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A NEW POWER SYSTEM RESTORATION AND RECONFIGURATION USING FIELD PROGRAMMABLE GATE ARRAY

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ABSTRACT

The aim of this paper is to optimize the system after restoring and reconfigure the faulted area in a distribution network after isolating the faulted block. Restoration involves changing the switch status to maximize the supply to loads that are left unsupplied after fault removal. After system optimization using reconfiguration, Field Programmable Gate Array (FPGA) is used in order to control the switches by generating the pulses for the stable configuration. In the proposed system restoration and reconfiguration process is achieved in 16 bus system and simultaneously load flow analysis is performed before and after the fault and the same is verified in MATLAB. Optimization using Binary Particle Swarm Optimization (BPSO) is done in order to get the most stable configuration for restoration process by minimizing the LBI (Load Balancing Index).

Keywords: *Load Balancing Index, Field Programmable Gate Array and Binary Particle Swarm Optimization*

1. INTRODUCTION

When the power plant cuts the power supply due to fault then they have to pay penalty to the consumer which leads to heavy loss in many countries. This is the area on which many real time researches are going on and still future can't be predicted. So up to 99%, continuity of the system can be maintained but due to fault, 1% can't be predicted. Hence the assurance to the customers that their system is 100% efficient cannot be given [1]. In order to overcome this problem and for system reconfiguration, through a process called restoration and optimization is done. It is the process of maintaining power balance after fault. When a fault takes place in a certain area of an electrical distribution system, it is essential for the system operators to isolate the faulted block and restore the service to the out-of-service area.

2. OBJECTIVE AND GOAL OF THE PAPER

The aim of our paper is basically to restore and reconfigure the faulted area in a distribution network after isolating the faulted block. Reconfiguration involves changing the status (OFF/ON) of switches where restoration involves changing the switch status to maximize the supply to loads that are left unsupplied after fault removal. Through this paper an attempt has been made to explain the power system reconfiguration using FPGA (Field Programmable Gate Array) which is used for pulse generation for the switches used in our proposed network. This paper is basically divided into three parts. In the first part, the restoration and reconfiguration in a 16 bus is done by allotting a fixed amount of power to the entire load in the system. During fault condition, loads which are affected due to the faulty load will restore them by taking the extra amount of power from nearby feeder. In the second Part of the paper, after achieving the restoration process, finding the best path for restoration using optimization process out of different paths is done by working on a test system(fig-1) having three feeders with different loads in each. In the test system, restoration and reconfiguration process for a generated fault in the system is done. For transmission of power it is known that switches have an important role for finding different path for reconfiguration. Our aim is to control these switch status in order to find the best solution. The test system consists of 16

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switches which are connecting different loads and feeders hence there will be total 216 combinations. The switches s1, s2, s3, s16 should always be kept closed so as to maintain the radiality. Hence for these switch we will assign 1 to indicate the close status. This will reduce the number of combination to 60. The required output will be one out of these combinations. Hence we will perform the load flow analysis [2] in order to get the least loss in the system corresponding to different status. Besides this corresponding to each combination, the LBI [3] is calculated. Objective of optimization is indicated by the minimization of LBI and corresponding to that minimum LBI our switch status will be required one and that will be switch status that system should have after the optimization.

The third part, the reconfiguration and optimization process simultaneously in our standard system is performed. In order to control the switch status for the stable configuration, the pulses are generated according to requirement. Generation of pulses is done with the help of Xilinx. For this, first of all the outcome of the MATLAB in the binary form will be fed to the Xilinx. Based on the input, it will generate the pulse which control the different switch status and minimizes the system losses. Finally, the output can be verified with the FPGA kit. The effectiveness of the proposed method is demonstrated by simulating tests in a proposed distribution network and verified the results using Xilinx and MATLAB.

The methodology used can be implemented in actual systems. The priority based solution can be generated i.e. instead of household supply, hospitals can be restored first. Such a generated solution will be more useful instead of randomly generated solution. Beside this the solution generated are based on LBI and system loss [4, 5], hence the generated results are more accurate and efficient. Also the switch status is also controlled by the pulses so the number of switching operation will be less based on the requirement. Beside all this, the control of switch in digital form will lead to minimum loss and maximum efficiency of the system.

3. RESTORATION

Restoration can be define as the "The act of restoring something or someone to a satisfactory state". This conceptual term can be correlated to our power system. Restoration in power system can be linked as follows "whenever there is a fault in the system the normal or working component will try to get the power through other way. This process of maintaining the power balance after fault is called restoration". As per present scenario, our generation is not sufficient to fulfill our requirement. Thus, it is needed to develop some new solution for maintaining the continuity and efficiency of the system. The primary objectives of power system planning and operation are to minimize system outages, load interruptions and equipment damage under emergency conditions. These goals are becoming more difficult to achieve under current conditions, because of the Increasing pressures resulting from fast system demand growth and increased system complexity. Power system behaviour under emergency conditions as well as during restoration processes depends on its characteristics as related to real and reactive power balance and the installed control and protective systems. The restoration process is also a function of pre-disturbance conditions, post disturbance status and post-disturbance target systems. Therefore, the understanding of the factors involved in power system collapse and the restoration procedure is crucial to the proper operation of modern power systems. Besides, the power system in present time becomes so vast that if something happens in one part then it will greatly affects the other part and has a great influence on it. Therefore to satisfy all these conditions, it is needed to restore in a proper way using best algorithm. The major issues associated with system restoration, including those associated with system characteristics and operating conditions. It is argued that restoration planning and training is an ongoing activity that involves system operators, planners, protection staff and trainers. It also involves a variety of analytical tools to aid in the planning and execution stages.

4. MULTI-AGENT PROCESS FOR RESTORATION

Multi-agent technique [6] attracts more and more attention in many fields such as computer science and artificial intelligence. The multi-agent system is a decentralized network to solve problem. All the agents work together to obtain a global goal which may beyond the capability of each individual agent. A multi-agent system is ideal for control of energy resources to achieve higher reliability, higher power quality and more efficient (optimum) power generation and consumption. Because multi-agent systems process data locally and only transfer results to an integration centre, computation time is largely reduced and the network bandwidth is very much reduced compared to that of a central control. Multi-agent systems also allow scalability such as when new resources, loads or interconnections are

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added to the system and extensibility such as performing new tasks or communicating a new set of data that becomes available.

5. OPTIMIZATION

In an optimization problem the values of the variables that lead to optimal value. In mathematics, optimization or mathematical programming refers to the choosing of the best element from some set of available alternatives. In the simplest case, this means solving problems in which one seeks to minimize or maximize a real function by systematically choosing the values of real or integer variables from within an allowed set. This formulation, using a scalar, real-valued objective function, is probably the simplest example; the generalization of optimization theory and techniques to other formulations comprises a large area of applied mathematics. More generally, it means finding "best available" values of some objective function given a defined domain, including a variety of different types of objective functions and different types of domains. For a fault in the system whole process of restoration and reconfiguration will be performed on the test system. There can be a lot of paths for restoration. A load which is being affected by the faulted load can be restoring using different path. Question is that, what will be the correct and most suitable path for the restoration. This will be done by checking all the possible solution in the system. Corresponding to all these possible solution, different parameters will be calculated like LBI, losses etc. Based on these parameters, the best solution will be used for the optimization. Therefore, optimization in a system is done to get the most stable solution for a different path for the restoration and reconfiguration. Now based on different combination, list of solution is collected. Elimination of these solutions will be done based on system constraints. So for rest of the solution, the load flow analysis is performed. Corresponding to each solution, LBI is calculated. Finally minimum loss of the system and least LBI leads to the stable configuration.

5.1 Selection of Algorithm for Optimization

5.1.1 Optimization Techniques

Optimization problem can be been solved using following algorithms [7]:

1. Particle Swarm Optimization.
2. Binary Particle Swarm Optimization.

5.2 System Constraints for BPSO

The system constrains which should be maintained for BPSO are as follows [7]:

1. No feeder section can be left out of service.
2. Radial network structure must be retained.
3. Bus voltage magnitude can't exceed upper and lower limits.

6. FPGA

FPGA [8] is a type of integrated circuit (IC) containing a matrix of logic cells that can be programmed by a user to act as an arbitrary integrated circuit. For example, one can implement a processor, a digital filter or an interrupt controller on the basis of FPGA. Larger FPGA's even allows user to create complex system-on-chip (SoC) containing several interconnected components. The process of FPGA engineering usually involves writing a description in a special language (hardware description language "HDL" or Verilog). The FPGA configuration data (firmware) is then created by special software from this description. Given the cost of an FPGA firmware development (which is relatively low) and the ability to reprogram FPGA's many times, it isn't surprising that FPGA's has conquered a noticeable part of the market. The pros and cons of FPGA's (versus ASICs "application-specific integrated circuits") are summarized in the following table:

- Low design costs, simplified design flow.
- Shorter time-to-market.
- Re-programmability.

Hardware is needed as well as software platform to generate the pulses. In FPGA architecture using the Xilinx platform can generate the pulses. Generated pulses will be used to control the switch status before and after the faults. It will minimize the losses and number of switching operation. The FPGA pulses will be transmitted in the communication cables which will be parallel to the line. So for communication cables we need low voltages only. And further signals can be decoded and the loads can be online or offline. Beside this system mapping is possible in Xilinx architecture to control the whole system. It also increases the speed of operation of the system. Beside all this advantage the best thing is that implementation of any type of algorithms is very is in Xilinx because the syntax and logic are almost same as in the C-programming.

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7. PROBLEM FORMULATION & SOLUTION

7.1 Problem Formulation for Restoration

For representing any system with the nodes (N) formed by the network blocks and switches (S) which connects the two blocks that may be in opened or closed position. For each load its required power must be known. Thus by calculating the demand of each node, the total demand of any feeder will be calculated. After finding total demand of the feeder, find the reserve capacity by subtracting the total demand of the load which forms the total capacity of the system. All the loads and feeders are connected through the buses which transmit the power to the various loads. Considering a three feeder system for simplicity, there is one special connection between the loads of feeder to the load of other feeder. This special connection is working in such a way that connection is NO (normally open) condition when there is no fault in the system but it will close if there is a fault in the feeder. The special switch will close according to the requirements of restoration in the different feeder. To analyse the system as a tree which have its sub-tree should be connected in a proper way. The advantage of tree configuration is that it is efficient in order to maintain distribution feeder continuity and radiality. In fig-1, the status of a 3 feeder network having 6 loads in each feeder is shown. In general the feeder will work normally and each feeder will provide the necessary amount of power to each load depending upon their requirement and some amount of power will always be there as in reserve mode. Initially the switch D will be in NO condition as there is no fault in the system. If there is a fault in the system then the complete system status will change.

7.2 Fault Analysis

For any power plant the main aim is to restore power as fast as possible. Otherwise plant may have to pay more penalties to the consumer because of heavy interruption. In the power system it cannot give the assurance that system will work 100% efficiently. Even 0.1% irregularity in the system can lead to a big fault in the system. But it can restore the system after the fault by alternate path. If fault occurs in the system the loads which are getting the power through the faulted load will also get affected because of the fault. Hence the healthy loads are getting affected. So it can't restore the faulted load and we have to repair it manually, that is the only option for the faulted load. For the affected load, the power will be supplied through another way. With the help of another feeder, it can restore the loads by maintaining the continuity of the system. Just after a fault, the faulted load will be isolated from the near-by connected load. These near-by loads will make a sub-trees that has to be restored. In the system, there are two sub-trees; they are load 3 and load 4, 5, 6 that is to be restored where each of sub-trees is basically a sub problem that has to be solved separately because they have no direct relation after the fault. The sub-tree formed will depend on the faulted block. In the proposed system the feeder 1 and 2 are having extra 10-10 unit and feeder 3 is having 5 units and each blocks in the feeder requires 5 units. If a fault is present at load 2. The near-by loads of the faulted load will separate themselves from the faulted load in order to save the non-faulty loads from the faulty load. After a fault the un-served load will make the list of sub-tree. This sub-tree will be equivalent to a sub-problem and that must be solved separately. In the above case if fault at load 2, then its near-by agents 1, 3 & 5 will separate themselves from the faulted load 2. Before fault the power is supplied through load 2 for the loads 3, 4, 5 & 6. Because of the fault in load 2, loads 3, 4, 5, 6 will be cut off from the network. At this stage, to restore these loads through another way is our main concern. Those blocks which are in off condition will find the possible path starting from the initial block (1) to the end block (18) and then these blocks will check the power availability to the feeder and then blocks will be restored according to the power availability of the feeder. If all the feeders don't have additional power for the blocks then in that condition our blocks can't be restored. The switch D (shown in figure) will be closed to restore the loads. The switch D will close for the load 3, 4, 5 & 6. Hence it will get required amount of power from the near-by feeder and can restore it. Therefore, load 3 connects itself from load 14 of feeder 3 and it will be restored. Feeder 3 is having zero additional units, load 4 and 5 will be connected from the load 11 and 12 of feeder 2 and it can be restored. Feeder 2 is having 0 buffer unit, finally the load 6 will not be restored as no feeder is having additional amount of units. Based on this restoration algorithm, the switch D and it works when fault is occurs in the system. The algorithm maintains a list of solution which is initially vacant and to which the solutions are added as it is found that the maximum number of solution in the list and it can be changed by the operator. In the list, the best solution will be taken as the final conclusion for fault analysis. This approach has taken initially for a small level but it can be extended for large systems.

7.3 Algorithm for Restoration using Multi-agent

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[6]

1. Open all switches connected to the faulted block to isolate it. For each switch that is opened, a sub-tree is generated, which have to be restored, except for the switch that connects the faulted block to a block the feeder is still feeding normally (a block that is "before" the fault).
2. Based on step 1, make change in the bus connectivity matrix and from the load status array. Put zero in bus connection matrix for no connection between node and put zero for unfed node in load status array.
3. If there is a connection between two unfed node(load[i,j]=1) change it by loop Switch(load[i,j]=2).
4. Create a list of the blocks still being fed and containing at this moment only the blocks the substation is still feeding, if any.
5. Check if there is a loop switch between a fed block and an unfed one. (Possible connections are represented as 2 in bus-connectivity matrix).
6. The unfed block which is only connected to faulted block (node or load) cannot be restored.
7. If there is a loop switch between fed and unfed block, check the feeder at which the fed block is getting power.
8. If that feeder has additional power for unfed block, connect the fed and unfed node and make necessary changes in the load connectivity matrix and load status array.
9. Now move to next unfed block and repeat from step 3.
10. After checking the each unfed block, repeat again from step 3 for 'n' times where n= number of fault node (block) from starting.
11. Check the load status and which node the value to load status is zero and that cannot be restored.

8. IMPLEMENTATION OF ALGORITHM IN DISTRIBUTION SYSTEM

8.1 Fitness Function

To make the stability and reliability of the distribution it is very important to keep the load balancing via feeder reconfiguration so that network could be enhanced. The objective of this optimization problem can be expressed by the minimization of the load balancing index (LBI) [9].

$$LBI = \sum_{i=1}^{N} L_i \left(\frac{|I_i|}{I_i^R} \right)^2 \quad \ldots \quad (1)$$

Where:

N: Total number of branches in the system after restoration,

L_i : Length of branch i,

I_i : Complex current flow in branch i,

I_i^R : Current rating (ampere capacity) of bus i.

The LBI value should be minimum in-order to get the best solution by adjusting the switch position. According to the switch operation the complex current is flowing through sectionalized switches in the simplified model. The reconfiguration problem cannot be solved by the traditional methods because of the non-linearity of the system after the fault. The PSO method is used for the above case for optimization which is explained in reference [10].

8.2 Test system for BPSO Implementation

The test system, as shown in Fig. 2, includes 13 distribution transformers and 16 branches. The network is supplied by three substations and each branch has been considered with a switch (1), (2). The network has three meshes: branch 3, 4, 5 and 6; branch 7, 8 and 9; branch 10, 11, 12, 13 and 14. For each group of branch, only one switch on one of the branches can be opened, in order to maintain the radial structure. As branch 15 does not belong to any mesh, it must be closed to keep it connected with the source. In the first part, the restoration process has been achieved on the system. The method is now been implemented on standard IEEE bus. The first important criterion is the system switching loss which will be different for the different paths by which the restoration is done on

the system. Hence to find the system losses, load flow analysis has to be performed so that the system losses can be found. The minimum loss will correspond to the most stable configuration.

Each feeder has their fixed number of loads. Each feeder has different equipments like buses, tie lines switches and loads. Feeder 1 has five buses b1, b2, b3, b4, b5. All the buses are connected from each other by switches S. Beside this for connecting

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one feeder to another we have some special switch which will come in existence when there is fault in the system. Now the question is how to get the best path. So the minimum LBI corresponding to the loss will result to the most stable solution.

The last part of the paper deals with the controlling of the switch status by generating the pulses corresponding to required solution using Xilinx. As the manual operation requires a lot of switching operations and has a great complication. In addition, it is difficult to control the switch status from a remote area. Hence to verify the same, the FPGA hardware kit is used.

9. RESULTS AND ANALYSIS

This part contains all the results and analysis including tests on standard system. To verify the results, different software is used. As it is already discussed for a test system having three feeders with some fixed load in each as shown in fig 1. In the proposed system the feeder 1 and 2 are having extra 10-10 unit and feeder 3 is having 5 units and each blocks in the feeder requires 5 units. Now if a fault is present at load 2. The near-by loads of the faulted load will separate themselves from the faulted load to save the non-faulty loads from the faulty dead. After a fault the un-served load will make the list of sub-tree. This sub-tree will be equivalent to a sub-problem and that must be solved separately. For the fault at load 2, its near-by agents 1, 3 & 5 will separate themselves from the faulted load 2. Before fault the power is supplied through load 2 for the loads 3, 4, 5 & 6. Because of the fault, loads 3, 4, 5, 6 will become useless and they will be out off from the network. At this stage, restoration of these loads through another way is required. Those blocks which are in off condition will find the possible path starting from the initial block (1) to the end block (18) and then these blocks will check the power availability to the feeder and then blocks will be restored according to the power availability of the feeder. If all the feeders don't have additional power for the blocks then in that condition, blocks can't be restored. After the separation of near-by agent from the faulted load the special switch D will come in to the network. The switch D will be closed for the load restoration. In the above system the switch D will close for the load 3, 4, 5 & 6. Hence they will get required amount of power from the near-by feeder and can restore themselves. Hence load 3 connects itself from load 14 of feeder 3 and it will be restored. Now feeder 3 is having zero additional units, load 4 and 5 will connected itself from the load 11 and 12 of feeder 2 and it can be restored. Now feeder 2 is having 0 buffer units, finally the Refer figure – 4 for results

9.1 Reconfiguration Output

After restoration, reconfiguration process is performed on test system. The simulation results are as shown below:

- Minimum LBI= 6.0669.
- Switch status correspond to the minimum LBI that must be open=6, 8, 13.
- So this configuration will be stable after optimization.
- Status 1 1 1 1 1 0 1 0 1 1 1 1 0 1 1 1

9.2 Restoration and Reconfiguration Outputs

To perform the restoration and the optimization simultaneously on the standard system to a particular fault condition system will generate the different possible solution and then best solution will be selected by optimization. Here the minimization of LBI is the basis of optimization.

- Minimum Load Balancing Index: 6.063301e+000.
- Switch status corresponding to Minimum Load Balancing Index that must be open: 6, 9, and 15.

In the above output for a fault in the load for the explanation will be as follows:

The load four will separate from the system by disconnecting the switch S12 and S13. Now corresponding to that fault condition all the three feeder will be restored and simultaneously it will reconfigured by the BPSO.

Table 1: Open switch and load balancing index before and after feeder reconfiguration, when fault is in Bus 4:

	Open switch	Load balancing index
Initial condition	5,9,13	6.536
Final solution	6,8,12,13	6.989

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9.3 FPGA Output

In FPGA, the input will be taken from the output of MATLAB Programme. The output of the MATLAB programme corresponding to a most stable configuration after optimization. Corresponding to this stable configuration, the pulses are generated using Xilinx. To verify the same programme in hardware, the programme is feed in FPGA kit. For the figure shown below the output results is explained as; the software used for the FPGA kit is Quartus. The sample output for a fault on a load 4 using FPGA kit is as shown in figure -5. When there is fault on load 4 then it cannot be restored and rest of the LED will be restored by proper optimization processes. FPGA kit which is shown has 16 LED & 16 switches. These LED's are like loads and the switches ON will show the loads are in good condition. According to initial condition given, the LED's will be made to glow. That means loads are getting supply from feeder. All switches are in ON position showing the healthy loads. Now, if any fault comes in some load. Then in FPGA kit, the operator has to switch OFF the load 4 by operating that switch number which is allocated to that load 4. After switching it OFF, FPGA which is uploaded with coding done in Xilinx, FPGA will run the coding and comes to a result by showing LED's. So by seeing the LED's we can easily get to know which load will get affected, being a healthy load, due to faulted load. After clearing of fault from the faulted load, again the switch can be bring back to ON condition and hence, restoring the system to its original condition.

10. CONCLUSION

The methodology used can be implemented in real networks. The priority based solution can be generated. Such a generated solution will be more useful instead of randomly generated solution. The solution generated will be very quick & fast and can perform the required operation within system and hence the various phenomenons like black out and brown out in the system can be avoided. Beside this the solution generated are based on system losses hence the losses will be automatically reduced. For optimization the generated results are more accurate and efficient. The switch status is also controlled by the pulses hence number of switching operation will be less based on the requirement. Hence it can be implemented in switchgear efficiently in order to control the losses where high switching operation leads to high losses. Beside this the control of switch in digital form will leads to minimum loss and maximum efficiency of the system.

Since this paper includes combination of different parts like restoration, optimization and FPGA hence it can control the system through electronic means from a distant place for the fault in the system. So the operator can react fast on the system from the distant place when the fault has occurred.

As we have considered system losses as the only constraint and also the system taken is very small compared to the real systems. As power system restoration is a complex procedures that one should see different type of instability, standing phase angle and cold load pickup and so on. These constraints can be considered will be considered for future research.

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Appendix

The DE1 package includes:

- DE1 board.
- USB Cable for FPGA programming and control.
- CD-ROM containing the DE1 documentation and supporting materials, including the User Manual, the Control Panel utility, reference designs and demonstrations, device datasheets, tutorials, and a set of laboratory exercises.
- CD-ROMs containing Altera's Quartus® II 6.0 Web Edition software and the Nios® II 5.0 embedded processor.
- Bag of six rubber (silicon) covers for the DE1 board stands. The bag also contains some extender pins, which can be used to facilitate easier probing with testing equipment of the board's I/O expansion headers.
- Clear plastic cover for the board.
- 9V DC wall-mount power supply.
- Layout and Components:

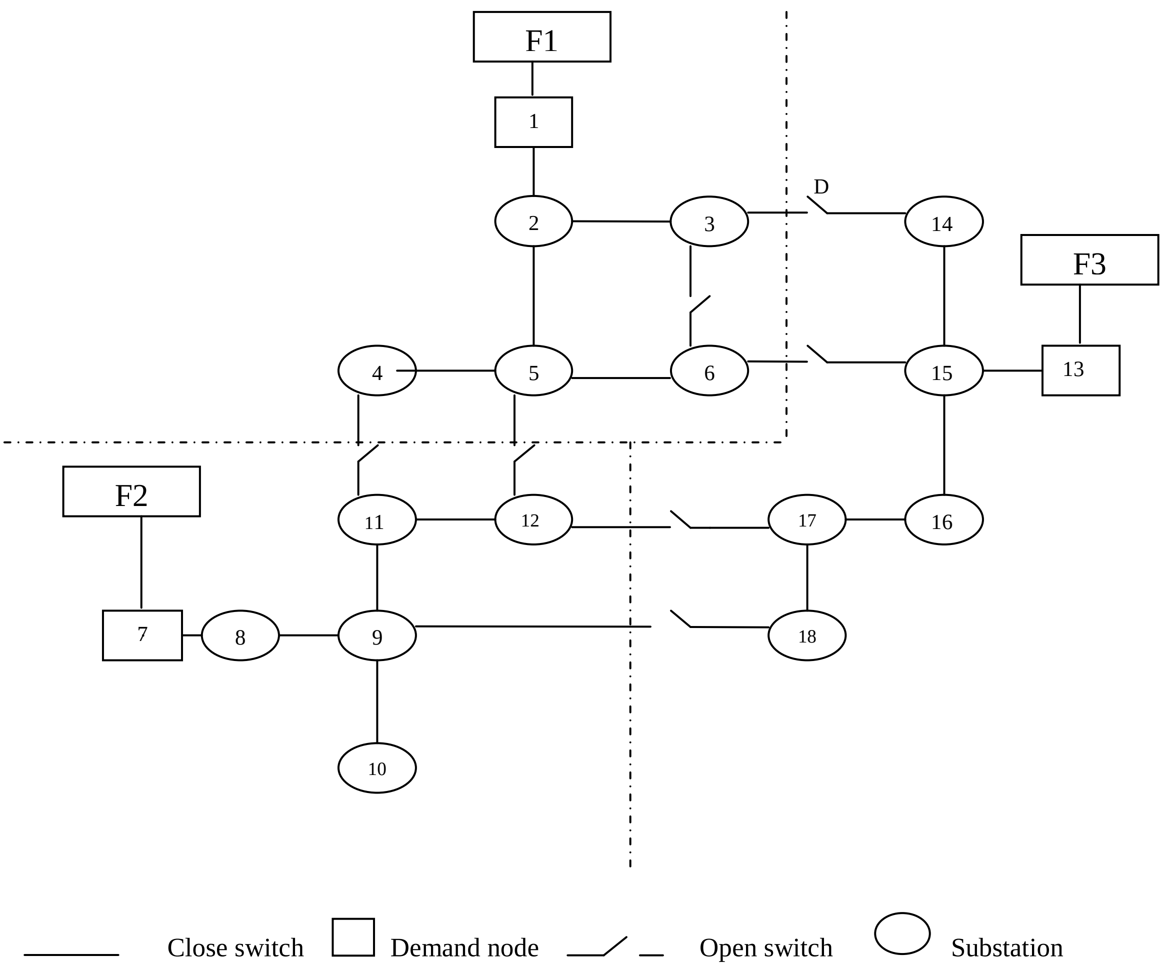

Fig. 1 Initial test system status for restoration

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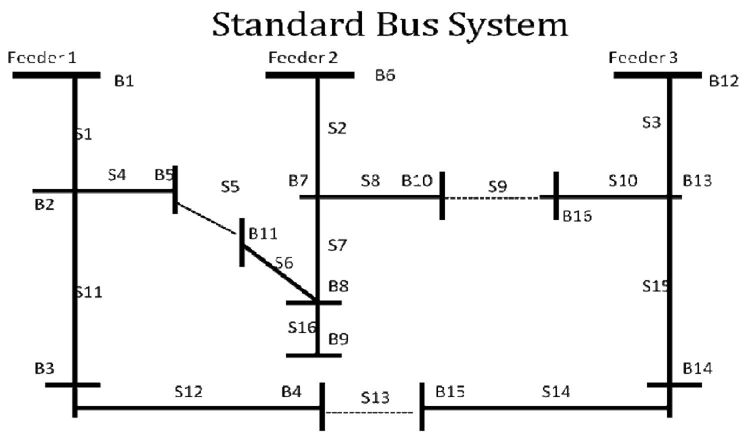

Fig. 2 Schematic Diagram of a 16-Bus Distribution system

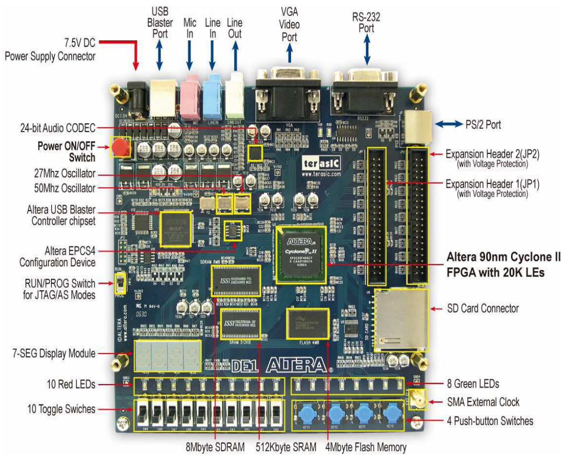

Fig. 3 The layout of DE1 and its component for FPGA are below:

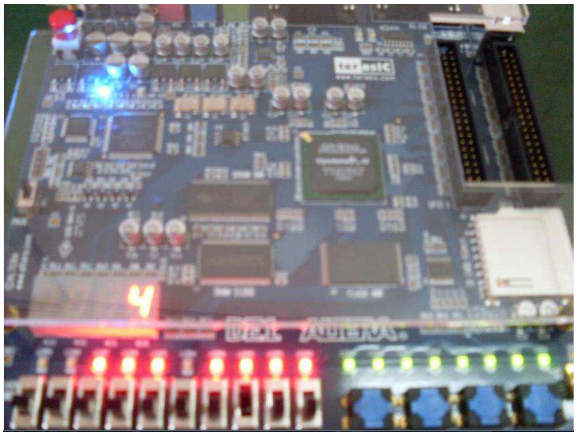

Figure -5 Sample output for a fault on a load 4 using FPGA kit

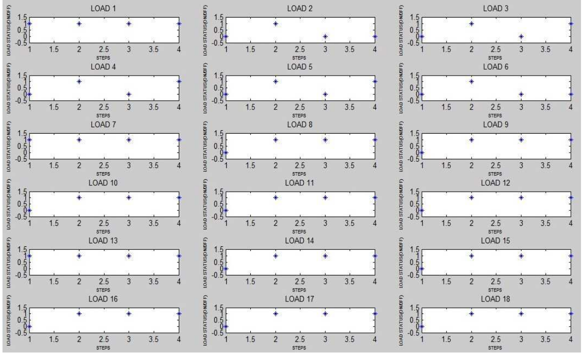

Fig. 4 Results for the restoration in the MATLAB program