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Understanding Power System Voltage Collapses Using ARISTO: Effects of Protection

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Abstract-- **This paper is based on a project work of the course "Power Engineering Design Project" given by the Division of Electric Power Engineering, Chalmers University of Technology in Sweden in Fall semester, 2008. The project has focused on simulating power system voltage collapse scenarios using Advanced Real-Time Interactive Simulator for Training and Operation (ARISTO) software. The simulated voltage collapse scenario was successfully implemented. To understand the effects of protection on voltage collapses, the study also focused on different "blackout mitigation" schemes to prevent the complete system blackout such as modification of settings of distance relays and blockings of critical circuit breakers on the transmission systems. The simulation results have shown that with these measures, substantial part of the system can be prevented from blackout. The Nordic 32-bus system is used in the study.**

Index Terms-- **ARISTO, voltage collapse, blackout, island operation, system restoration.**

I. INTRODUCTION

Power systems world-wide have experienced significant disturbances leading to severe and widespread system blackouts in recent years. Examples are large-scale blackouts as seen in the USA, Italy, Sweden and Denmark in 2003 [1]-[4]. These blackouts are typically of low probability but are of great concern to the modern society. Blackouts may lead to thousands or even millions consumers having no electricity during a long period of time. The blackouts could contribute to serious disturbances to national economic activities which results in heavy economic losses and damages to the production processes and/or equipments, and even to human life. For all those reasons, an electric network must be secure and reliable. Of course, potential security improvements could be achieved through transmission system facility reinforcement and generation supply expansion. However, these reinforcements are often long-term, costly, and uncertain. Understanding the reasons behind the blackouts could lead to effective short-term solutions. The simulation of these sequences of events on the system can serve as the basis for understanding main factors causing outages of an electric power system. The main goal of this project is to simulate power system blackouts due to voltage collapses and propose emergency protection schemes to prevent those blackouts. There are several blackout preventive measures as will be reviewed in Section II. In this paper, a mitigation scheme based on load shedding and the blocking of distance protection relays for critical transmission lines is used. The central question of this project would be to determine for which lines the distance relays should be blocked and when so as to give the most effective results, *i.e.,* to prevent a total system voltage collapse. This would lead to a partial blackout in some areas with the rest of the network having limited supply, and hence helps in making the restoration of the system much faster and easier. One could argue that blocking of protection relay could lead to failures of transmission lines. However, we are more concerned with the security of the system as a whole in an emergency situation.

The paper is organized as follows: In the next section, a brief review of voltage collapses and methods for voltage collapse preventions are presented. In Section III, a description of the ARISTO simulator is given. Also in this section, a power system blackout scenario using the Nordic 32-bus system is implemented in the simulator. Section IV presents the blackout prevention method by critical circuit breakers blocking. The restoration process after blackout is described in Section V. Finally, the conclusions are made in section VI.

II. VOLTAGE COLLAPSES AND PREVENTION METHODS

A. *Voltage Stability and Voltage Collapses*

Voltage stability refers to the ability of a power system to maintain steady voltages at all buses in the system after being subjected to a disturbance from a given initial operating condition. It depends on the ability to maintain/restore equilibrium between load demand and load supply from the power system. Voltage instability that may result occurs in the form of a progressive fall or rise of voltages of some buses. A possible outcome of voltage instability is loss of load in an area, or tripping of transmission lines and other elements by their protective systems leading to cascading outages [5],[6].

The term voltage collapse is used to describe the process by which the sequence of events accompanying voltage instability leads to a blackout or abnormally low voltages in a significant part of the power system. Stable (steady) operation at low voltage may continue after transformer tap changers reach their boost limit, with intentional and/or unintentional tripping of some load. Remaining load tends to be voltage sensitive, and the connected demand at normal voltage is not met.

The driving force for voltage instability is usually the loads. In response to a disturbance, power consumed by the loads

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tends to be restored by the action of motor slip adjustment, distribution voltage regulators, tap changing transformers, and thermostats. Restored loads increase the stress on the high voltage network by increasing the reactive power consumption and causing further voltage reduction. A run-down situation causing voltage instability occurs when load dynamics attempt to restore power consumption beyond the capability of the transmission network and the connected generation. The power transfer capability and voltage support by generators are further limited when some of the generators hit their field or armature current time-overload capability limits. Voltage stability is threatened when a disturbance increases the reactive power demand beyond the sustainable capacity of the available reactive power resources. A typical voltage collapse scenario could be summarized as shown in Fig. 1 [5],[7].

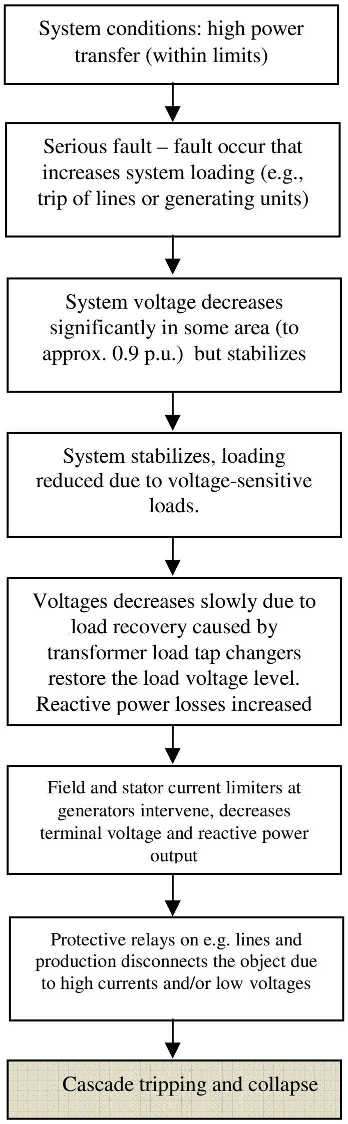

Fig. 1: Flow chart of a typical voltage collapse scenario

In the power system blackouts occurring in 2003, some common situations can be observed as high electricity demand, heavy power transfers, important components were under maintenance (lines and generators) [6],[8]. Then unscheduled outages appear that further weakens the system, such as in Sweden: Loss of Oskarshamn nuclear unit 3; or in US-Canada: loss of transmission lines in Indiana, disconnection of Eastlake 5 generating unit and Stuart-Atlanta 345 kV line in Ohio. Then the following triggering event occurred leading to the blackout. In Sweden, a double bus-bar fault at the 400kV substation in Horred occurred; in US-Canada it was the tripping of the Harding-Chamberlain 345kV line in Ohio. These outages create some transient activities such as power flow surges, overloads, voltage problems and the protection system could in some cases further worsen this situation resulting in a system blackout.

B. Voltage Collapse Preventions

There are certain measures to protect the system from a total collapses. These are modification of the setting of transmission line distance protection, smart islanding, and blocking the circuit breakers, blocking of transformers tap changers, load shedding. These are briefly described as follows:

- Modification of protection settings: In order to protect the system, we can change the distance protection setting in such a way that the line protection will not see the overloading of lines in emergency cases as a fault in Zone-3 setting which triggers the trip and worsens the system situation [9].
- Smart Islanding: The goal is to keep energized as many load areas as possible by creating islands by intentional separations of subsystems before the problem in one system propagates to the neighboring systems. The islanding is a useful alternative to complete blackout because it becomes much easier to restore the system from an island than from a complete system blackout [10].
- Circuit-breaker blocking: Another way to maintain a line under operation consists in forcing a circuit breaker to not operate, i.e. to not trip and disconnect a line [11]. In a real case, it would be done by programming an infinite time for Zone- 3 actions. It is possible to do this using ARISTO. The ability of ARISTO to use this solution will authorize safeguarding of a part of the electric network, which is a much more suitable situation than a complete system blackout.
- Tap-changers transformers blocking: As we have discussed earlier, tap changers actions restore the load voltage and thereby increase the loading of the system after a fault occurs. Under such situation, tap changers worsen the system conditions. It would be desirable to block the tap actions to avoid further load recovery until system voltage (high voltage side) can be recovered by other voltage control means [5].
- Load shedding (under frequency and under voltage): In extreme situations when the frequency has declined too much, load must be shed in order to save the system from a blackout. In addition to under frequency load shedding, load can also be shed upon low voltage situation [5],[6].

In this paper, the combined circuit-breaker blockings and load shedding measures are used. The conditions which lead to cascading outages are carefully analyzed to determine the most effective blocking and load shedding positions. It would be ideal to come to a generic method to select the optimal blocking and shedding scheme for any particular emergency conditions. However, this is outside the scope of this project.

III. SIMULATING VOLTAGE COLLAPSES IN ARISTO

This section describes the ARISTO software and the simulation of a power system voltage collapse in ARISTO using the Nordic 32-bus system which approximately represents Swedish high voltage transmission network [12].

A. Description of ARISTO

ARISTO is an Advanced Real-time Interactive Simulator for Training and Operation. The simulator can simulate power system dynamics operation in real-time [13]-[14]. The simulator has unique properties, combining handling of detailed dynamic phenomena with simulation in real-time. The interactive graphic user interface is very suitable to give a deep understanding of power system behavior. The simulator is capable of real-time simulation of large systems. The architecture of the software is as shown in Fig. 2.

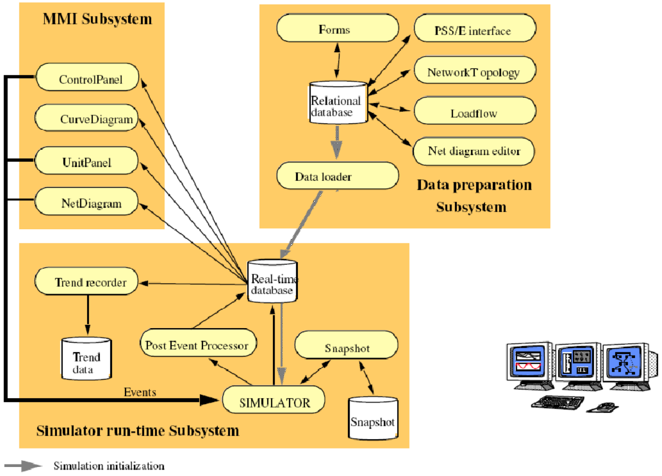

Fig. 2: The architecture of ARISTO [13]

The ARISTO simulator is developed by the Swedish Transmission System Operator (Svenska Kraftnät), and is used for power system analysis and to train the power system operators.

One of the unique features of this software is the "Event Panel" where the "operator" can send instructions to the simulators. It is particularly useful for creating different scenarios, i.e. a sequence of events with certain time-stamped for each event in the scenario. The scenarios are sent to the simulators to see the dynamic responses of the systems.

Other facilities that are used to control/monitor the system are the "Curve Diagram" where the generator frequency, the bus voltage, the line transfer power, and the generator output power are represented in different graphs. Every variation of those parameters can be checked and analyzed there. The "Event Browser" is also an important facility of ARISTO because each control action done by the "operator" or actions by the system and the precise time at which the actions happened are recorded here. By observing the Event Brower, one can easily notice different actions/responses of the system to certain events occurring in the systems, especially automatic actions by the protections systems.

The ARISTO simulator is also used for educational purpose, e.g., in teaching in a course on "Power System Operation" and "Project Engineering Design Project", and in research at Chalmers University of Technology in Sweden [9],[15].

B. The Nordic 32-bus System

In this study, we use the Nordic 32-bus system to simulate different voltage collapse scenarios. The single-line diagram of this system is shown in Fig. 3. This Nordic 32-bus system can be divided into 4 main areas:

- North: mostly consists of hydro power plants and some load centers.
- Central: consists of a large amount of load and large thermal power plants
- Southwest: consists of some thermal power plants and some load
- External: connects to the North, it has a mix of generation and load.

To interconnect the north and the central area three lines and one double line, all of them series are compensated, and line distance protections are used.

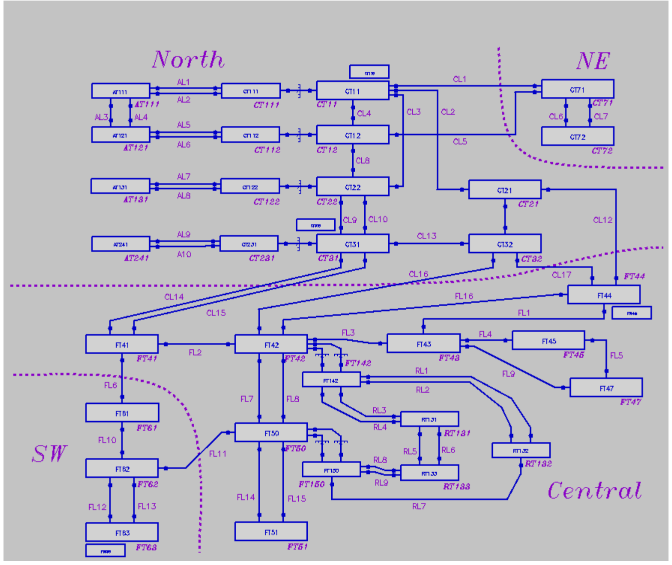

Fig.3. Nordic 32-bus system in ARISTO

Each bus has specific loads, generators, tap changers and Static VAr Compensations. The north part has more generators and the central and south west parts have more loads. The ARISTO switchyard model used in this project has the details of the circuit breakers, disconnectors and basic protections settings.

C. Simulation of A Power System Voltage Collapse Scenario

1) Simulating the Pre-fault condition

A scenario is created in which some generating units and some transmission lines are put on scheduled outage. That is that generators in FT63 (G1, G2), RT131 (G1) and FT44 (G2), totaling to 1421.8 MW, are switched off. Transmission lines CL14 and CL17 which link the central and the north part of the network are disconnected. After the disconnection of those generating units and lines, the system stabilizes by itself after different automatic control actions and moves to a new steady-state condition. Further manual load sheddings are needed to relieve the overloading conditions over the line CL15. The other line power transfers also increase due to outages of CL14 and CL17. However their loadings are within acceptable limits. The single-line diagram for the pre-fault steady-state condition is shown in Fig. 4.

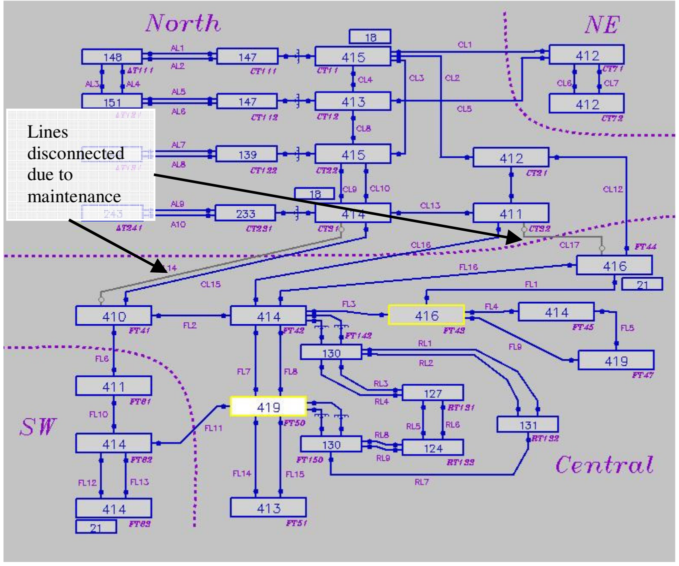

Fig.4. Pre-fault conditions of the blackout scenario in ARISTO

Table I shows the balance between generation, load and compensation of the normal operating condition and our pre-fault condition.

TABLE I
POWER BALANCE FOR NORMAL AND PRE-FAULT CONDITIONS

	Normal condition		Pre-fault condition	
	P(MW)	Q(MVAr)	P(MW)	Q(MVAr)
Generation	11187.8	1665.7	8904.2	334.7
Load	-10938.2	-3358.8	-8692.0	-2565.1
Reac.comp.	0.0	-1380.6	0.0	-1537.6
Cap.comp.	0.0	935.8	0.0	954.0
Losses	-249.6	2137.9	-212.2	2214.1
Margins	4152.2	5709.3	4635.8	5440.3
Connected capacity	16950MVA		13540MVA	

D. *The Voltage Collapse*

A triggering event in our voltage collapse scenario is a double bus bar fault which occurs at bus FT44. The bus-bar protection trips which disconnects FT44 from the rest of the system. This results in disconnections of lines FL16, FL1, and CL12. Also two generating units connected to this bus are disconnected. Immediately after this fault cleared, the south part of the network, the system voltage collapse quickly. From Fig. 5, the sequence of the voltage collapse can be observed. Due to weakened transmission system, the loading of remaining lines increases, and lack of generation in south area, the voltage at switchyard in the south area (FT42, FT62 and FT150) decreases substantially. Tap changer operations to increase the load voltage worsen the situation as explained in Section II. The consequences of these are as follows: the power transfers in critical lines (CL15, CL16) increase and oscillate, the lines are thereby disconnected by Zone-3 distance relays due to increased currents and reduced voltages. Thus, the central area is separated from the north. As discussed earlier, the central area is mainly load area, the generation in this area is not enough to supply its load, undervoltage protection relay trip the loads and generator, loss of load in this area is an obvious fact.

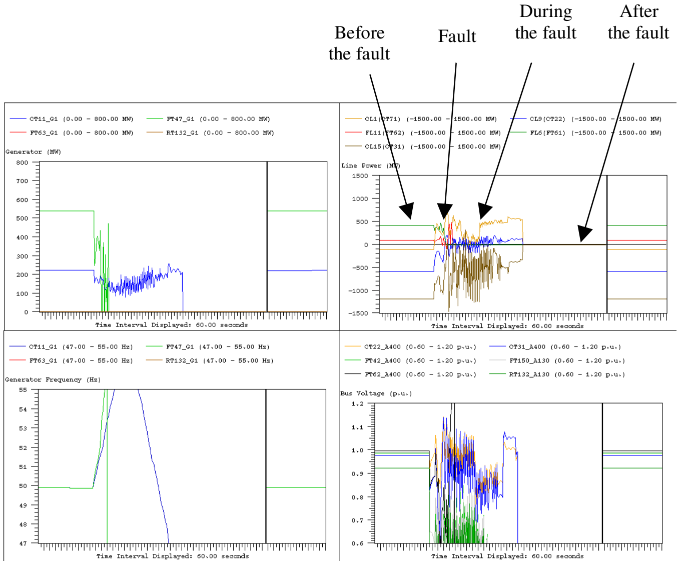

Fig.5. System response during fault leading to blackout

In the north area, the voltage and frequency increases due to loss of load in the south area, the supply–demand balance was heavily distorted causing the system frequency to reach its upper limit and the generators are disconnected by the operation of over frequency protection. This loss of generation in the north area leads to total blackout of the entire system. This situation is of course not desirable, and must be avoided to the extent possible. It is important at least to limit the area of the outage, to avoid complete system blackout.

IV. BLACKOUT MITIGATION BY CIRCUIT BREAKER BLOCKINGS

In order to limit blacked-out area as described in Section III, different control actions can be taken. In this section, the events that lead to voltage collapse are analyzed. This includes triggering events, such as faults, tap changer operations and distance relay operations. Based on the analysis mitigation actions will be proposed.

From the event browser different switching actions that took place were analyzed and the following observations were made:

- The fault instantaneously caused the isolation and tripping of FT44 losing two generation units due to low voltage limit and two additional generation units at FT47 due to high frequency limit being reached.
- Two additional generation units at FT62 tripped on low frequency limit.
- Immediately after the fault was cleared, line distance protection triggered and disconnected CL12, FL1 and FL16 on zone 2 at CT21, FT43 and FT42
- There was large power transfer from north to south that led to the triggering of distance protection relays on line CL16 and FL6 in zone1 at CT32 and FT41 switchyards.
- Tripping of CL15 and CL16 causes the separation of the northern part from the central resulting in the rise of frequency in the northern part due to the massive loss of

load. At the same time in the southwest and central the frequency and voltage drops significantly. At FT41 a generation unit was tripped due to low frequency and at FT51 two units were tripped on undervoltage. These trippings further worsen the network condition.

- Load-shedding was carried out at FT41 but not sufficient to save the system.
- In the northern and north eastern part ten units were disconnected due to high frequency limit reached which lead to the total blackout of the northern and north eastern parts.

Table II shows the summary of the power balance for system conditions during mitigation and after the fault. To reduce complete blackout into island operation, the operation of distance protection relays is investigated such that it should not trip due to load encroachment into Zone-3 and also more load shedding need to be carried out more quickly. If there is tap changer operation which further worsens the situation it should be blocked.

TABLE II
POWER FLOWS FOR SYSTEM CONDITIONS DURING MITIGATION AND AFTER THE FAULT

	Mitigation		After fault	
	P(MW)	Q(MVAr)	P(MW)	Q(MVAr)
Generation	9569.1	1806.5	3511.4	1078.9
Load	-9246.5	-2809.9	-3476.6	-994.0
Reac.comp.	0.0	-1225.8	0.0	-1815.3
Cap.comp.	0.0	1098.5	0.0	55.1
Losses	-322.6	1130.6	-34.7	1675.3
Margins	4150.9	4668.5	4733.6	2096.1
Connected capacity	15150MVA		8850MVA	

The mitigation process keeps track of voltage, frequency and load flow in the system. If the voltage exceeds the upper limit, the reactive power compensation (inductive) takes action in the system, otherwise if the voltage is below the lower limit the capacitive compensation and tap changer take action. The frequency variation will be related to decreasing or increasing generation and load shedding. If the lines are overloaded, the distance protection will be blocked for a very short duration while carrying out immediate load shedding to reduce the power transfer on the critical lines. This process will be repeated until the system is stabilized. The main reason for the total blackout is the high power transfer from the north to the south in combination with the separation of the northern part from the central. The total blackout could be avoided by carrying out some load shedding in the southwest to reduce the high power transfer from the north to the southwest. In order to avoid cascaded tripping of the heavily loaded lines before completing the load shedding, the distance protection relay on line CL16 need to be blocked. This will avoid unwanted distance protection tripping of the line CL16 which lead to the separation between the north and the south. When line CL16 was allowed to trip due to line distance protection it leads to the islanding of the entire north and north east areas as shown in Fig. 6.

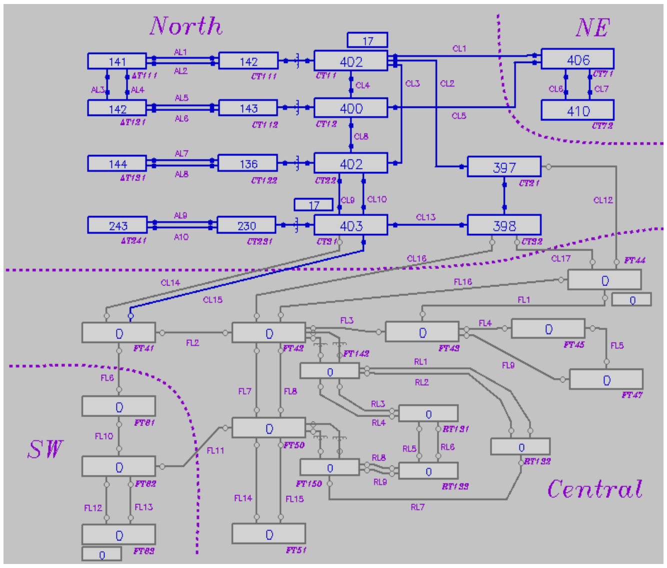

Fig.6. Stable conditions after the fault with the mitigation actions.

As it can be seen the generators and switchyards in the north stabilizes after the fault (Fig. 6) compared with what was seen in the complete system collapse. The graphs during the fault with the mitigation actions are shown in Fig. 7.

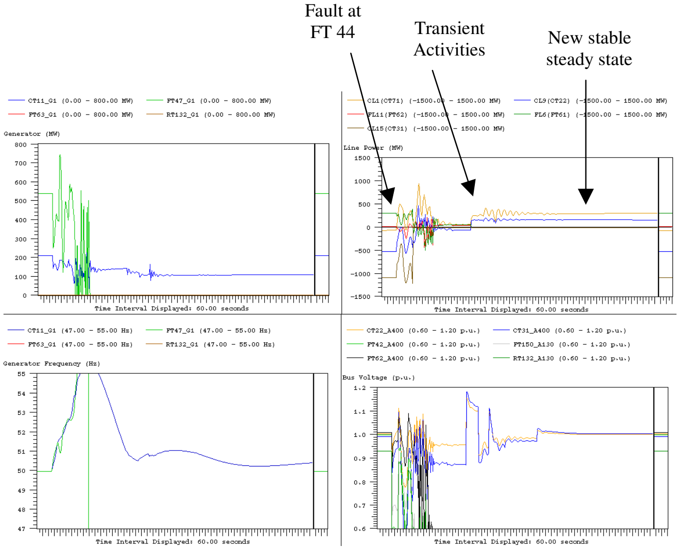
Fault at FT 44
Transient Activities
New stable steady state

Fig.7. Transient curves of the fault with the mitigation actions

Because we have carried out load shedding and we are blocking the line distance protection on the line CL16, the transient responses shown in Fig. 7 are not as severe as in the total blackout case shown in Fig. 5. When CL16 trips and separation between the north and southwest takes place the immediate loss of load is not that high so that the generators in the north trips due to over frequency as they did in the total blackout case. Since generation in CT11 is able to withstand the separation we have an intact islanding operation in the north.

V. POWER SYSTEM RESTORATION

After a severe cascade outage against which no universal means exists, the restoration of a power system is complicated owing to the absence of voltage in large territories [16]. The operations for which electric energy sources required cannot be performed. For the power stations to resume operation it is necessary to start the technological processes that consume a relatively large power for their auxiliary's services. If in the process of a power system's blackout, there occurred separation of some regions with formation of "islands" where generating stations are still under operation, from these stations energy is supplied to the idle-standing stations putting them into operation step-by-step. Two major strategies for restoring a power system following a blackout are known: the build-up strategy and the build-down strategy. Different approaches are used depending on the size of the interrupted area, the possibility to receive assistance from interconnecting systems, the amount of black-start capability in the system and the type of production in the system [15].

To initiate the system recovery, the restoration plan must be done as soon as possible. Firstly, the hydro power plant in north area was fully available to pick up the recovery of the demand in north and some of the demand in south and central area then also intact grid in north area. Then, the 400 kV lines and switchyard were energized to build up the grid from north area toward south area (CL15 and FT41).

The restoration should be started in an area with a lot of generation units, and with a unit which can be started quickly and have fast output variations in order to balance the consumptions variations. In this system, this is the north area with many hydro-power plants whose output power is easy to regulate. After the north and central area are interconnected and the grid is energized, the generators in the south can be started up and some loads can be connected to the grid. During connection of the load and starting generators, it takes some time and the system must be stabilized between each connection. The procedure for connecting a generator and a load could be done as described in Fig. 8, until all loads are restored.

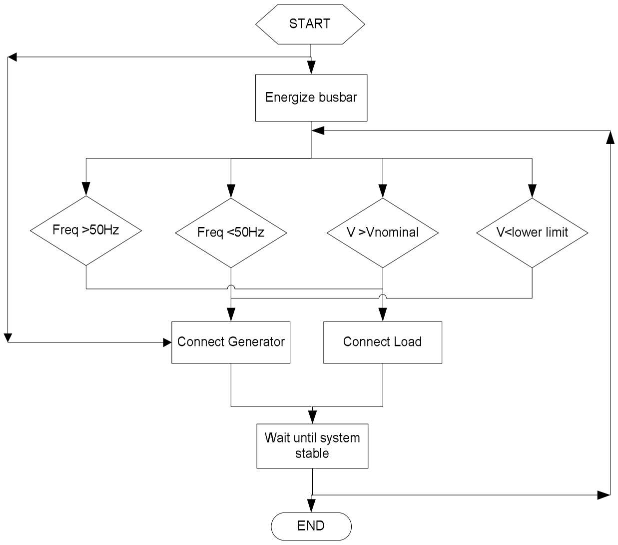

Fig. 8. Flowchart for restoration procedure

The load must be connected to the grid if the frequency and or voltage are higher than the acceptable limit and vice versa for generators. This process will be repeated until all the loads and generators are connected to the system.

VI. CONCLUSIONS

This paper presents the education-cum-research project work on understanding power system blackout due to voltage collapse. Voltage collapse scenario was successfully implemented in a highly interactive and advanced power system dynamic simulator ARISTO.

The project help students understand in depth the factors contributing to voltage collapse, which was the primary purpose of the project.

Secondly, the project also attempted to investigate the possible measures to prevent power system voltage collapse. The combined measures of circuit-breakers blocking and load shedding were chosen to mitigate the blackout area. In the mitigation process, the state of the system (voltages, frequency and power transfer) must be analyzed and then a proper action to stabilize the system is taken using load shedding in the south and south east area, reducing generation in the north and north east areas, and blocking of distance relay operation to facilitate load shedding (blocking of tripping of lines due to distance protection relay is achieved by blocking circuit breaker operation). The results have shown that with proper and timely control actions (blocking and load shedding), a total power system blackout can be avoided. Instead, major part of the system could be save, which will greatly reduce the social costs of the actual blackouts.

The restoration of the system after the system collapse has also been successfully demonstrated. The process takes long time to restore the system. This justifies the need to avoid complete system collapse by putting in place measures that would lead minimize the blacked-out area.

VII. ACKNOWLEDGMENT

The authors would like to thank Dr. Evert Agneholm from Gothia Power AB for his help in using ARISTO.

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IX. BIOGRAPHIES

Didi Istardi was born in Kendal, Indonesia, on November 18, 1977. He graduated BSc in Electrical Engineering from the Bandung Institute of Technology, Indonesia in 2000. He is currently study MSc degree in electric power engineering at Chalmers University of Technology, Göteborg, Sweden.

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Le Anh Tuan received his Ph.D. in 2004 in Power Systems from Chalmers University of Technology, Sweden, and his MSc. degree in 1997 in Energy Economics from Asian Institute of Technology, Thailand. Currently he holds a project leader and lecturer position at the Division of Electric Power Engineering, the Department of Energy and Environment, Chalmers University of Technology, Sweden. His research interests include power system stability, power electronic solutions to optimize power system operation, power market and deregulation issues.

Lina Bertling is Professor in Sustainable Electric Power Systems and Head of the Division of Electric Power Engineering, at the Department of Energy and Environment, at Chalmers University of Technology, in Gothenburg, Sweden, since January 2009. She has been with Svenska Kraftnät, i.e. the Swedish Transmission System Operator during 2007-2009. She has been with KTH School of Electrical Engineering (EES), in Stockholm, during 1997-2009 where she finalized her Docent degree and became Associate Professor in 2008, and Ph.D. in 2002 all in Electric Power Systems. At KTH she has been the founder of the RCAM (Reliability-Centred Asset Management) research group. She was a visiting postdoctoral student at the University of Toronto, associated with Kinectrics Inc. during 2002/2003. Her research area is electric power system planning on system and equipment level, and wind power integration with quantitative approaches for reliability and maintenance prediction. She was the general chair of the 9th International conference on probabilistic methods applied to power systems (PMAPS) in Stockholm, in 2006. Dr. Bertling is a senior member of IEEE and a member of Cigré, Cired, World Energy Council, and the Royal Swedish Academy of Engineering Sciences.