Configuration Validation Using ATP Simulation For An Automatic Shipboard Power System Restoration Method

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Abstract – **When a fault occurs in power systems, protective devices detect fault areas and disconnect the faulted sections of the network by opening circuit breakers, fuses etc.. Some loads become unavailable after the fault and should be re-energized, as quickly as possible, after the fault has been isolated. The re-energizing procedure is called service restoration. In Navy shipboard power systems (SPS), the automated reconfiguration for service restoration is a new focus area of research. The main objective of restoration on the SPS is to restore as much out-of-service load as possible by reconfiguration with priority given to critical loads. Once the switching actions to restore a load have been determined, the next step is to make sure that there are no operating constraint violations because of those switching actions. To check for constraint violations, line flows and voltage at each node need to be determined via a Load Flow. In this paper a method using ATP simulation, during runtime, to determine if the suggested switching actions for restoring loads violate any operating constraints, have been presented.**

Keywords – shipboard power system (SPS), reconfiguration, restoration and simulation.

I. INTRODUCTION

The electric power systems in U.S. Navy ships supply energy to sophisticated systems for weapons, communications, navigation and operation. It is very important to maintain availability of energy to the connected loads that keep systems operational. One type of electric system used in navy ship is AC radial configuration. The electric system uses three-phase power generated and distributed in an ungrounded delta configuration. Ungrounded systems are used to ensure continued operation of the electric system in the presence of a single-phase ground fault. The voltages are generated at levels of 450 volts AC at 60 Hz. The generators are connected in a ring configuration, which provides more flexibility in terms of generation, connection and system configuration. The system is configured radially downstream of the generator switchboards.

Faults in a Shipboard Power System (SPS) may occur due to material casualties of individual loads or widespread fault due to battle damage. In addition to load faults, casualties can happen to cables, power generating equipment, or power distribution buses, which can lead to conditions of having inadequate power generation capacity for all attached loads. After a fault occurs, protective devices operate to isolate the faulted section. This may lead to unfaulted section(s) that are not getting supply. Therefore it is required to automatically and quickly restore supply to these unfaulted sections of the SPS to improve system survivability. This can be achieved by changing the configuration of the system by opening and/or closing switches to restore supply to maximum number of loads in the unfaulted sections of the SPS or in other words by performing Service Restoration.

An Expert System based Restoration method (XRest) for SPS was developed at Power System Automation Laboratory (PSAL), Texas A&M University. In this method loads are restored one by one in the order of priority. Some of the loads are designated as vital and some as non-vital. Vital loads are given higher priority than non-vital loads, during restoration. One major component of the XRest is the module that suggests the switching actions required to re-energize a load. These suggested switching actions, if performed, will lead to a new configuration. The other main module of XRest is a configuration validation module. The function of configuration validation module is to check for current or voltage constraint violations in the suggested configuration (configuration obtained by incorporating the suggested switching actions). To perform constraint checking, current flows in lines and the voltage at nodes are required. These can be determined by performing a load flow on the suggested configuration. If there are any violations then those switching action(s) cannot be performed and the load is unrestorable.

In the literature, various papers can be found which deal with the voltage and current constraint problem. A simplified load flow program has been developed to check the feasibility of a new configuration for a distribution network suffering from faults [1]. An ac load flow analysis has also been performed to evaluate the effect of reconfiguring a distribution system [2]. A Distribution Load Flow (DISTLF) has been developed to perform load flow on a reconfigured network to obtain the branch currents and node voltages for checking constraints [3,4]. In most of the papers, to check for constraints, either a separate program for load flow analysis has been developed or an approximate or simplified load flow program has been developed.

Load Flow methods mentioned in the previous paragraph are not available and not described thoroughly in the papers for the implementation by others. Hence a load flow routine needed to be developed for XRest. Alternative Transients Program (ATP) is a very popular and free tool which is used in modeling and running simulation studies. It also has a Load Flow routine which can be used to perform three phase load flow on an electrical network. But this routine cannot be used for ring connected AC radial SPS networks, details of which is discussed in section III. In order to achieve the objective of configuration validation, some other method is required which can give the current and voltage information for the SPS network. In the work presented in this paper, ATP simulation is used which gives circuit solution for the SPS network. The results obtained from this simulation can then be used for constraint check, instead of results obtained from a load flow.

In the work presented here, a runtime configuration validation module for an automatic expert system based reconfiguration methodology for load restoration in a SPS will be discussed. This module uses ATP simulation to obtain results similar to that of a fast three phase load flow, details of which will be presented. The expert system based restoration program determines the switching actions needed to restore each load. The configuration validation module was developed in C++ and ATP. The SPS considered in the present study is based on the layout profile of an U.S. surface combatant ship. Test results obtained after performing restoration, which uses the configuration validation module, will be shown and discussed in this paper.

II. Expert System Restoration in SPS

In this section first overview of a navy SPS is given and then a brief overview of Expert System based Load Restoration method for an SPS is presented. An SPS consists of various electrical components such as AC generators, load center switchboards, transformers, static loads, induction motors, power panels, circuit breakers (CB) and many three-phase and single-phase cables [5]. Although most of the loads are three phase loads, there are some single phase loads which can cause unbalance in the three phase system. There are low voltage protective devices called low voltage release (LVR) and low voltage protection (LVP) which are placed with the electric motor in the power system to protect it from low voltage conditions. When a low voltage condition is present the LVP/LVR opens thereby de-energizing the load. When the low voltage condition is cleared, LVRs are automatically switched back to power again whereas LVPs require an operator to manually restart it and restore load. The load center switchboards supply power to power panels or individual loads either directly or via automatic bus transfers (ABT) or manual bus transfers (MBT). The loads are designated as vital or non vital. For vital loads, two sources of power (normal or alternate) are provided from separate paths via ABTs or MBTs. When vital loads lose supply through its normal path, for example because of faults during battle, supply is restored through the alternate path provided via ABT or MBT. When the vital load is supplied via an ABT, switching to alternate path occurs automatically. Whereas a vital load supplied via a MBT requires manual operation by an operator to switch to alternate path. For an ABT, if the supply is restored to the normal path, it automatically switches back to the normal path. The status of switches (CB/ABT/MBT/LVP/LVR) defines the configuration of the SPS. During reconfiguration for load restoration statuses of these switches are required to be changed in order to achieve the new configuration.

The Restoration scheme consists of various systems such as Geographical Information System (GIS), Failure Assessment System (FAST) and Expert System Restoration (XRest). Fig 1 shows the block diagram representation of the overall Expert System Restoration scheme. Real time measurements are continuously updated in real time tables in the GIS database. The real time data consists of current, voltage, generator frequency, CB status, LVR/LVP status, and BT status measurements. The FAST takes historical data from the Historical database, frequency, voltage and current deviation limits from the Constraint database and real time data from the GIS database to detect and locate a fault. Once a fault has been detected and located, the output of FAST, the affected loads and faulted component information, is provided as input to the XRest module. Various static, connectivity and real time information from the GIS database are also provided as input to XRest module. It also takes as input, the node voltage limits and cable current limits as input from the Constraint database. The XRest then determines whether the loads are restorable. Then it outputs the list of restorable and unrestorable loads and the switching operation sequences for each restorable load. The operation sequence represents the control commands for CBs, MBTs and LVPs.

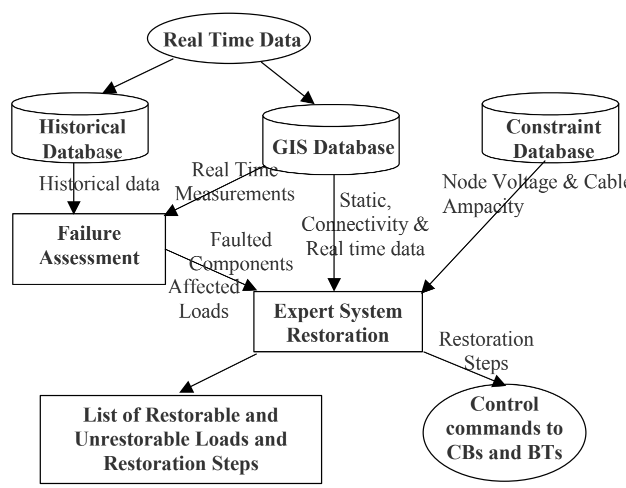

Fig. 1 Block diagram of overall Expert System Restoration scheme

III. ATP Based Configuration Validation Module

In this section, the reason for choosing ATP simulation for configuration validation module is presented. Then details of the configuration validation module is presented. Also use of ATP simulation in configuration validation module is discussed.

ATP (Alternative Transients Program) is a well-known simulation tool that can be used for simulation of both electromagnetic and electromechanical phenomena in complex networks. It not only allows for detailed component modeling, but also for modeling of various types of fault disturbances and integration of control system modules to the simulated network. So it is well suited for modeling of various electrical components of SPS and to run various fault scenario on modeled SPS.

ATP software provides a load flow routine. PSAL (Power System Automation Laboratory) investigated the use of this routine for performing load flow analysis of a navy SPS. A very scaled down circuit with a configuration similar to a SPS was used. In this SPS, there were three buses connected in a ring configuration. Two buses had one generator each, on them. One of these buses was chosen as the slack bus while the other was chosen as a PV bus. The distance between the two generator buses, as in the real SPS, was small, so the impedance between the tie line connecting these buses is quite small. So the voltage level at these buses were almost equal. The third bus and the slack bus, each had a three phase load on them. The ATP load flow routine was then used to perform load flow on this SPS, but it did not converge. When the impedance of the tie line connecting these two buses was increased to a high value, convergence was achieved but then in that case the voltage magnitude at the PV bus was changed by the routine. The ATP Load Flow routine therefore cannot be used to perform three phase load flow on ring connected AC radial SPS networks.

When ATP circuit simulation is performed, it produces a binary output file which contains voltage and current information at each measuring node in the network for each time step of simulation. Studies were done for various scenarios to estimate the time when ATP simulation has reached steady state. The voltage and current measurements at the time step when the system reaches steady state are similar to the results obtained by doing a Load Flow analysis. Authors realize that a steady state circuit simulation would have performed the calculations faster, but since ATP is easily available and the SPS was already modeled in ATP at PSAL, the authors were motivated to use ATP circuit simulation to develop the configuration validation module.

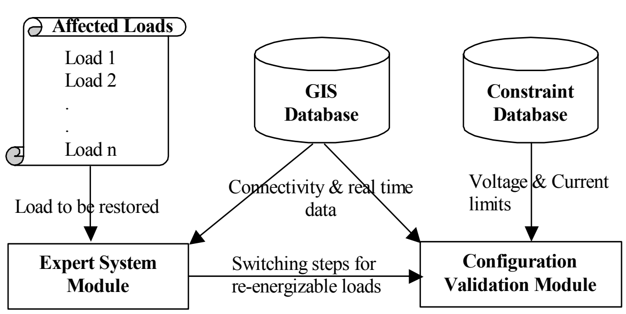

Fig. 2 Block diagram for XRest

Fig. 2 shows the block diagram for XRest. XRest takes the list of affected loads as input. XRest basically consists of two modules – Expert System module and Configuration Validation module. For each affected load, the Expert System module tries to find an alternate path for re-energization. It also takes connectivity and real time data as input from GIS database. If an alternate path is found, then the switching operations for that path are suggested as output. These switching operations serve as input to the configuration validation module shown in Fig. 3. Fig 3 shows the block diagram representation of the configuration validation module. Post fault CB status and BT, LVP, and LVR position are obtained from the Restoration database to bring modeled network to post fault configuration. Then the suggested switching actions for load re-energization are performed on the post fault configuration to obtain the new configuration. Then ATP Simulation is preformed on this new configuration. From the ATP Simulation output file, the currents flowing in all the cables and voltage at each load node are extracted. Thereafter checking is performed to determine, if current in any cable exceeds the upper current limit for that cable, or if voltage magnitude at any load node lies outside the upper and lower voltage limits for that load node. These checking are performed by comparing the current and voltage values with the appropriate current and voltage limits obtained from the Constraint database. If there are any current or voltage limits violation then the suggested switching actions for that load are rejected. But if there is no violation then the suggested switching actions are accepted and are updated in the Restoration database. Also these switching actions are included in the output of the overall restoration scheme. Then the next load, from the list of affected loads, is considered.

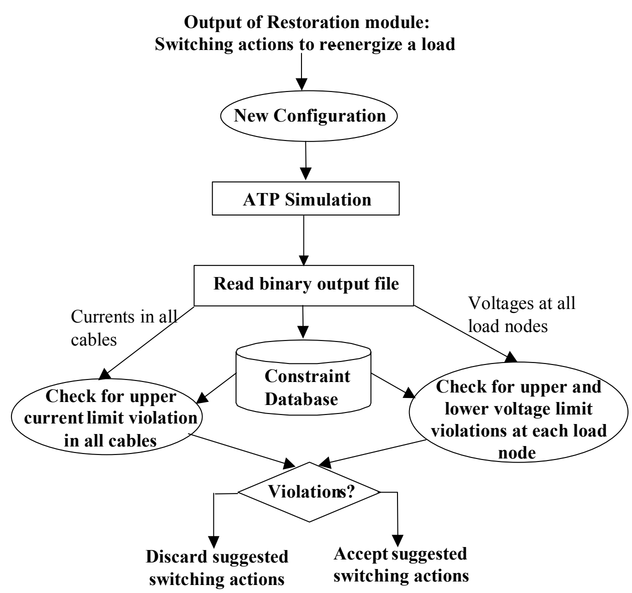

Fig. 3 Configuration Validation module

In order to run ATP simulation, as discussed earlier, a computer model of a test system of an SPS was designed and modeled in ATP Various electrical components and monitoring elements, present on a SPS, were modeled.

As mentioned earlier, ATP simulation is performed on a SPS configuration, which incorporates the switching actions suggested by the Restoration module. In order to incorporate these switching actions, status of switches are required to be changed in the present configuration. Configuration of a network is actually defined by the status of switches present in that network. Also since the Restoration of SPS, as discussed in previous section, is an automatic process, the change in the present configuration is required to be performed at runtime. In the SPS, the configuration at any given moment is defined by the status of CBs, BTs, and LVPs/LVRs present in that SPS at a given time instant. Change in present configuration actually involves opening and closing of switches (CBs, BTs, and LVPs/LVRs). The output of the Restoration module consists of one or more of the following action:

- Opening or closing of CBs
- Transferring MBTs
- Opening or closing of LVPs

To obtain the new configuration, one or more of the above mentioned switching actions are required to be performed at runtime, in the input files that are required to run ATP simulation on the SPS. In order to achieve this, the following changes were made in the input files for ATP simulation of the SPS:

- All the CBs were replaced by switches.
- All the BTs were replaced by three switches – one on normal side, one on alternate side and one on load side of BT.
- All the LVPs were replaced by switches

The suggested switching actions, by Restoration module, are performed to the ATP simulation files, at runtime, by an automated program developed in C++. This program changes the status of switches in the ATP simulation files. For example, if the new switching action suggested by the Restoration module was to open a CB then in that case the switch which replaced that CB will be opened by the program. In case of a BT, for example, if the new switching required to transfer that BT to the alternate side then the switch on the normal side will be opened and the switch on the alternate side will be closed by the program. The ATP application (TPBIG.exe) is called by the C++ program, and ATP simulation files are passed to it to perform ATP simulation.

To measure the current in each cable and voltage at all load nodes, measuring switches were placed at appropriate locations. As explained earlier, voltage and current magnitudes are extracted for the time step when the steady state has been reached. A module to read the current and voltage measurement from the binary output file of ATP simulation was developed. The last step in the configuration validation module is to perform actual constraint checking by comparing the actual current and voltage measurements with the appropriate upper current and upper and lower voltage limits. If there are no violations, then the switching actions are accepted and the load is set to be restorable otherwise the load is marked as unrestorable and the switching actions are discarded.

IV. TEST RESULTS

In this section a test example is presented which explains the procedure mentioned in the previous section. The test system, shown in Fig. 4, was modeled in ATP. This test system is a reduced version of the SPS on a surface combatant ship. The system operating voltages were 440 V and 115 V. In the functional mode of the ship, the generation capacity of the system was 5.0 MW, and the total load in the system was 2.69 MW. As shown in Fig. 4, the test system had three generators with one for emergency service and three main switchboards that form a ring configuration with bus-tie cables. Downstream of the main switchboards, there were five load center switchboards, eleven transformers, twenty-six static loads, nineteen induction motors, and many three-phase and single-phase cables. The circuits downstream of the main switchboards were distributed in radial configuration.

A Fault was simulated on a LC cable C1305, as shown in Fig 4. Because of this fault, circuit breaker CBSB0305 will open and isolate the faulted section. This will prevent electrical supply from loads downstream of cable C1305. The FAST module determined the faulted components and found four loads, designated as affected loads, have lost supply. These loads were - Gal1, Gal2, Elex3 and Elex4.

XRest is then executed to obtain switching actions to restore supply to as many affected loads as possible from the list above. The XRest module then suggested switching actions required to re-energize the load. For each load determined as re-energizable by XRest, voltage and current constraints checking was performed on the suggested new configuration. Steps performed by the configuration validation module are presented below.

The switching action suggested to restore the Elex4 load is to transfer MBT4 to its alternate side. This switching action was incorporated in ATP simulation files by closing the switch corresponding to MBT4 on the alternate side and opening the switch on the normal side in the ATP input file. Then ATP simulation was performed and its output was stored in a binary output file. From this file, voltage and current values were read and a constraint check was performed. The output of the constraint check result obtained in this case are shown in Table I, under heading Elex4, for a few cables and a load node. As shown in the table, the voltage and current values for all load nodes and cables, for this case, were within the specified limits. Hence constraint checking showed no constraint violation. Load Elex4 is marked as restorable and the switching action, transfer MBT4, is given as output. Also the status of bus transfer MBT4 is changed from the normal to the alternate side in the Restoration database.

The switching action suggested to restore the load Elex3 load is to transfer MBT3 to its alternate side. This switching action was incorporated in ATP simulation files by closing the switch corresponding to MBT3 on the alternate side and opening the switch on the normal side. Then ATP simulation was performed and the constraint checking showed current violation in cable C1116 which is the cable just upstream of load LCP9.

Table I Test Results

Load: Elex4										
Current Constraints					**Voltage Constraints**					
Serial No.	**Cable Name**	**Upper Current Limit (amps)**	**Actual Current (amps)**	**Constraint Violated**	**Serial No.**	**Load Name**	**Upper Voltage Limit (volts)**	**Lower Voltage Limit (volts)**	**Actual Voltage (volts)**	**Constrain t Violated**
1	C1101A	347.6	270.157	No	1	AcCprsr1 AB	462.0	418.0	443.528	No
2	C1101B	347.6	269.853	No	2	AcCprsr1 BC	462.0	418.0	444.048	No
.	.	.	.	.	.	.				
.	.	.	.	.	.	.				
143	C3313C	90.2	50.1160	No	76	Wtrpmp4 CA	462.0	418.0	441.683	No
Load: Elex3										
Current Constraints										
Serial No.	**Cable Name**	**Upper Current Limit (amps)**	**Actual Current (amps)**	**Constraint Violated**	**Serial No.**	**Load Name**	**Upper Voltage Limit (volts)**	**Lower Voltage Limit (volts)**	**Actual Voltage (volts)**	**Constrain t Violated**
1	C1101A	347.6	269.237	No	No voltage constraint check is performed as a current violation has already been met.					
2	C1101B	347.6	269.174	No						
.	.	.	.	.						
.	.	.	.	.						
143	C1116C	90.3	92.9151	**Yes**						

The results obtained from constraint checking for load Elex3 are shown in Table I, under heading Elex3. From this table we can see that the upper current limit in this cable is 90.3 amps., but the actual current flowing in this cable is 92.9151 amps. Hence there is a current constraint violation. Once this constraint violation was encountered the program comes out of constraint checking loop, without performing any further current constraint checking for remaining cables or voltage constraints checking for load nodes, and the suggested switching actions, to restore load Elex3, are discarded. There is an upper current constraint violation at cable C1116 therefore load Elex3 is marked as unrestorable and switching action – transfer MBT3, is discarded and no changes are made in Restoration database.

Although the Expert System module of XRest module determined that both Elex3 and Elex4 were restorable, the configuration validation module determined that only Elex4 was restorable and Elex3 was unrestorable because its configuration would result in a current constraint violation. The Expert System did not found an alternate path, for re-energization for the other two loads Gal1 and Gal2. So the configuration validation module was not called for these loads. The final output of the Restoration scheme will look similar to what is shown in Table II.

Table II Output of Restoration Program

S. No.	**Loads to be Restored**	**Restorable/ Unrestorable**	**Switching actions required for Restorable loads**
1	Elex4	Restorable	Transfer MBT4
2	Elex3	Unrestorable	-
3	Gal1	Unrestorable	-
4	Gal2	Unrestorable	-

V. CONCLUSIONS

Checking for constraint violations for validating a configuration during a Reconfiguration process is an important task. In this paper a configuration validation module using ATP simulation in an expert system based automatic reconfiguration methodology for load restoration in SPS was presented. This configuration validation module checks for constraint violations and validates the suggested configuration changes. Test results showing various steps involved during the configuration validation module were also presented. When there is a current or voltage constraint violation, then in that case the load for which restoration was being performed was marked as unrestorable otherwise it is deemed as restorable. Future work in this area consists of trying to restore a load during a current constraint violation by shedding non-vital loads, and developing a suitable configuration validation module to complement that function.

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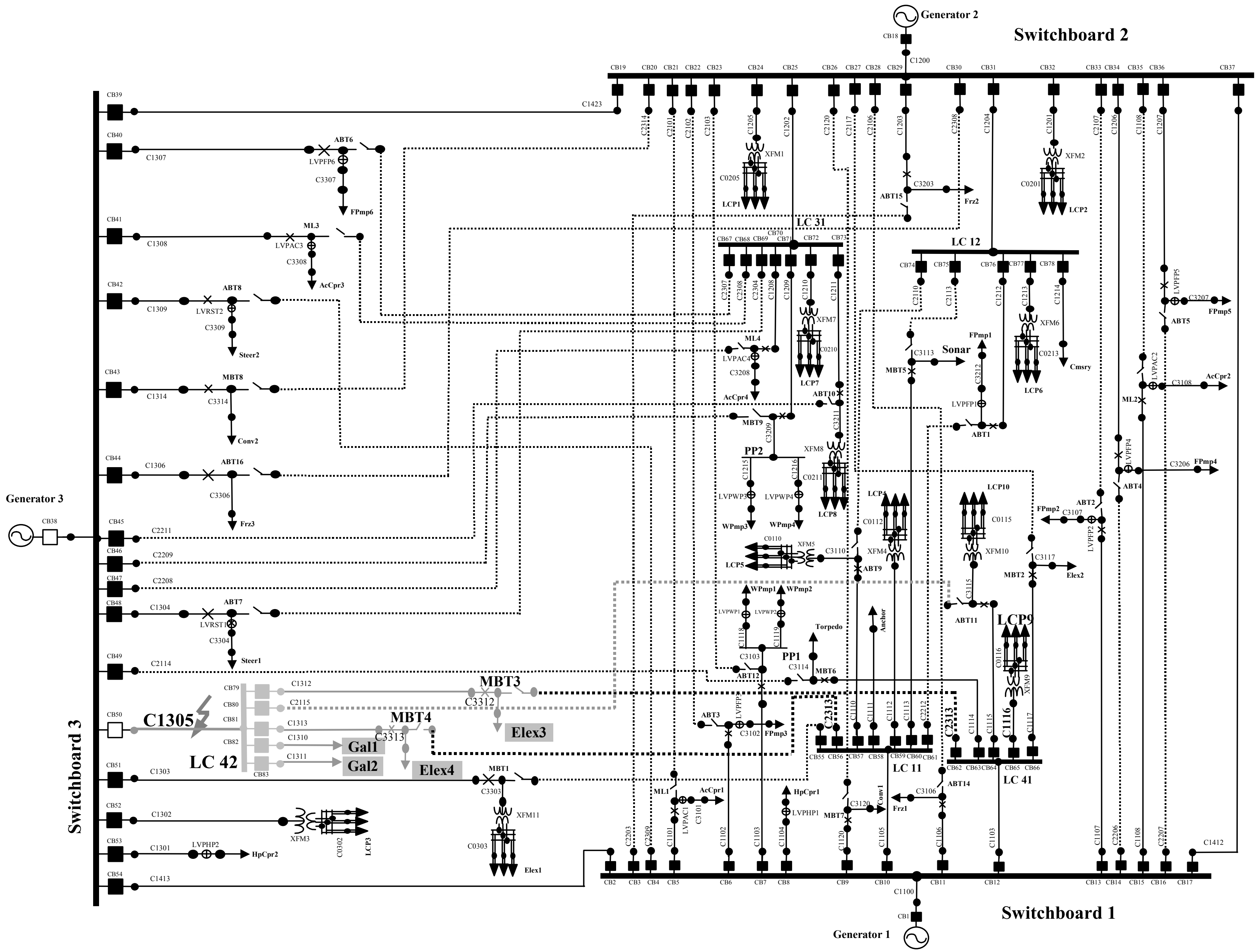

Fig. 4 Fault Scenario on Test System