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GENERATION OF LOW POWER TEST SET BY MERGING FUNCTIONAL BROADSIDE TEST BASED SKEWED LOAD TEST CUBES

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ABSTRACT

Low power test set is generated by merging of the skewed load test cubes that are extracted from the functional broadside tests. The use of functional broadside tests ensures that switching activity of the extracted tests does not exceed that possible during functional operation of the circuit. As the switching activity is prevented from exceeding the switching activity that the circuit is designed for, the power during the application of tests also does not exceed that possible during functional operation of the circuit. The test cubes which are extracted from functional broadside tests preserve the functional operation conditions and the merging of these test cubes helps in the test compaction and thereby increasing the fault coverage.

Keywords: Functional broadside tests, Skewed load tests, Skewed load test cubes, Switching activity, Transition faults.

I. INTRODUCTION

A scan-based test causes power to be dissipated that can exceed the power dissipation that is possible during functional operation. Low-power test generation procedures address this issue by generating tests with reduced power dissipation or reduced switching activity [1]–[8]. In [9] it was shown that procedures, which attempt to reduce the power dissipation of a test set, may result in switching activity that is significantly lower than that possible during functional operation. This can have several negative effects.

(a) Reduced switching activity typically implies that the size of the test set is increased [10]. This is due to the fact that each test detects fewer faults. Thus, a test set with unnecessarily low switching activity is also unnecessarily large.

(b) A test with a low switching activity exercises the circuit less than a test with a high switching activity. Consequently, the ability of the test set to detect unmodeled defects may decrease when the switching activity is reduced.

An approach to limit the power dissipation of scan based tests is to use functional broadside tests [11]. The switching activity of functional broadside tests [11]-[12] is guaranteed not to exceed the switching activity possible during functional operation. Functional broadside tests are two-pattern scan based tests that avoid overtesting by ensuring that a circuit traverses only reachable states during the functional clock cycles of a test. Overtesting is related to the detection of delay faults under non-functional operation conditions. One of the reasons for these non-functional operation conditions is the following. When an arbitrary state is used as a scan-in state, a two pattern test can take the circuit through state-transitions that cannot occur during functional operation. Hence functional broadside tests require that the scan-in state would be a reachable state, a state that the circuit can enter during functional operation, and that the state transitions that the circuit makes during the functional capture cycles of the test would be possible during functional operation. As a result, during its functional capture cycles, a functional broadside test guarantees to create functional operation conditions.

The first functional capture cycle of a functional broadside test is applied under a slow clock. Therefore, any signal transitions that are created during the scan-in operation are expected to settle during this clock cycle. The second functional capture cycle is applied under a fast clock. With functional operation conditions during both cycles, it is guaranteed that the switching activity and hence the power dissipation during the second, fast functional clock cycle will not exceed that possible during functional operation. In the procedure described in [6], functional broadside tests are generated first and included in the low-power test set. To increase the fault coverage, nonfunctional broadside tests are generated and then modified by complementing input values one at a time. The goal of the modification is to reduce the switching activity such that it will not exceed the maximum switching activity of a functional broadside test. The result is a low-power broadside test set with the same fault coverage as a nonfunctional broadside test set, and with switching activity that is bounded by the switching activity that is possible during functional operation.

The procedure from [8] generates skewed-load tests such that the switching activity during their fast functional clock cycles is bounded by the maximum switching activity of a functional broadside test. In its first step, the procedure modifies a functional broadside test into a skewed-load test by complementing as few input values as possible. In its second step, the procedure modifies the skewed-load test so as to increase the number of faults it detects while ensuring that its switching activity does not exceed the maximum switching activity of a functional broadside test. The procedure described in [7] applies a process that extracts a set of incompletely specified broadside test cubes T_c for target faults from functional broadside tests. It obtains a low-power broadside test set by merging of test cubes from T_c.

The proposed procedure aims to derive skewed-load test cubes from functional broadside tests, and merge these test cubes for the generation of low power test set. By avoiding the inclusion of functional broadside tests in the low-power test set, and using test cube merging to form tests, the procedure is able to generate compact low-power test sets. The maximum switching activity of a functional broadside test is used to bound the switching activities of the tests that are obtained by merging. Thus, the switching activity is prevented from being unnecessarily low or too high. The procedure generates functional broadside tests, and extracts skewed-load test cubes from them as they are generated. The procedure continues to generate functional broadside tests as long as effective skewed-load test cubes are obtained.

This paper is organized as follows. Section 2 describes the extraction of skewed-load test cubes from functional broadside tests. Section 3 describes the test cube merging procedure. Section 4 presents results.

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II. EXTRACTION OF SKEWED-LOAD TEST CUBES

Broadside tests and skewed-load tests are denoted uniformly by $\langle s_{i0}, v_{i0}; s_{i1}, v_{i1}\rangle$, where s_{i0} is the scan-in state. During the first cycle of the test, the present-state s_{i0} and the primary input vector v_{i0} determine the input pattern to the combinational logic of the circuit. In a broadside test, s_{i1} is the next-state obtained for s_{i0} and v_{i0}. In a skewed-load test, s_{i1} is obtained by a single shift of s_{i0}. The present-state s_{i1} and the primary input vector v_{i1} determine the input pattern to the combinational logic during the second functional clock cycle of the test. Switching activity is the number of transitions obtained during the second functional clock cycle of a test.

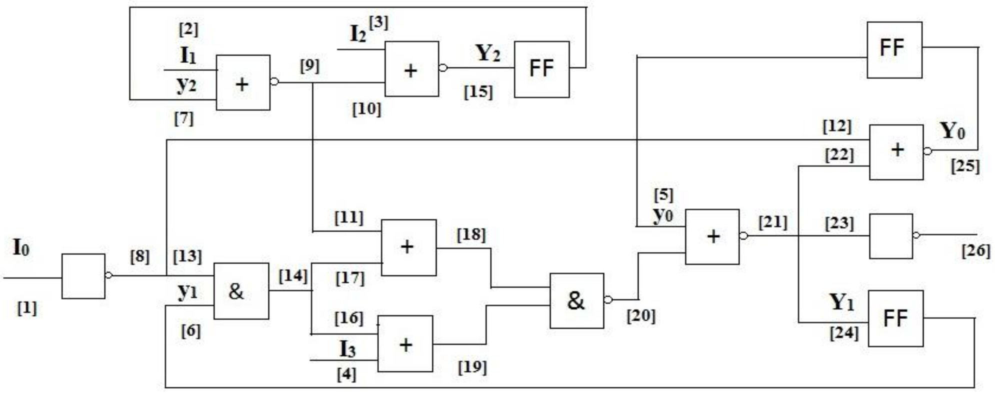

Figure1. ISCAS-89 s27 benchmark circuit

Table1. Functional broadside test set

i	t_i	swa(t_i)
0	<000,1000;100,0001>	9
1	<100,0001;000,0010>	5
2	<000,0010;000,0100>	7
3	<000,0100;001,1001>	9
4	<001,1001;101,0011>	8
5	<101,0011;000,0110>	5
6	<000,0110;000,1101>	9
7	<000,1101;101,1010>	7
8	<101,1010;100,0101>	11
9	<100,0101;001,1011>	10
10	<001,1011;100,0111>	8
11	<100,0111;000,1111>	6
12	<000,1111;100,1110>	3
13	<100,1110;100,1100>	2

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The procedure first generates functional broadside tests. The input vectors are generated randomly and reset state is considered as the initial state. The test set $\mathbf{t_i}$ thus obtained for ISCAS-89 s27 benchmark circuit in Fig. 1, and the switching activity swa(t_i) thus calculated for every test is given in Table 1. The primary input values are applied at the lines I_0 ,I_1 ,I_2 ,I_3 and the state variables are applied at lines y_0 ,y_1 ,y_2 respectively The maximum switching activity F_{max} for this test set is 11.

Hence it must be ensured that the switching activities of the tests which are to be generated and included in low power test set must not exceed this value. For a circuit with p state variables, s_{ia} (j) denotes the value of present-state variable j under s_{ia}, for $0 \le a \le 1$ and $0 \le j < p$. For a skewed-load test, the circuit is assumed to have a single scan chain that is shifted to the right which implies that $s_{i0}(j) = s_{i1}(j+1)$ for $0 \le j < p-1$. A test **t** is not a skewed-load test if there exists a present-state variable j, where $0 \le j < p-1$, such that $s_{i0}(j) \neq s_{i1}(j+1)$. In this case, shifting s_{i0} by one position to the right will not result in s_{i1} as required for a skewed-load test. The procedure obtains from **t** a test cube that satisfies the conditions of a skewed-load test by unspecifying $s_{i0}(j)$ and $s_{i1}(j+1)$ for every $0 \le j < p-1$ such that $s_0(j) \neq s_1(j+1)$.

For example, considering the functional broadside test t_1 = <100, 0001; 000, 0010>, the state s_{11} = 000 cannot be obtained from s_{10} =100 by a single shift of the scan chain. The conflict occurs between $s_{10}(0) = 1$ and $s_{11}(1) = 0$. The procedure unspecifies these values to obtain the test cube <X00, 0001; 0X0, 0010>. By considering the functional broadside test t_3 = <000, 0100; 001, 1001>, the state s_{31} = 001 cannot be obtained from s_{30} =000 by a single shift of the scan chain. Here the conflict occurs between $s_{30}(1) = 0$ and $s_{31}(2) = 1$. The procedure unspecifies these values to obtain the test cube <0X0, 0100; 00X, 1001>.In a similar manner, all the tests in the functional broadside test set can be modified by unspecifying the necessary values to obtain the skewed load test cubes as shown in the Table 2.

Table2. Set of Skewed Load Test cubes Extracted From Functional broadside Tests

i	t_i
0	<000,1000;100,0001>
1	<X00,0001;0X0,0010>
2	<000,0010;000,0100>
3	<0X0,0100;00X,1001>
4	<0X1,1001;10X,0011>
5	<X01,0011;0X0,0110>
6	<000,0110;000,1101>
7	<0X0,1101;10X,1010>
8	<X01,1010;1X0,0101>
9	<XX0,0101;0XX,1011>
10	<001,1011;100,0111>
11	<X00,0111;0X0,1111>
12	<000,1111;100,1110>
13	<X00,1110;1X0,1100>

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These test cubes can be unspecified further by considering a fault from the set of faults F and without losing the fault detection capabilities. This helps in test compaction, as merging could be done better if a test consists of more number of unspecified values. The procedure considers the values in a random order. It is possible to consider all the values and produce a minimally specified test cube for every fault. When the procedure considers $s_{i0}(p-1)$, $s_{i1}(0)$, $v_{i0}(j)$, or $v_{i1}(j)$, for $0 \leq j < n$, where n is the number of primary inputs, it replaces the value with an unspecified value. When the procedure considers $s_{i0}(j)$, for $0 \leq j < p-1$, it replaces both $s_{i0}(j)$ and $s_{i1}(j+1)$ with unspecified values. If the fault is still detected by applying the unspecified values, the procedure accepts the unspecified values, and considers additional values with these values unspecified. If the fault is not detected, the procedure restores the specified values that it unspecified in the last step. This is advantageous for test compaction, since more test cubes can be merged to obtain tests that detect more faults. However, the specified values of a test cube **t** preserve values from a functional broadside test. These values are important for creating functional operation conditions. Therefore, it is important to avoid unspecifying values unnecessarily.

By considering a slow to rise transition fault i.e. 0→1 transition fault at the line I_2, the skewed load test cube t= < X00, 0001; 0X0, 0010 > can be further unspecified as c = < X00, XX01; 0X0, XX10 > without loss in the fault coverage. The set of skewed load test cubes $\mathbf{c_i}$ thus obtained by further unspecifying the values, considering a fault from a set of faults F, is as shown in the Table 3.

Table3. Set of skewed load test cubes unspecified further

i	c_i
0	<0XX,1XX0;10X,0XX1>
1	<X00,XX01;0X0,XX10>
2	<XXX,X01X;XXX,X10X>
3	<0X0,01X0;00X,10X1>
4	<0XX,1X0X;10X,0X1X>
5	<X01,X0X1;0X0,X1X0>
6	<XX0,0X10;0XX,1X01>
7	<0X0,X101;10X,X010>
8	<X01,1010;1X0,0101>
9	<XX0,010X;0XX,101X>
10	<001,10XX;100,01XX>
11	<X0X,0XXX;XX0,1XXX>
12	<00X,XXX1;X00,XXX0>
13	<X00,XX1X;1X0,XX0X>

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III. MERGING OF SKEWED-LOAD TEST CUBES

Merging of the obtained skewed load test cubes to form low-power tests can produce compact test sets, and it can satisfy the constraints of test data compression. The fault coverage of $\mathbf{c_i}$ is significantly lower than that of a skewed-load test set. Therefore, merging of the test cubes from $\mathbf{c_i}$ such that each test cube appears only once in the final test set is not sufficient for detecting all the target faults that can be detected by skewed-load tests. Considering a fault $f \in F$, a test **t** that detects the fault f and a set of test cubes $\mathbf{c_i}$, the procedure constructs a skewed-load test **t** for f as follows.

The procedure considers the test cubes from $\mathbf{c_i}$ one at a time in a random order. When a test cube **c** is considered, the procedure applies the following steps. The procedure merges **t** and **c** into a test that is equal to **t** in all its specified values, and equal to **c** in all its specified values that do not conflict with the corresponding values of **t**. Unlike the case in [7] where the merging operation is not possible if the functional broadside test cubes which are intended to be merged have conflicting values, the merging operation proposed in this procedure is applicable even if **t** and **c** have conflicting values. For conflicting values, the value from **t** is used. This increases the flexibility in obtaining new tests from the test cubes in the set $\mathbf{c_i}$.

By considering a slow to fall transition fault f (at line I_2) from a set of faults F, the test that detects fault f is obtained which is given by **t** = <000,0010;000,0100>.Now considering the test cubes from the set of skewed load test cubes $\mathbf{c_i}$ one at a time, merging operation is performed. For example if a test cube c = <0X0,01X0;00X,10X1> is considered, merging is performed such that if specified values of t and c are conflicting, the value from t is used. The test thus obtained by merging is given by t = <0X0,00X0;00X,01X0>. All the test cubes in the test set are merged with the test **t** and the resulting skewed load test set is shown in the Table 4.

Table4. Set of Merged Skewed Load test Cubes

i	t_i
0	<0XX,0XX0;00X,0XX0>
1	<X00,XX10;0X0,XX00>
2	<XXX,X01X;XXX,X10X>
3	<0X0,00X0;00X,01X0>
4	<0XX,0X1X;00X,0X0X>
5	<X00,X0X0;0X0,X1X0>
6	<XX0,0X10;0XX,0X00>
7	<0X0,X010;00X,X010>
8	<X00,0010;0X0,0100>
9	<XX0,001X;0XX,010X>
10	<000,00XX;000,01XX>
11	<X0X,0XXX;XX0,0XXX>

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12	**<00X,XXX0;X00,XXX0>**
13	**<X00,XX1X;0X0,XX0X>**

After considering all the test cubes from $\mathbf{c_i}$, the procedure specifies the remaining unspecified values of t randomly. For t to be considered a low-power test, its switching activity as a fully specified test should not exceed the maximum switching activity F_{max} of the functional broadside tests. The low power test set thus obtained is as shown in the Table 5.

Table5. Low Power test Set

i	t_i	swa(t_i)
0	<100,0110;010,1100>	9
1	<001,0111;000,0100>	5
2	<100,0110;010,1101>	11
3	<001,1100;100,1110>	4
4	<010,1111;001,0101>	9
5	<000,0010;000,0100>	7
6	<100,0110;001,0100>	4
7	<000,0010;000,0111>	7
8	<000,0000;000,0110>	6
9	<000,1010;000,1100>	7
10	<100,1110;010,1100>	4
11	<001,0101;000,0111>	3
12	<100,0011;110,0101>	10
13	<011,1011;001,1101>	4

IV. RESULTS

The procedure is implemented using VHDL and is simulated using Xilinx 13.1.The functional broadside tests are generated for ISCAS-89 benchmark s27 and skewed load test cubes are extracted from them. Low power test set is obtained by merging those test cubes whose switching activity does not exceed F_{max}.

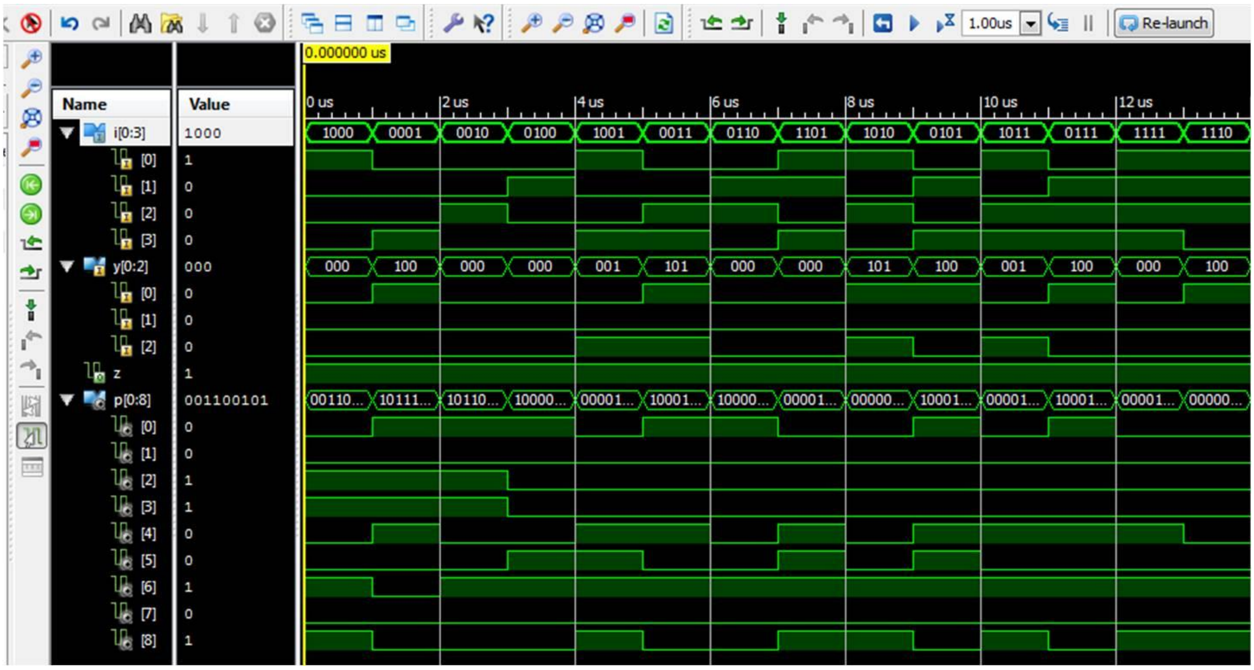

Figure2. Switching Activity of Functional Broadside Tests

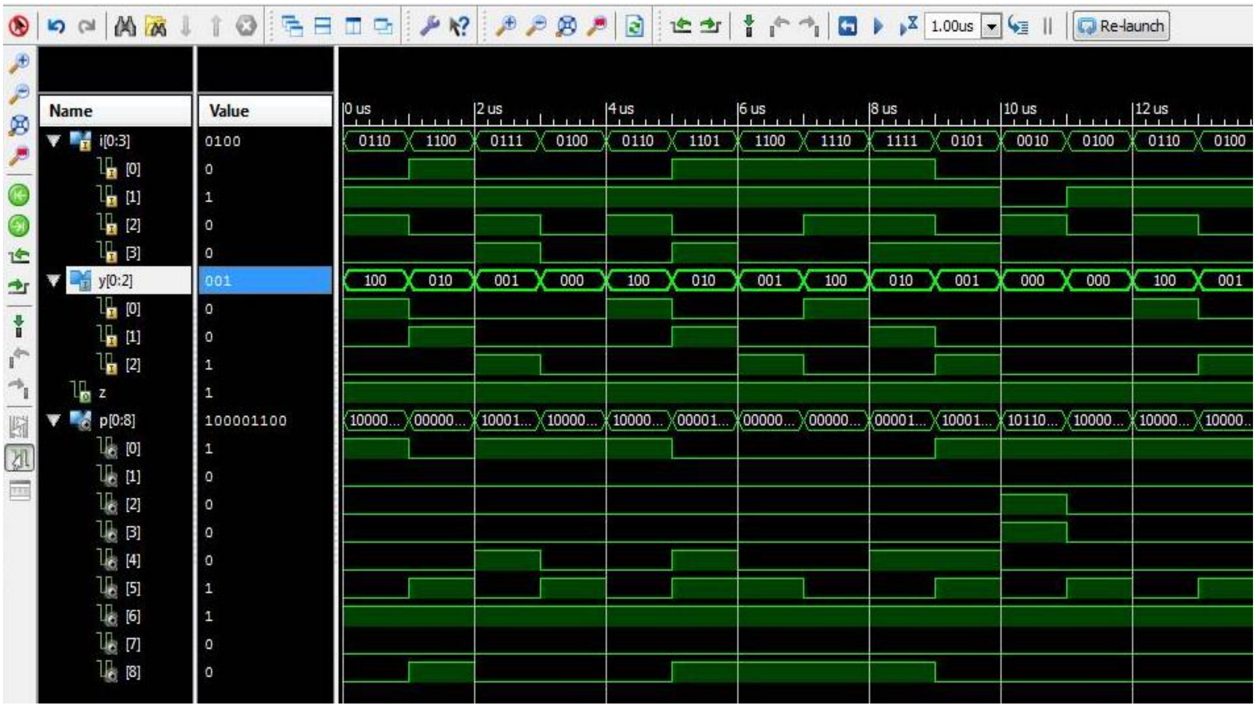

Figure3. Switching Activity of Skewed Load Tests that are Included in low Power test Set

It is observed from Figs 2 and 3 that the number of transitions that occur in skewed load tests that are derived from the functional broadside tests is less when compared with the number of signal transitions that occur in the functional broadside tests. Thus the switching activity obtained by the skewed load test cubes is within the bound and is definitely less when compared with that of functional broadside tests, thereby minimizing the power consumption during the test application.

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Detection of slow to fall (1→0) transition delay faults at lines 9 and 14 (line numbers are specified in square brackets in Fig.1) of the ISCAS-89 benchmark s27 by skewed load tests are shown below in the Figs 4 and 5.

Figure4. Detection of slow to fall (1→0) fault at line 9 of s27 circuit by skewed load test

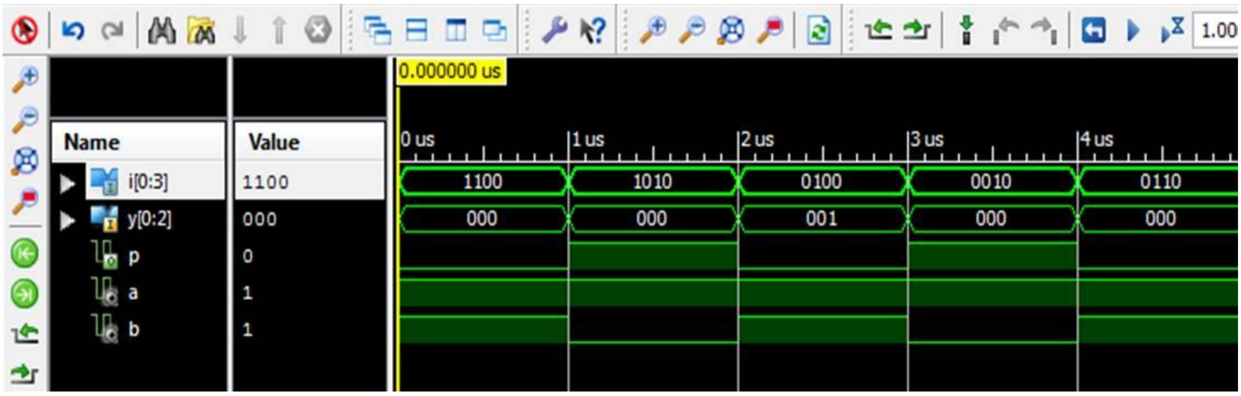

Figure5. Detection of slow to fall (1→0) fault at line 14 of s27 circuit by skewed load test

V. CONCLUSION

Reduction of the test power consumption has become the major concern as test application consumes more power than that required in the normal circuit operation. The proposed idea uses functional broadside tests for the extraction of skewed load test cubes and hence is capable of reducing the power consumption by making the circuit traverse the states, which it does during its normal functional operation. The extracted test cubes preserve the functional operating conditions, whose switching activity is bounded by the maximum switching activity of the functional broadside tests. Low power test is generated by merging of the skewed load test cubes and test cube merging was implemented in a way that would ensure that the fault coverage of the final test set will not be limited by the fault coverage of functional broadside tests.

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