers have also proposed a closed loop system architecture for self-timed adaptive supply-voltage scaling targeted for asynchronous circuits [2]. In their architecture, FIFO buffers are used in both inputs and outputs of the processor. The FIFO-buffers average the computational workload to adjust the supply voltage and frequency. The feedback is based on actual path delays of the circuit. The feedback signal controls the DC-DC converter based on the information derived from the FIFO's. After this architecture, other researchers used a similar configuration to adapt the power supply voltage to lower the power consumption in digital signal processors (DSPs) [3]. The structure of the proposed system architecture in [3] is the same as [2], but they designed a configuration for synchronous designs, and variations in the computational workload were taken into account as well. Like the self-timed variable voltage system of [2], input data is buffered into a FIFO type of buffer to enable averaging of the workload. Then, the control loop controls the processing rate to avoid queuing overflow and underflow of the FIFOs. The controller in this methodology consists of a voltage regulator, a ring oscillator, a rate-compare block and a programmable look-up table (LUT). The controller block decides to change the voltage and frequency based on the processing rate and existent LUT. Another famous approach, presented in [4], uses a proportional, integral and derivative (PID) control method in the closed loop system. In this methodology, voltage samples are used to control a VCO to change the frequency as feedback signal for the buck converter. The reference signal and feedback signal come into the controller as variable frequency clocks, both feed into counters, and the numbers of transitions are counted for a fixed period of time. A PID controller, based on the calculated error value between its inputs, decides to change the voltage and frequency of the circuit. In addition to these fundamental works, some other methods were presented in these years. In [5], two separate loops for controlling frequency and voltage were presented. A DVFS system was designed and fabricated in [6] using a delay synthesizer.

Until now, the proposed structures provide discrete supply voltages based on an average value of workload variations. In this paper, we present a controller that reaches pseudo continuous supply voltage adaptation through prediction and tracking of the circuit's supply current. Furthermore, the most recent works are based on workload averaging rather than on workload tracking.

III. OVERVIEW OF THE FUZZY LOGIC (FL) CONTROLLER

A typical feedback control loop is represented in Fig. 2. A FL controlled system uses the same control topology. Fig. 3 presents the internal structure of the FL system. As it is shown in this figure, the FL controllers consist of three blocks: a fuzzification module, a set of *if-then* rules and a defuzzification unit [7]. The fuzzification unit converts a quantified, numerical or control variable into a qualitative value. In this block, for each control state, a membership function should be considered.

Figure 2. Typical feedback control loop

Figure 3. Internal structure of a FL controller

A membership function is a function that specifies the degree to which a given input belongs to a set, and thus its relation to a concept. Under this definition, the output of a membership function is always limited to a value between 0 and 1. In binary logic, the output is either 0 or 1, whereas in FL, the output lies in the interval $[0, 1]$. A brief definition of fuzzy set theory is given as next.

Suppose that $X = \{x\}$ is a universe of discourse, i.e. the set of all possible elements with respect to a fuzzy concept. Then a fuzzy subset A in X is a set of ordered pairs $\{(x, \mu_A(x))\}$, where $\{x\} \in X$ and μ_A is the membership function of A ; $\mu_A(x) \in [0, 1]$ is the grade of membership in A [7].

There are three main issues in the design process of membership functions: the number of partitions for each control state over its universe of discourse (UD), the shape of each membership function in each partition, and UD partitioning including partitions, boundaries and overlaps between partitions. All these factors for designing membership functions carry some information about the system. Different shapes of membership functions have been already proposed [8]. And obviously, there exist different mathematical models for the fuzzification of a variable. Fig. 4 gives examples of functions that can be used in a fuzzification procedure. In our case, the circuit's workload and its variations are two inputs of the FL block. So, for each of them, we have to consider some membership functions and model them with corresponding mathematical equations. The second block in Fig. 3 is the fuzzy engine block or *If-then* rules which gather the knowledge needed to successfully control the output voltage. With the fuzzified input variables, this unit computes a qualitative output result for the controller [9]. This block is the most important block in designing FL controllers and plays a crucial role on the controller operation as its role is to model the whole behavior of the configuration. The third part is the defuzzification method that converts the resulting fuzzy set to a number that can be sent to process as a control signal. There are several defuzzification methods like centre of area, centre of gravity method for singleton, bisector of area, mean of maxima, etc. The centre of area method is often used although its computational complexity is relatively high. The crisps output value for centre of area is the abscissa under the centre of gravity of fuzzy set as:

$$u = \frac{\sum_i \mu(x_i) x_i}{\sum_i \mu(x_i)} \quad (2)$$

where x_i is a running point in a discrete universe and μ_i stands for its membership value in the membership function. Note that for the continuous cases, in (2) the summation should be replaced with integral.

Figure 4. Some examples of membership functions in fuzzification stage

IV. PROPOSED ADAPTIVE VOLTAGE (FREQUENCY) SCALING CONFIGURATION BASED ON FL CONTROLLER

As there is a strong correlation between supply current and workload [10], the proposed configuration is based on observing the supply current of the processor and also its variations. The configuration of the dynamic voltage scaling approach using a FL controller is shown in Fig. 5. In this method, we use the supply current and also the derivative of the supply current as two inputs of the FL block. The reason for using the derivative of the supply current is that it helps us to *predict* the variations of the workload. If we can predict variations of the supply current, then it is easier for the actuators to act sooner. Consequently, the amount of saved power could be increased significantly, not to mention finishing the executing task on time. We will show an example to explain how the prediction in this configuration will happen. Suppose that we have considered three membership functions for each of the two input states and one output state of the FL block as shown in Fig. 6. Worth mentioning is that although there exist many possible shapes for membership functions, the form of the particular used function does not influence in a significant way the output result of a FL controller. Note that the number of qualitative levels that should be used for fuzzification section depends on the complexity and performance of the controller. Here, we just consider three levels for showing how the controller works and how the prediction will happen. We divided the range of supply current and its derivative into three levels and it causes to have a set of nine *if-then* rules. These rules are shown in Table I. The *if-then* rules block computes a qualitative value for the supply voltage based on its membership function and the defuzzification operation. By applying (2), the controller computes the appropriate supply voltage for the circuit. Suppose that the supply current is belonging to the *small* area of its membership functions and the derivative of the current is belonging to *zero* area. Based on the rules of Table I, the supply voltage should go to the *small* function in its membership function. But if the derivative of supply current belongs to *positive*, it shows that the supply current is increasing and so that we can raise the supply voltage to compensate delays of other components in the closed loop configuration. So, the fuzzy engine orders the supply voltage to go to the *Medium* area (see the second rule in Table I). All the rules in Table I follow this style to predict the workload variations. Also, by this configuration we can have a pseudo continuous supply voltage that results in more savings of power and energy of the circuit under control. It should be taken into account that these rules are not unique and that it is possible to add for example the second derivative of supply current variations to predict the supply current changes with more accuracy.

Figure 5. Dynamic Voltage (Frequency) Scaling configuration based on tracking supply current by FL controller

Figure 6. Sample Membership functions for supply current and its derivative (as inputs) and supply voltage (as output) of the FL controller (fuzzification part)

Also, it should be taken into account that this algorithm can be implemented for frequency control considering the effects of the critical path time of the circuit.

V. EXPERIMENTS

Several experiments have been conducted to evaluate different aspects of the controller. In the first simulation, we designed a controller and implemented it on a sampled supply current of a processor near to reality. This supply current is shown in Fig. (7.A.a) and its derivative is shown in Fig. (7.A.b). Based on the theoretical explanation of section III and IV, we have considered nine Gaussian membership functions for supply current. These functions are defined between $150\mu A$ to $600\mu A$, without losing the generality, with a symmetrical shapes and widths. Each supply current membership function has 50% overlaps with its neighbor membership function (functions). We have considered five Gaussian membership functions for derivative of supply current from $-250 mA/sec$ to $250 mA/sec$. Consequently, we defined 45 *if-then* rules based on the rules shown in Table I. Nine symmetrical Gaussian membership functions for supply voltage have been considered as well. These membership functions have 50% overlap with each other and have same widths too. We used also the centre of area as the defuzzification method. The result of this simulation is shown in Fig. (7.A.c). As one can see from the supply voltage values, the FL can track the variation of supply current very well. The output surface of FL controller is shown in Fig. (8.b). In this figure, the entire span of supply voltage based upon the entire span of supply current and its derivative is displayed. It shows pseudo continuity of the output voltage with variations of workload.

We simulated a PID controller on another supply current signal and compared the results with the FL controller. Suppose that we have a supply current signal like the one shown in Fig. (8.a). We trained the PID controller with some simulation testing to find out what coefficients are the best for the proportional, integration and derivative part of the controller. Finally, with a trial and error method we found that with $k_p = 100$, $k_i = 2$ and $k_d = 1$ we can track the supply current very well.

TABLE I. IF-THEN RULES FOR CONTROLLING SUPPLY VOLTAGE

Current		D(Current)		Supply-voltage	
If	Small	and	Zero	Then	Small
If	Small	and	Positive	Then	Medium
If	Small	and	Negative	Then	Small
If	Medium	and	Zero	Then	Medium
If	Medium	and	Positive	Then	Big
If	Medium	and	Negative	Then	Small
If	Big	and	Zero	Then	Big
If	Big	and	Positive	Then	Big
If	Big	and	Negative	Then	Medium

These rules are made for the fuzzy engine block of the FL controller

7.A) Simulation results of FL controller on a sampled supply current

7. B) Output surface of FL Controller

Figure 7. Simulation results of applying fuzzy Logic controller (FLC) on a sampled supply current. A.a) Supply current of a sample processor, the variation of current is based on different applications, A.b) Derivative of supply current, A.c) Voltage (output) of FLC that goes to DC-DC converter, B) Output surface of FL Controller which shows variations rate of voltage (output) based on two inputs variations.

The tracking result is shown in Fig. (8.b). But when the shape of the supply current changed, similar to the supply current shown in Fig. (8.c), the PID could not track the variations with the same coefficients and we have to change coefficients again. The output of PID block in the second experiment is shown in Fig. (8.d). But the FL controller can track this shape well. It is also important to mention that the FL controller works well regardless of the system's inputs, while the PID controller requires the mathematical formulation of the system to adapt its coefficients to be able to work properly. One of the main advantages of the FL controller is that the hardware implementation is easy because everything here is digital. Another advantage is that this controller can work on-line to track all workload circumstances with high speed and less error in comparison with other traditional control methods. Also by this configuration, we can have a pseudo continuous supply voltage that changes with workload variations. But in this case, it is not possible to mathematically prove that the whole closed loop system is stable.

VI. CONCLUSION

We proposed a dynamic fuzzy logic controller based on supply-current variation tracking for dynamic voltage scaling purposes. In this method, the fuzzy logic controller decides about changing the supply voltage of the circuit under control by observing and predicting the supply-current.

Figure 8. Simulation of PID controller on two different input supply current signals

The simulation results show the efficiency of the proposed configuration in comparison to a PID controller. Hardware implementation of proposed configuration is following with the authors. In future developments, it is suitable to evaluate robustness of configuration against noise and also to improve defining membership functions regarding to correlation between workload and its impact on changing membership functions.

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