International Journal of Engineering & Applied Sciences (IJEAS)
Vol.7, Issue 3(2015)39-57

MODELING of POWER NETWORK SYSTEM of the HIGH VOLTAGE SUBSTATION: a simulation study

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Recived date: October 2015; Accepted Date: December 2015

Abstract

Energy is one of the underlying data of the world's economic and social development. Have a rapid industrialization and urbanization environment, a rapid increase in population, the growth of energy consumption in an indispensable way, make the diffusion of innovation and economical and safe use of the existing energy sources essential. This case depends on the safe and controlled use of energy and the healthy operation of the power systems. The modeling and simulation studies of power systems with computers are being widespread and constituting the infrastructure of the emerging smart grid process. In this study, the modeling and numerical analysis of the interconnected transmission lines from Keban Dam, which includes one of the Turkey's biggest hydroelectric plant, to Elazığ province are carried out with MatlabTM/Simulink software. By implementing realistic modeling, the power transmission network, load flow analysis, voltage and current values in bus bars, short-circuit currents and zero sequence (neutral) currents are numerically calculated. In the study, the maximum short-circuit current which occurs at three-phase short circuit fault for the power network system is obtained as 2 kA. Based on simulation results, the load carrying capacity of the existing system, relay coordination, the control of insulation levels and possible leakage currents are figured out. In the light of the result of the feasibility study, the design of the power system can be realized.

1. Introduction

Electrical energy is transmitted to consumers after the processes of generation, transmission, and distribution. In Turkey, electricity generated in thermal, hydro and natural gas power plants are injected to the interconnected system by 380 kV and 154 kV power transmission lines and transferred to the closer substations through auto transformers of 154 kV voltage level. Afterward, it is reduced to 34.5 kV, 31.5 kV and 15 kV voltage levels at substations and transmitted to the consumption points. Distribution transformers decreases the voltage level from 34.5 kV to 400 V and final consumers as factories, offices, commercial institutions and homes can use this electrical energy at this voltage level. In this study, the transient analysis of load flow and short circuit of one hydroelectric unit and four substations forming the 380/154 kV transmission network of Elazığ province which is connected to the Turkish Electricity Transmission Company (TEİAŞ) was implemented for 0.2 s time duration with 50 μs sampling time [11]. Current-voltage variations at load flow analysis, short circuit currents, zero current and the coordination results of relays are analyzed in the numerical study carried out by the help of ***Matlab^{TM}/Simulink*** software. All data and parameters used in the study are realistic values obtained from TEİAŞ.

2. Analysis of Interconnected Power System and Modeling with *MATLAB™/SIMULINK*

2.1. Structure of the Interconnected System

Energy transmission lines are designed and arranged to be able to deliver all territories require the electrical energy. The system of the electricity transmission lines which satisfies the requirements of the electrical energy of the entire country or a particular region and provides the exchange of the energy between the production and consumption centers is called the interconnected system. The power plants feeding the interconnected system can be various types and sizes of thermal, coal, natural gas, oil, wind, geothermal and hydroelectric power plants. The output voltage level of the alternators in these plants can be 6.3, 6.9, 10.5, 10.8, 13.8 and 14.4 kV. The generators of the Keban Dam connected to the interconnected network generate energy at the voltage level of 14.4 kV. Therefore, the output voltage of the alternator is connected to the interconnected system after raising by step-up transformers (380 kV). The operation center which oversees the operation of the interconnected system in terms of the safety, quality and economics of the generation and consumption and also controls and coordinates the business maneuver is called the load dispatch center. Thus, when the power of plants in the province is not enough to feed their own regions, the absorption of energy economically at desired amount is provided from the interconnected system. Two load dispatch unit were constituted in this study. The program has been used to denote only the voltage and current values. Start-up and switching-off the load can also be done by means of the interconnected system. Turkish Interconnected System has been managed by General Directorate of the National Load Dispatch located at Gölbaşı, Ankara.

2.2. Load Flow in Energy Transmission Systems

The steady state conditions of the power transmission system are determined by the load flow analysis. Bus voltages and fault currents are important parameters in the load flow, and the result of load flow has a special significance in the analysis and design of the power system. The main purpose of the load flow is to determine the energy demand and ensure energy supply by calculating the bus voltages, impedances and loads of the lines, transformers and conductors.

Under steady-state conditions, the assumptions used in the load flow algorithms of the balanced three-phase systems are:

i. Generators meet the load demands of the system and total power loss in transmission lines.

ii. The amplitude of all bus voltages are in the nominal voltage ranges.

iii. Generators don't exceed their active and reactive power values.

iv. Transmission lines and transformers should not be overloaded.

These steps are followed by calculating the power losses of the system, losses in transmission lines and defining which region has the more power flow, and eventually load flow analysis is completed.

2.3. Short Circuit Analysis in Power Systems

In an energy system, lightning stroke, switching events, mechanical errors, ice loads, landslides, earthquakes, birds, insects, humidity, dirt and an overvoltage caused by similar reasons enforces the system components electrically. If the disturbing forces exceed the voltage insulation level, a short circuit occurs. The value of the short-circuit current is determined by the Thevenin equivalent circuit seen from the fault point towards the source that feeds the system. Short circuit events are examined in two ways as balanced and unbalanced short circuits. In a balanced system, if the amplitude of each phase current is equal to each other after the line fault, the type of short circuit is called as balanced fault.

If the amplitudes of line currents get different values amongst themselves after the fault occurs, the fault type is called as an unbalanced short circuit. Current and voltage calculations for unbalanced short circuit are complicated and more difficult than balanced system.

In the symmetrical power systems, short-circuit current calculations are investigated in two different parts as symmetrical and unsymmetrical faults. While three-phased short circuit is a symmetrical fault, line to ground, line to line and line-line-ground faults are unsymmetrical faults. Since the amplitude of the circulating currents at fault instant do not change with regard to phases, the fault is called as a symmetrical fault. When the fault currents alter with respect to phases, it is named as an unsymmetrical fault.

Relay coordination is carried out in lines according to the results of a short circuit. In protections done by relay coordination, radial, versatile and zone coordination are used. In ***Matlab^{TM}/Simulink*** model, system continuity is maintained by providing spare circuit breakers and operating all of them in coordination with each other.

2.4. Iteration Algorithm used in Analysis of the High-Voltage Substation Network System

In this study, transmission system is modeled by a set of buses or nodes interconnected by transmission links. Loads and generators, connected to various nodes of the system, inject and remove power from the transmission system. A transient study of the system is carried out with ***Matlab^{TM}/Simulink*** tool in this study. The **Load Flow** tool of the powergui block uses the *Newton-Raphson İteration* Method.

The iterative scheme of the Newton-Raphson formula in one-dimensional case is:

$$x^{m+1} = x^m - [f'(x^m)]^{-1} f(x^m) \quad (1)$$

General case of the n-dimensional equation may be obtained by generalizing the scalar derivative operator $f'(x)$ into an n x n matrix operator. Using Taylor Series Expansion, Newton-Raphson Iteration formula turns out to be:

$$f(x + \Delta x) = f(x) + f'(x)\,\Delta x + \text{high order terms (h.o.t.)} \quad (2)$$

In the case of the Taylor vector series, n scalar equations may be obtained as (neglecting the h.o.t.):

$$f_n(x + \Delta x) = f_n(x) + \frac{\partial f_n(x)}{\partial x_1}\Delta x_1 + \cdots + \frac{\partial f_n(x)}{\partial x_n}\Delta x_n \quad (3)$$

where, $\frac{\partial f_i(x)}{\partial x_i}$ the partial derivative of f_i with respect to x_i evaluated at x. Then, by matrix notation equation turns out to be:

$$f(x + \Delta x) = f(x) + J(x)\,\Delta x \tag{4}$$

where,

$$J(x) = \begin{bmatrix} \frac{\partial f_1(x)}{\partial x_1} & \cdots & \frac{\partial f_1(x)}{\partial x_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial f_n(x)}{\partial x_1} & \cdots & \frac{\partial f_n(x)}{\partial x_n} \end{bmatrix} \qquad \Delta x = \begin{bmatrix} \Delta x_1 \\ \vdots \\ \Delta x_n \end{bmatrix}$$

(5)

J(x) is the Jacobian Matrix off evaluated at x. As it can be seen in the equations, it is the generalization of the scalar derivative f'(x). And hence, more general case of the Newton Raphson Iteration Algorithm may be expressed as the following.

$$x^{m+1} = x^m - [J(x^m)]^{-1} f(x^m) \tag{6}$$

2.5. Analysis of Power Systems using *MATLAB^{TM}/SIMULINK* Model and Integration to Interconnected System

The realistic data of the network model are as follows:

i. The total installed capacity is 1083.6 MVA in the network model.

ii. The total peak load is 215 kW.

iii. While annual total active consumption is 1883.400 MWh, reactive total consumption is 188,340 MVArh.

iv. The model consists of 1243.566 km 154 kV network line and 657.314 km 380 kV network line which make 1900.880 km as a total line length.

v. The length of the 154 kV power transmission line that connects substations to the interconnected system is 1243.566 km.

Since short circuits, fault and load flow results can be observed best in 0.2 sec time interval, numerical study of power network system is implemented in ***Matlab^{TM}/Simulink*** software for 0.2 second duration and sampling time is selected as 50 μs. This sampling time is selected due to the performance constraints of the software. It is the minimum duration Simulink can operate in Discrete Mode and very sufficient for this simulation study.

Matlab^{TM}/Simulink yields investigating the transient behavior of the system and provides to make the fault analysis of the system. Generators used in power network, transformers, electrical characteristics of power transmission lines, and maneuver schemes were taken from TEIAŞ database (Fig. 1).

The active and reactive power of the transmission network model is also determined for 0.2 sec. In reactive power calculations, reactive power factor is assumed to be in the range of 0.95-0.99. In wye-wye connected transformers, the wye-wye points of transformers are grounded over 20 ohm resistances according to the earthing regulations. In the simulation study, substations, hydroelectric units, load distribution blocks, and bus bars are visualized using image processing algorithms. 3 large transformer station connected to the modeled network was examined.

Due to the complexity and vastness of the whole Elazığ province network system, Ferrokrom, Hazar-1, Hazar-2 and Maden (substations at the west part of the city) substation were isolated and removed from the network by circuit breakers. The remaining substations are modeled with ***Matlab***^{TM}***/Simulink*** software.

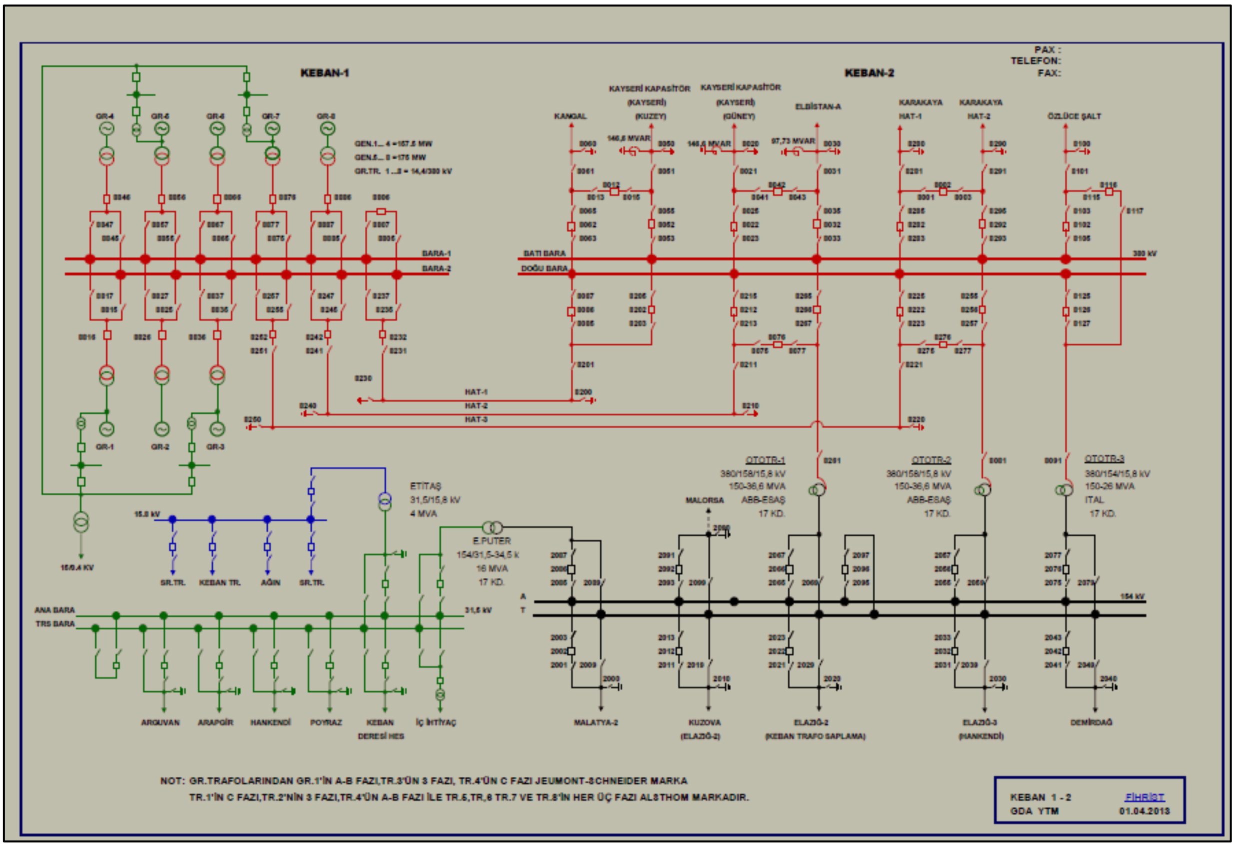

Figure 1: Single line diagram of the Keban Switchgear and HEPP High Voltage network (used in the modelling of the simulation study)

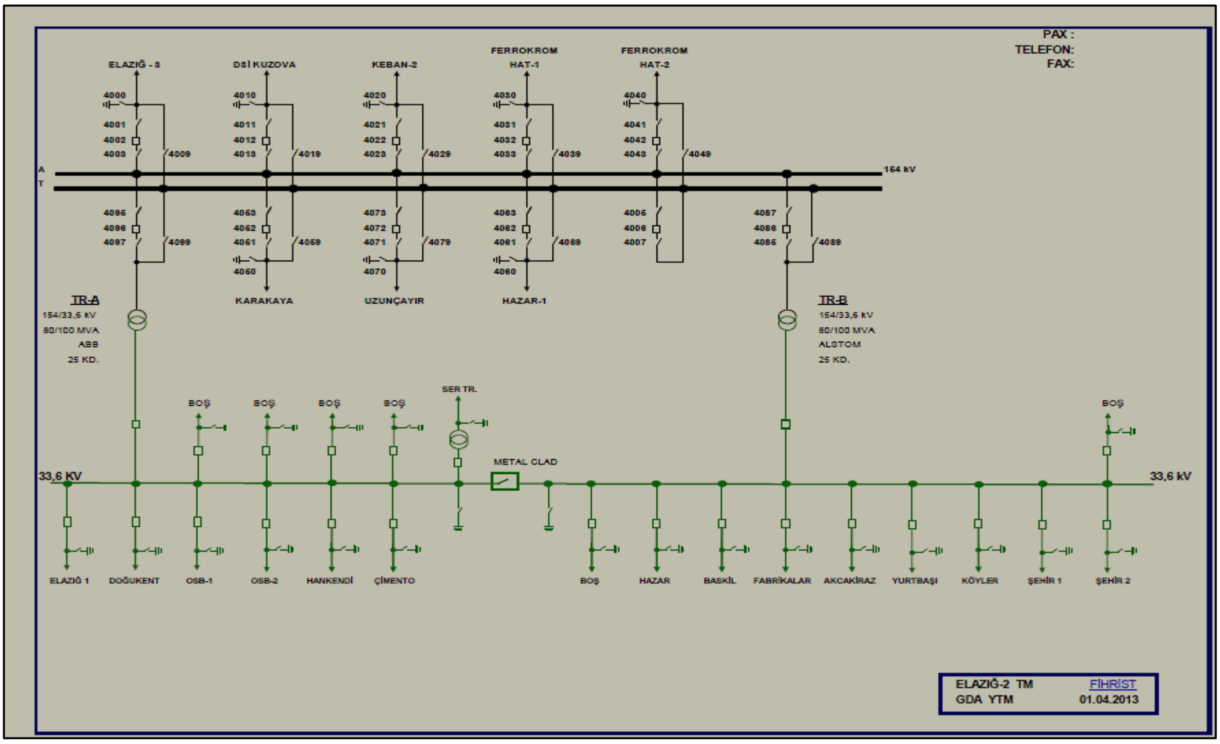

Figure 2: Single line diagram of the Elazığ-2 Substation High Voltage network (used in the modelling of the simulation study)

2.5.1. Modeling of the Substations (Transformer Station) with *Matlab*^{TM}*/Simulink*

Huge and complex systems may be transformed into simple systems by using the Simulink structure "Subsystem" used in the modeling of substations. The single-line diagrams of substations are seen to be a complex structure. Since so many substations are modeled in the study, building these structures on a single worksheet are too difficult and complex. Therefore, the block structure has been used.

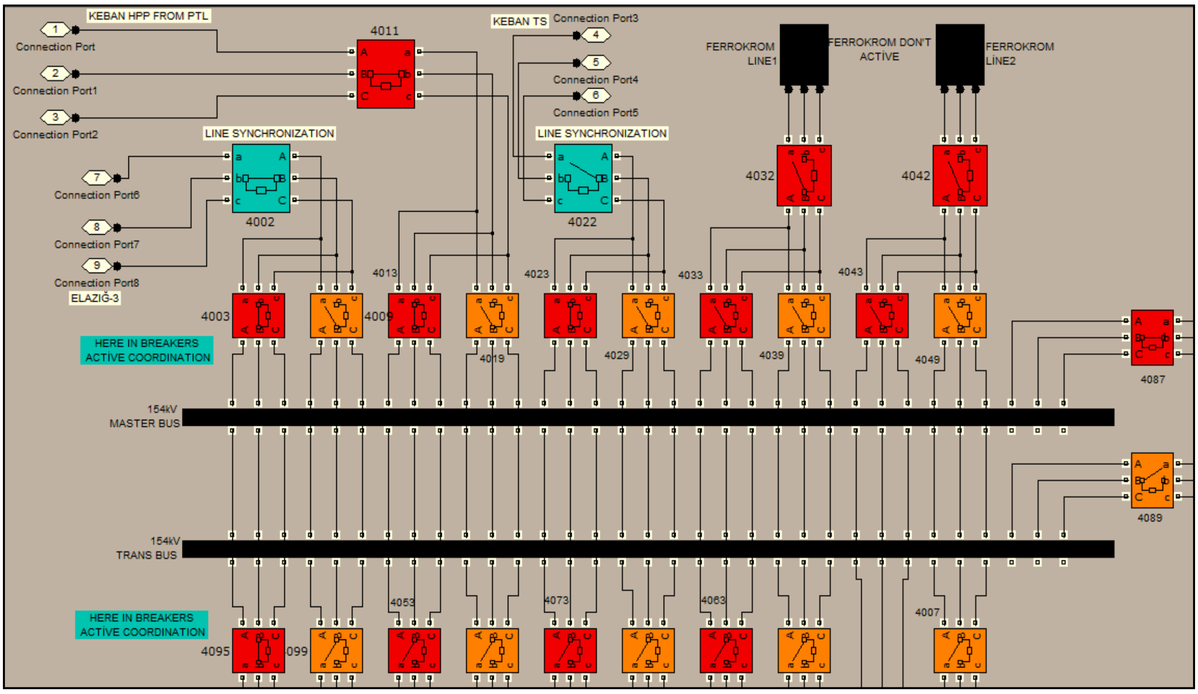

Figure 3: Interior Structure of Elazığ-2 High Voltage Substation Center (used in the modelling of the simulation study)

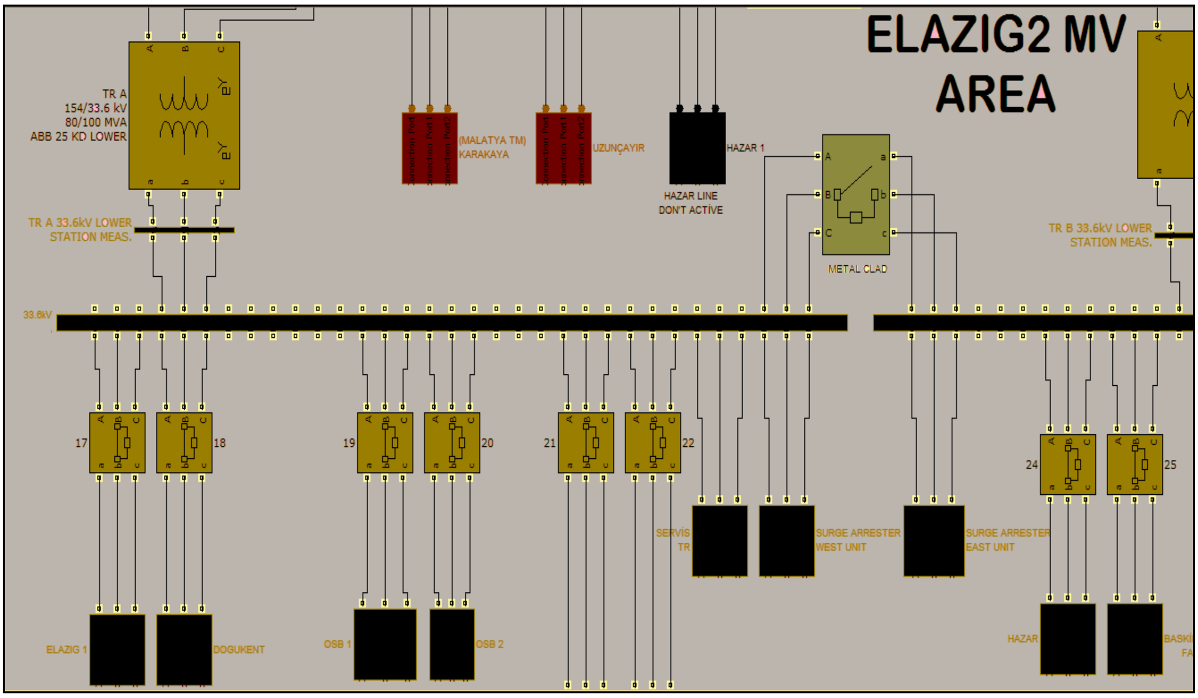

Figure 4: Interior Structure of Elazığ-2 Middle Voltage Substation Center (used in the modelling of the simulation study).

2.5.2. Modeling of the Power Transmission Lines with *Matlab^{TM}/Simulink*

Π-equivalent circuit was used in power transmission lines. 477 MCM Hawk conductor transmission line which is 24.97 km length was used between Keban-Elazığ-2 substations. Frequency, resistance, inductance and capacitance components, and length of the line parameters are found in the block diagram of π-equivalent circuit (Fig. 5). The power transmission line parameters are inserted to the simulation software with corresponding units. The length of the power transmission lines and the conductor cross sections were taken from TEIAŞ database and literature.

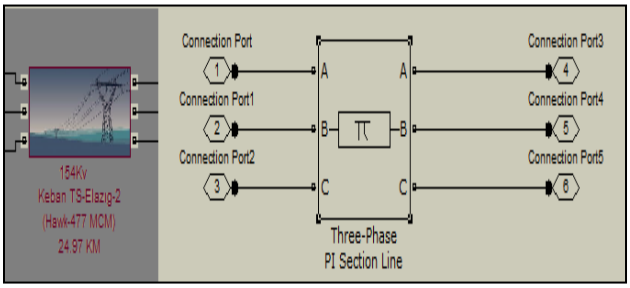

Figure 5: The block diagram of π-equivalent circuit

2.5.3. Modeling of the Transformers with *Matlab^{TM}/ Simulink*

The primary and secondary windings of the power transformers can be Y-Y, Y-Δ, Δ Y, and Δ-Δ connected in power transmission systems. In this study, the connection types were obtained from TEIAS database (Fig. 6).

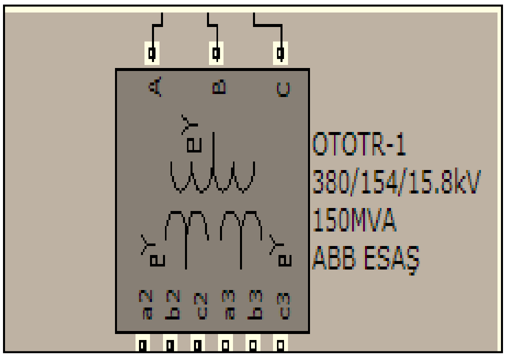

Figure 6: Modeling of the Transformers with Simulink Software

2.5.4. Modeling of the Generators with *Matlab*^{TM} */ Simulink*

Keban hydroelectric power plant consists of generators including 8 synchronous motor and 8 turbines which feed these generators with forced pipe, is modeled in Simulink Software as a HPP (Hydroelectric Power Plant) unit (Fig. 7.).

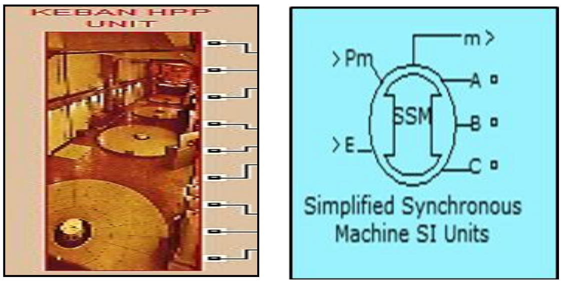

Figure 7: Modeling of Keban HPP Unit with Simulink Software

2.5.5. Modeling of the Load Components with *Matlab*^{TM}*/ Simulink*

Since transmission systems are three-phased systems, the realistic network model was designed using three-phased parallel RLC load in ***Matlab***^{TM}***/ Simulink.*** Voltage, active and reactive (inductive and capacitive) load components of the load are found in the block diagram parameters (Fig. 8). Reactive power was figured out by taking the power factor (Cosφ) between 0.95 and 0.99.

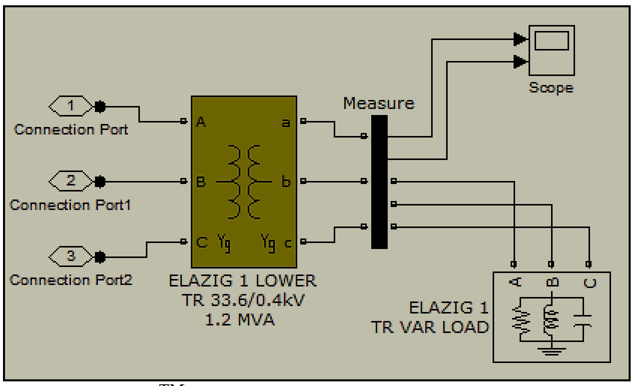

Figure 8: *Matlab*^{TM}*/ Simulink* Model of the Load Components

2.5.6. Modeling of the Circuit-Breakers with *Matlab*^{TM} */ Simulink*

Some unexpected faults may occur in power transmission lines and transformers. Defective electrical equipment should be de-energized as soon as possible. Faults in electricity network is detected by relays and open comment is given to circuit-breakers. Thus, circuit-breakers are one of the most critical devices in power systems. Circuit breakers in Simulink Software are actively engaged at specific regions for coordination purposes. The operation of active circuit breakers has been adjusted to switch the circuit off between 0.08 and 0.1 time interval. In addition, the formation of error has been desired in between 0.08 and 0.1. Therefore, relay coordination is an important paradox.

2.5.7. Modeling of the Instrument Transformer with *Matlab*^{TM} */ Simulink*

Instrument transformers used in power transmission systems to measure the current and voltage value of the line are important devices. There are two types of significant instrument transformers. First one is “Voltage Transformer” and the second one is “Current Transformer”. Since the block of 3-phase measurement system exists in Simulink Software (Fig. 9.), current and voltage are calculated together within this block. Per unit calculation is also available in this block. In our study, calculated values are sent into the blocks of Load Dispatch or HPP Unit Data Station.

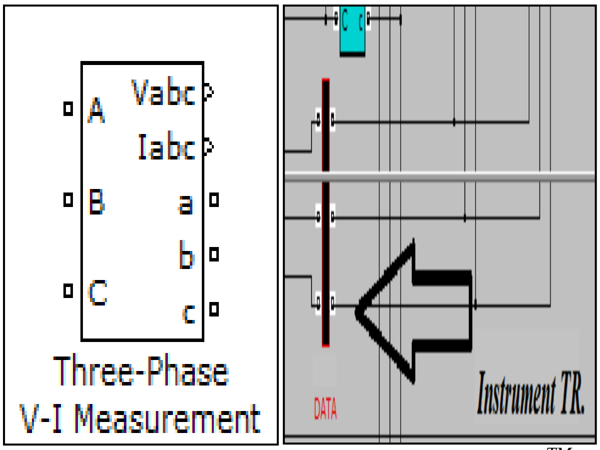

Figure 9: Modeling of the Instrument Transformer with *Matlab*^{TM} */ Simulink* Software

2.5.8. Usage of Power GUI Block in Power System Modelling

Power GUI Block is required in order to use the power system menu. In other words, it is used at each work contains a power simulation. To be able to acquire maximum performance, Power GUI block should be located at the top of the worksheet. However, at sub-systems the place of this block does not affect the performance of the study. It can be placed at the desired location. Only one block can be used for each model. Power GUI block measures the power flow, line currents and the voltage levels in the system. It also indicates the number of load, transformer and bus to the user. Therefore, it is one of the most important blocks of system analysis.

2.5.9. Modeling of the Fault with *Matlab*^{TM} */ Simulink*

Several faults may occur in transformers and transmission lines. Due to these failures, a short circuit, switching-off and energy losses occur in the network. Failures occurring in the power grid are called as the fault. There are three phases fault block in the Simulink program interface. The main feature of this block is, switching on and off time of the fault generation duration is adjusted by external Simulink signal or three-phase circuit switch which is the internal control timer.

The short circuit types created by three-phase fault block cause the most common type of faults such as balanced three-phase (3Φ) fault, line-to-line (LL), single line-to-ground (SLG), and double line-to-ground (DLG) faults. Fault was launched in between 0.08 - 0.1 second in convenient to the analysis of the power system. The use of fault blocks enables the selection of the appropriate relay and the circuit-breaker and also the suitable relay coordination with respect to the consisted short-circuit currents.

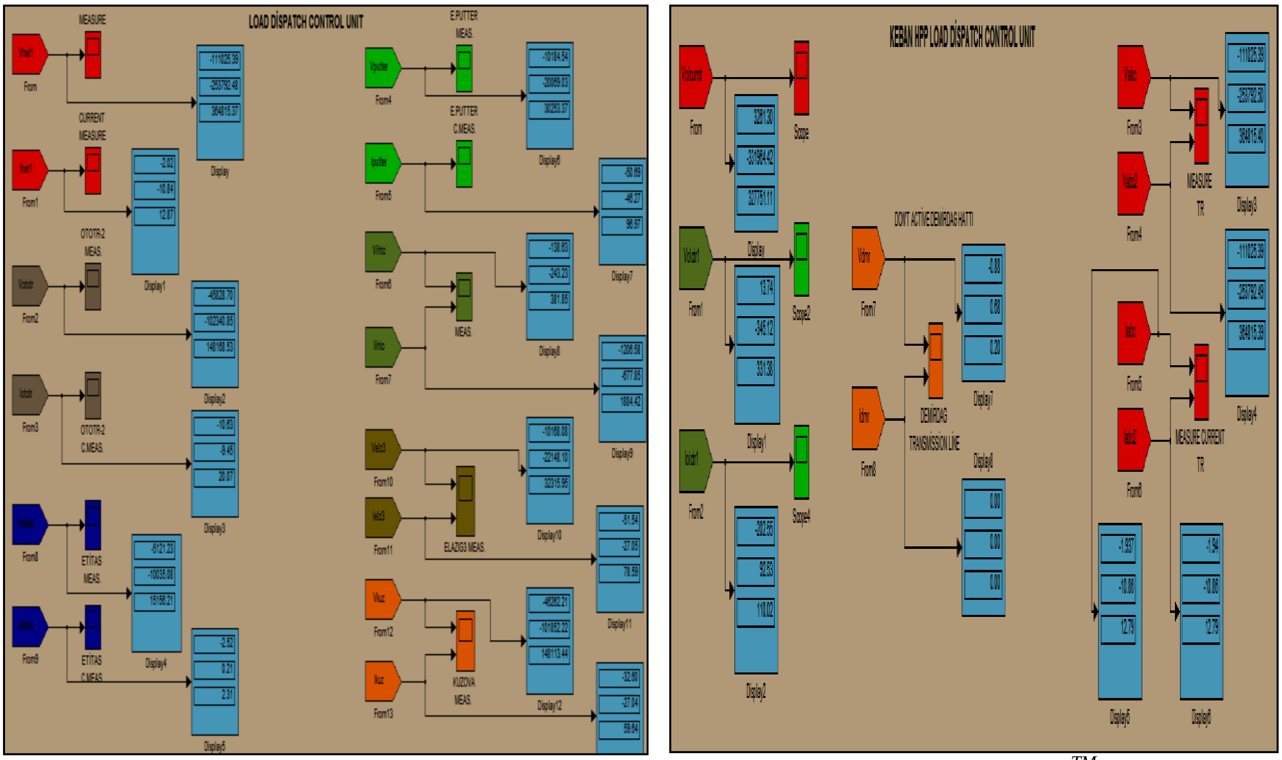

Figure 10: Modeling of the Load Dispatch Data Stations in the Network with *Matlab^{TM} / Simulink*

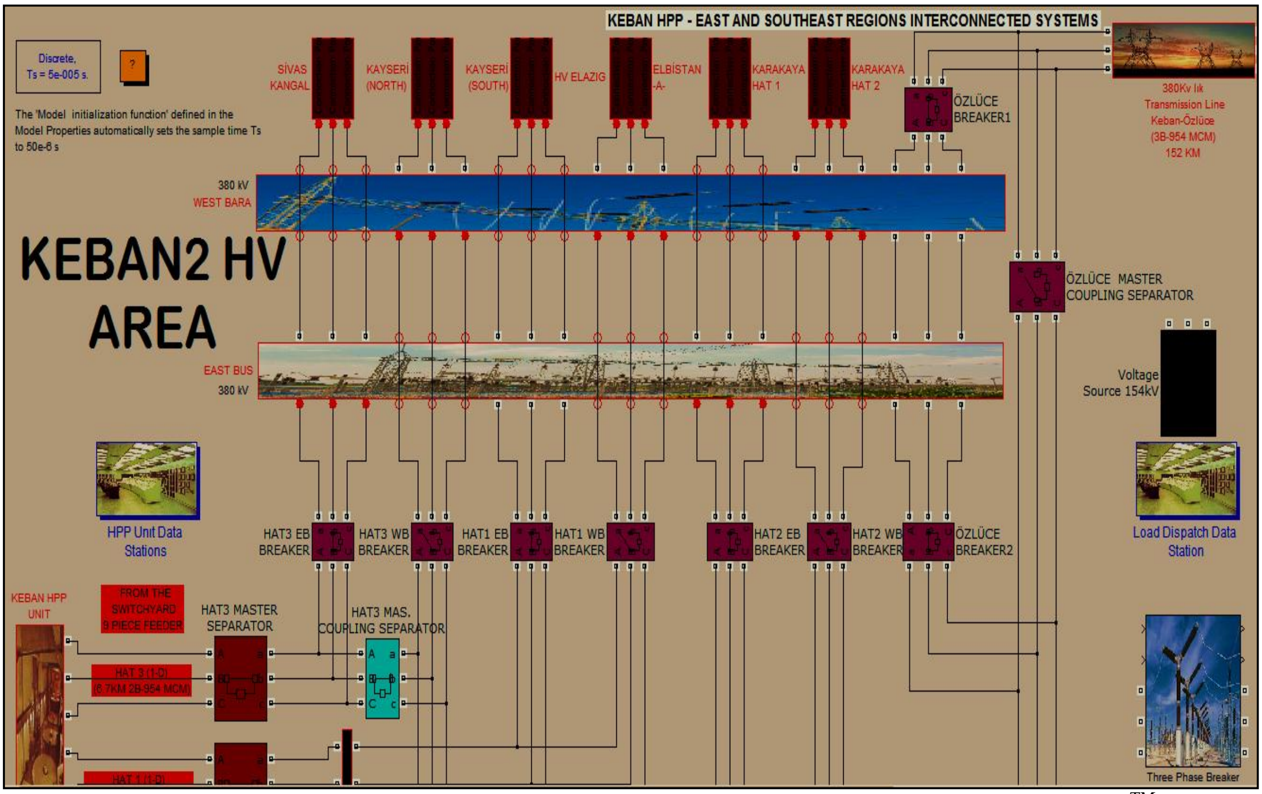

Figure 11: Modeling of the Keban Switching Substation and Interconnected System with *Matlab*^{TM} */ Simulink*

3. Results

380 kV voltage supplied from 6 main feeders (line 2 & 3) of our system into the interconnected network is denoted in Figure 12 and current waves for 0.2 time interval are shown in Figure 13.

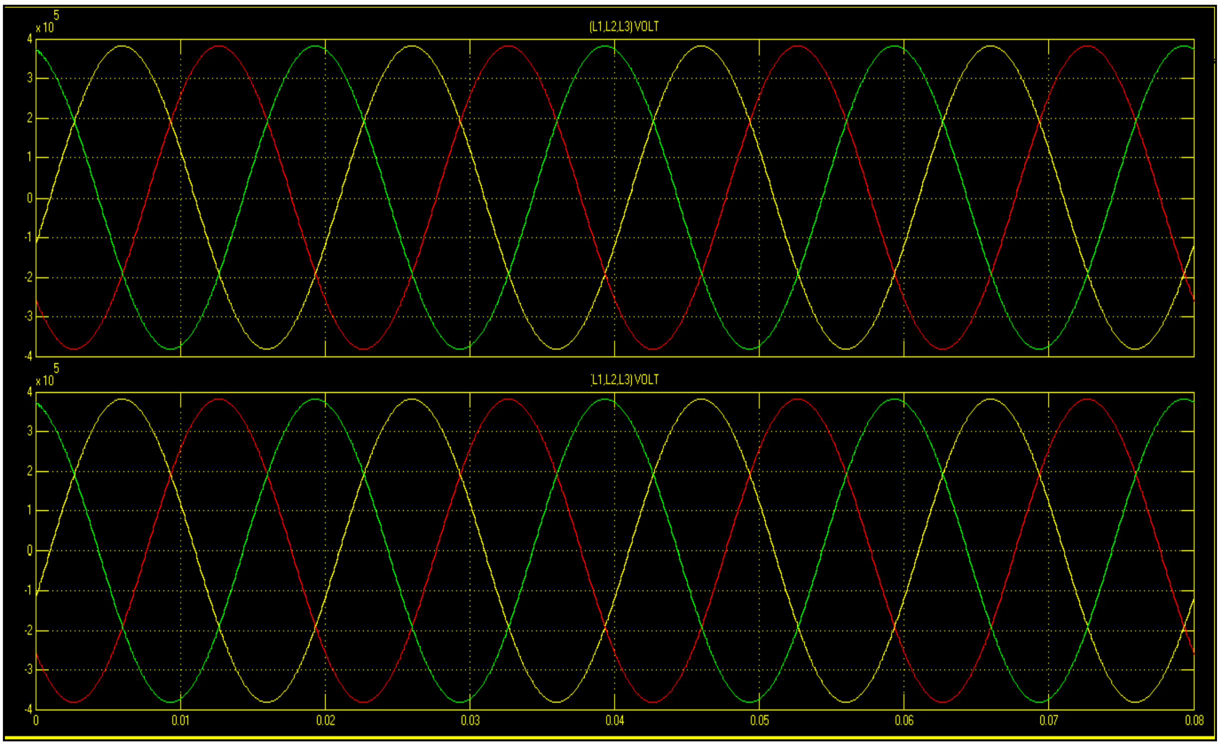

Figure 12: Voltage Waves at 380 kV feeder (data is obtained from 6 feeders) in the network of Line 2 & Line 3. Upper plot denotes Line 3 and bottom plot shows the Line 2 Voltage Waves.

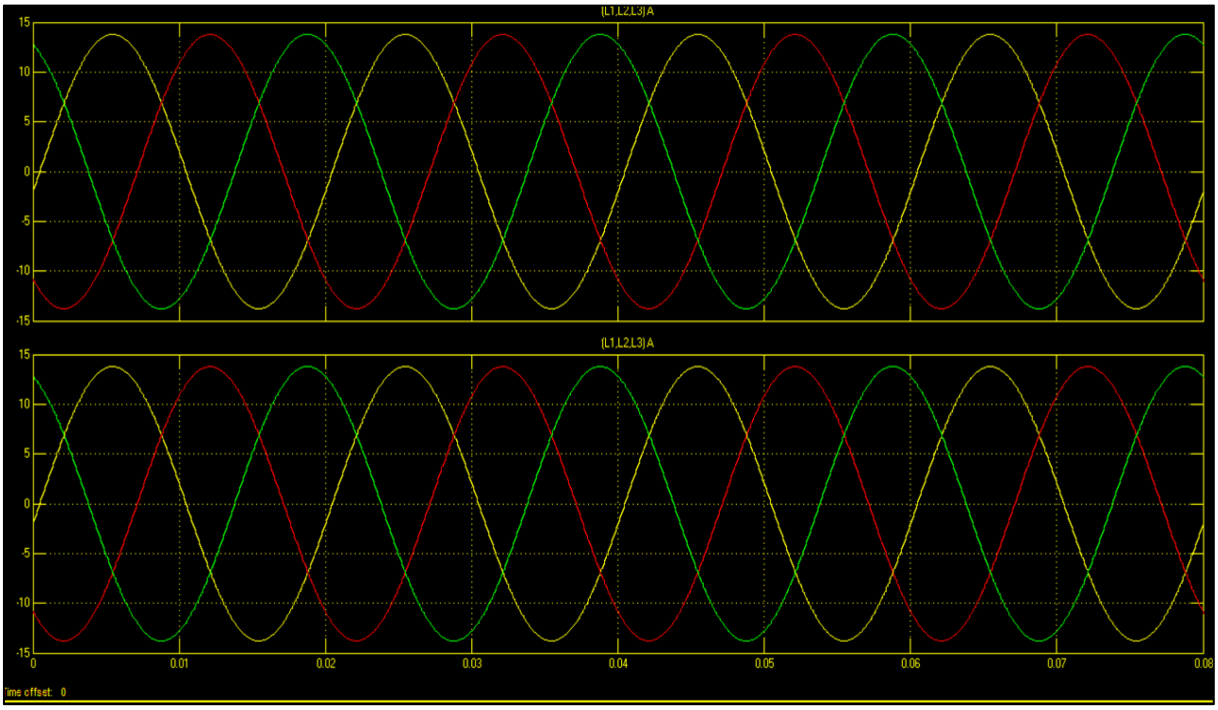

Figure 13: Current Values at 0.2 second from 380 kV feeder (data is obtained from 6 feeders) in the network of Line 2 & Line 3. Upper plot denotes Line 3 and Bottom plot shows the Line 2 current waves.

Nominal voltage and current values of 154/33.6 kV Transformer-A (TR-A) is shown in figure 14. These waveforms were obtained for the stable system. TR-A is located in Elazığ-2 Substation (Fig. 4.)

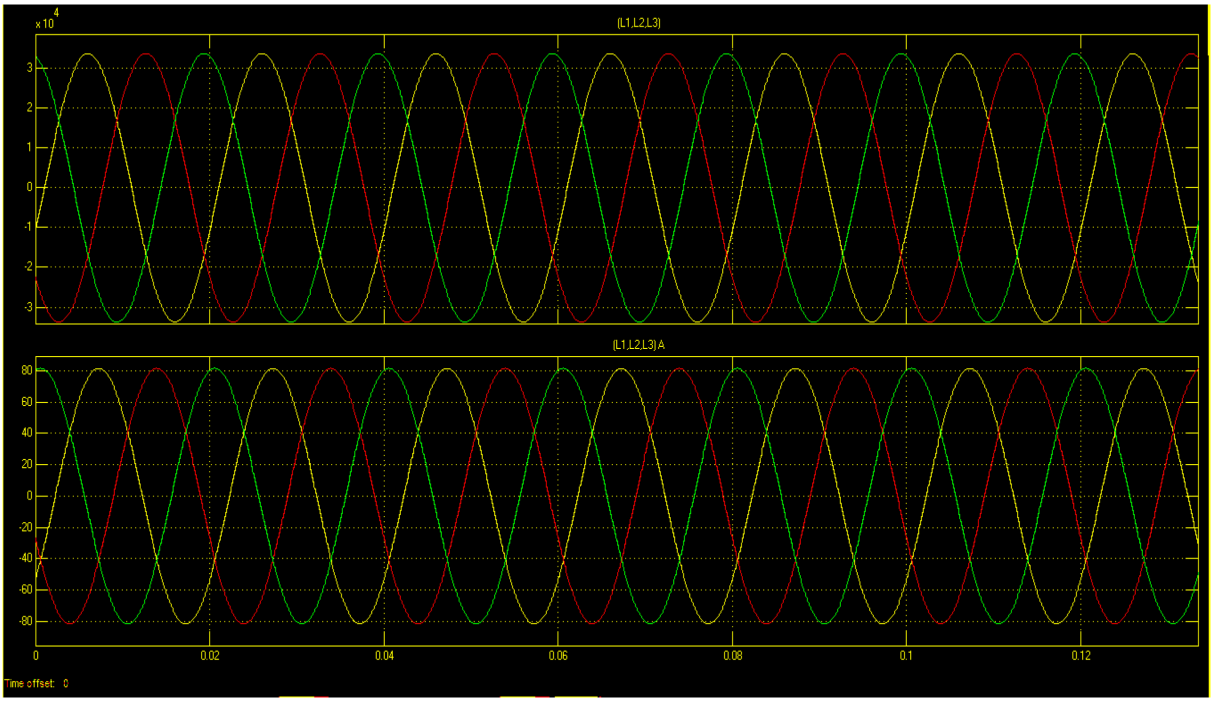

Figure 14: The secondary voltage of 33.6 kV distribution transformer TR-A in Elazığ-2 Substation is shown in upper graph and corresponding load currents are denoted in the bottom graph of the figure.

Figure 15 denotes that the strength of the current flowing from the Y-point of the E. Putter distribution transformer located in Keban Switching Plant is very low.

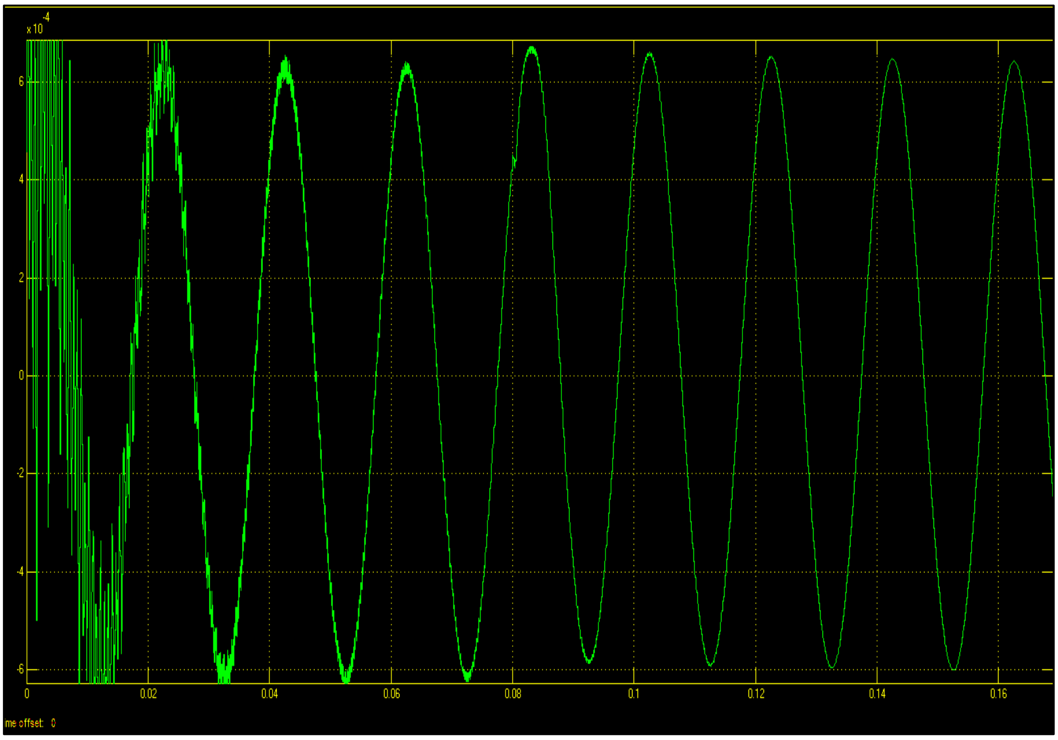

Figure 15: Zero Sequence Current of E. Putter Transformer in Keban Switching Plant

Due to the three-phase (3Φ) short circuit on the transmission line between Keban 154 kV bus bar and Elazığ-2 Substation, transmission line was bypassed from the circuit-breaker which is in active coordination in that area. The behavior of the circuit-breaker and the operation of switching-off the voltage by damping the current at the instant of 3Φ short circuit is shown in Figure 16.

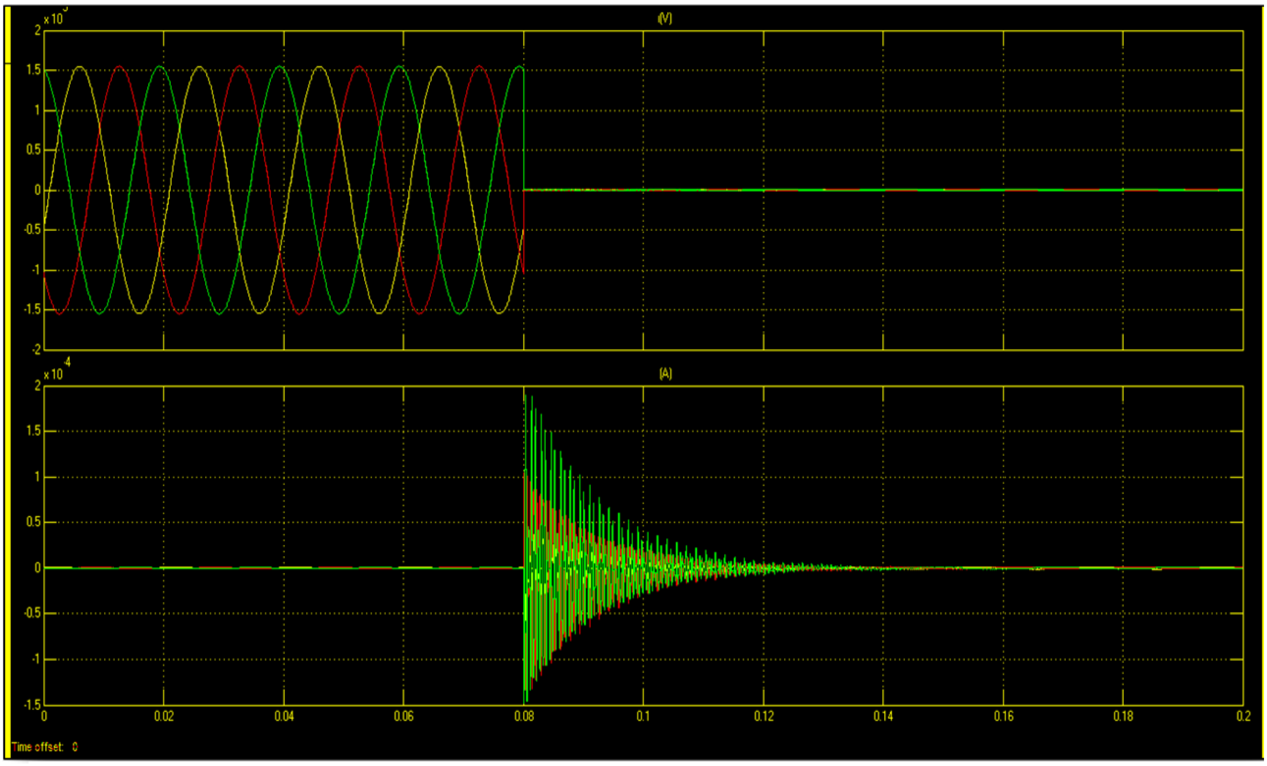

Figure 16: 3Φ short circuit formed on the transmission line between Keban 154 kV bus bar and Elazığ-2 Substation (Voltage & Current Levels)

When the relays in the network system haven't sensed the 3Φ short circuit occur at Keban Switching Center, current oscillations consisted (Fig. 17) and the resulting current grew up to four times larger than the current value of the stable system.

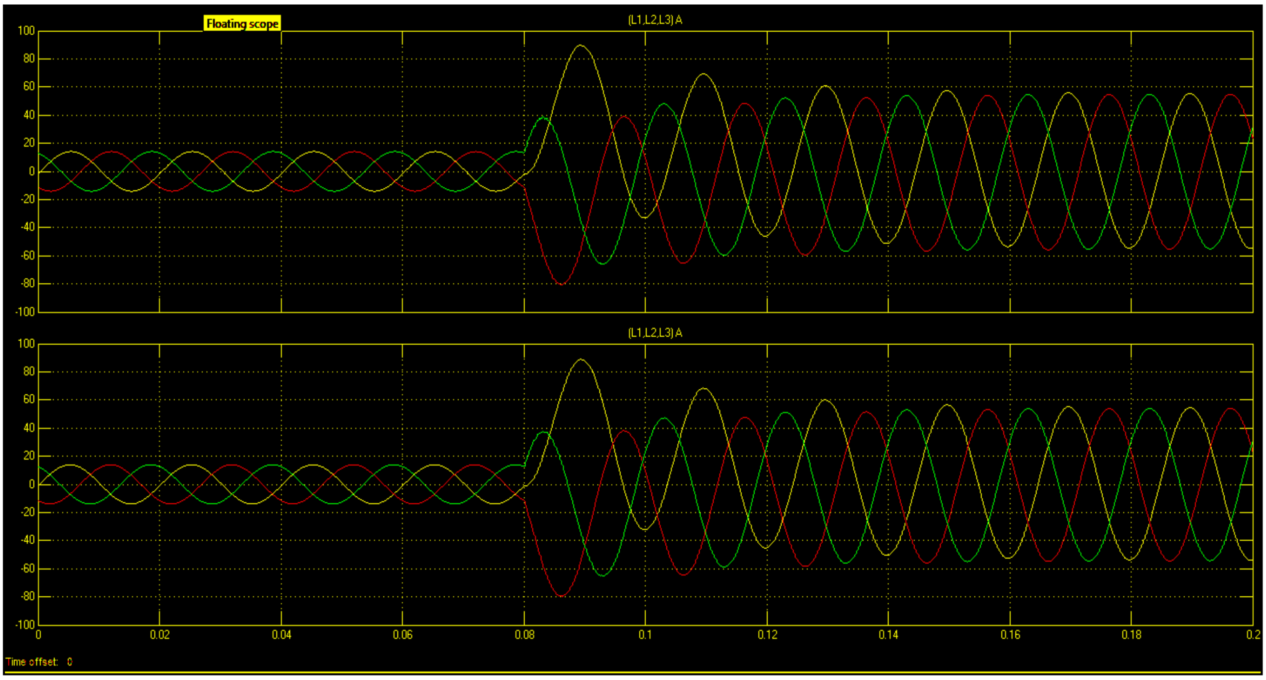

Figure 17: The view of the current oscillation due to the 3Φ short circuit formation at Keban Switching Center when relays don't sense the fault. Upper plot denotes Line 3 and Bottom plot shows the Line 2 current waves.

Since the unit auxiliary transformer in energy generation section is directly connected to the alternator sources, transient fault occurs (Fig. 18.1 & 18.2) in the case of convenient RL filter is not selected.

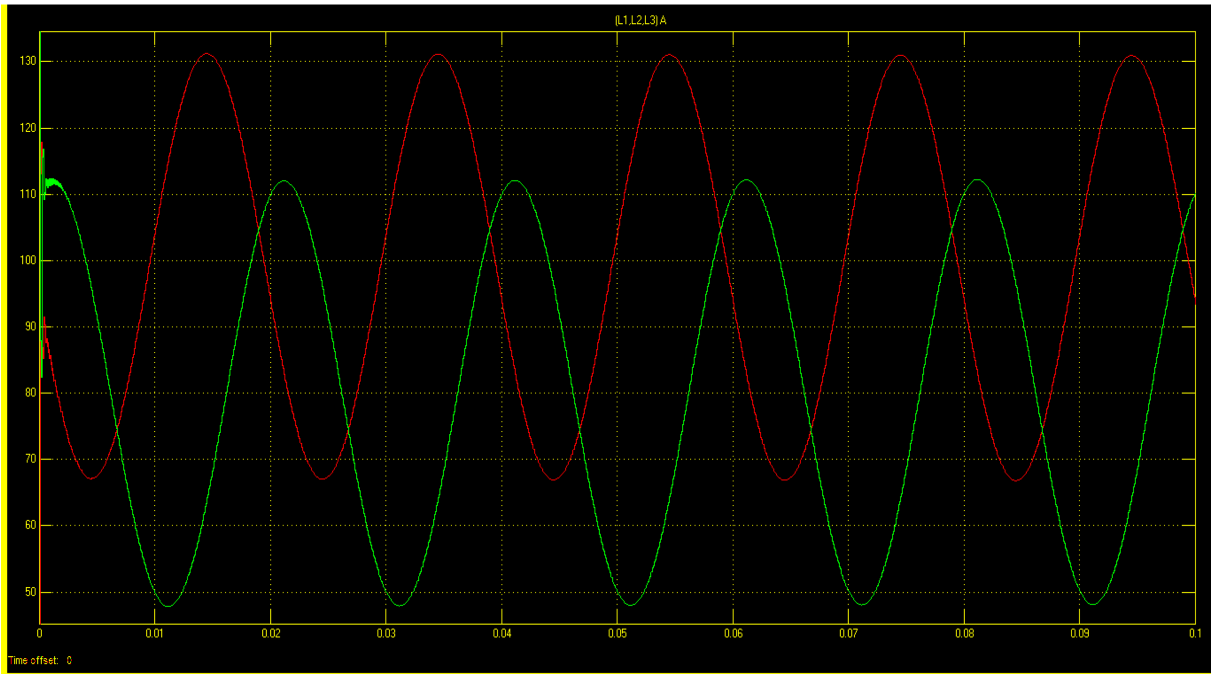

Figure 18.1: Current Waveforms when the Transient Fault consisted of the generator at Internal Supply Transformer in Keban HPP Unit. This fault occurs if current dependent RL filter is not selected.

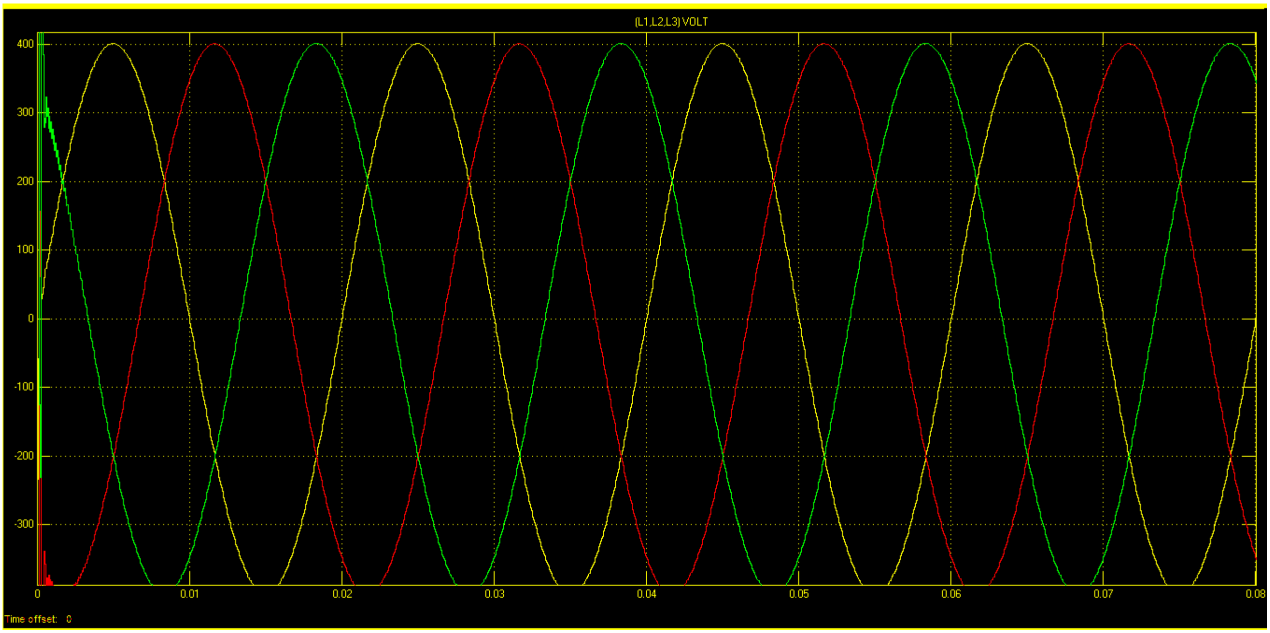

Figure 18.2: The Analysis of Transient Fault consisted of the generator at Internal Supply Transformer in Keban HPP Unit. Voltage Level is at desired value.

In Keban Substation, one of the circuit-breaker is broken and switches-off the circuit without any fault formation and de-energizes that line. Thus, voltage and current values of the line become zero (Fig. 19.1.). Kuzova Line also remains de-energized due to the broken circuit-breaker. Switching-off the line yields also current drop in the network system (Fig. 19.2.) and supply-demand equilibrium of the power system is deteriorated. To ensure the continuity of the system some load is dropped of the system.

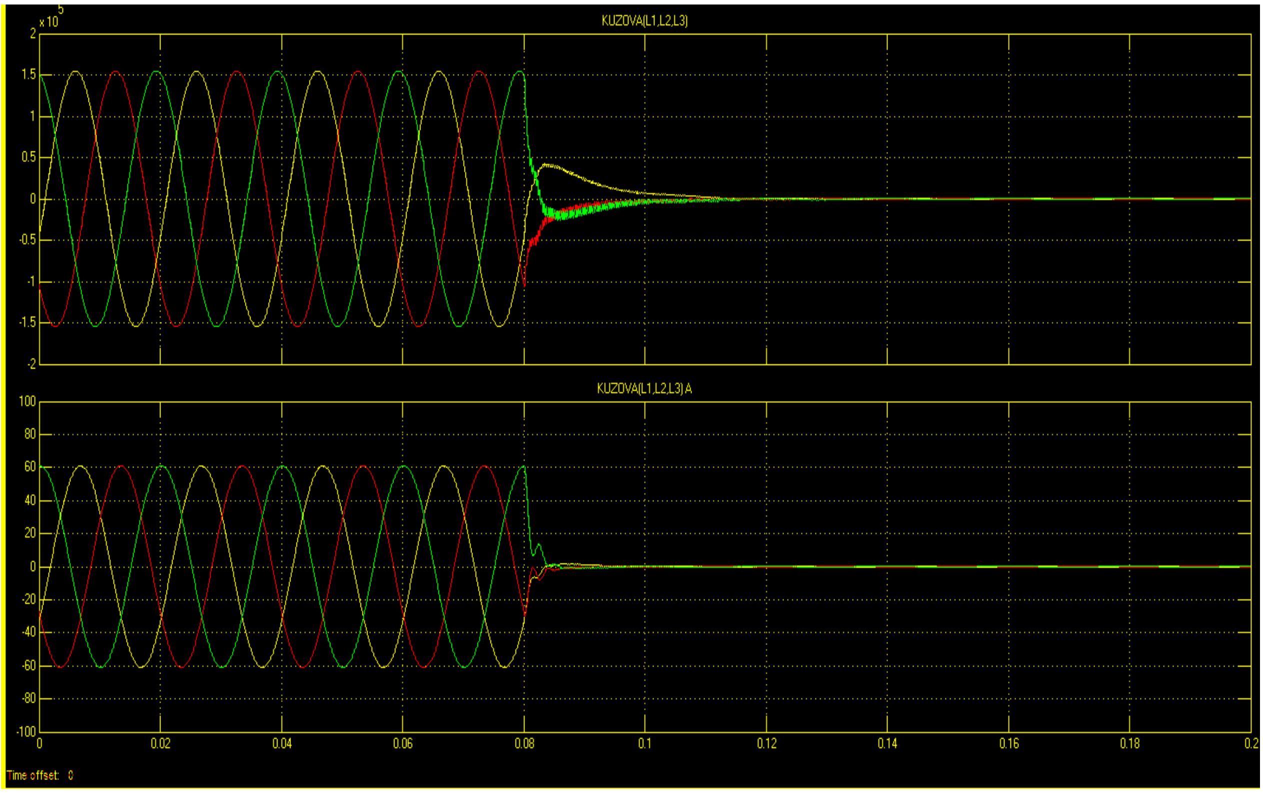

Figure 19.1: Voltage and Current fluctuations of the system due to Coordination Disorders at the 2012 numbered circuit-breaker (broken circuit-breaker) in Keban Transformer Switchgear Center.

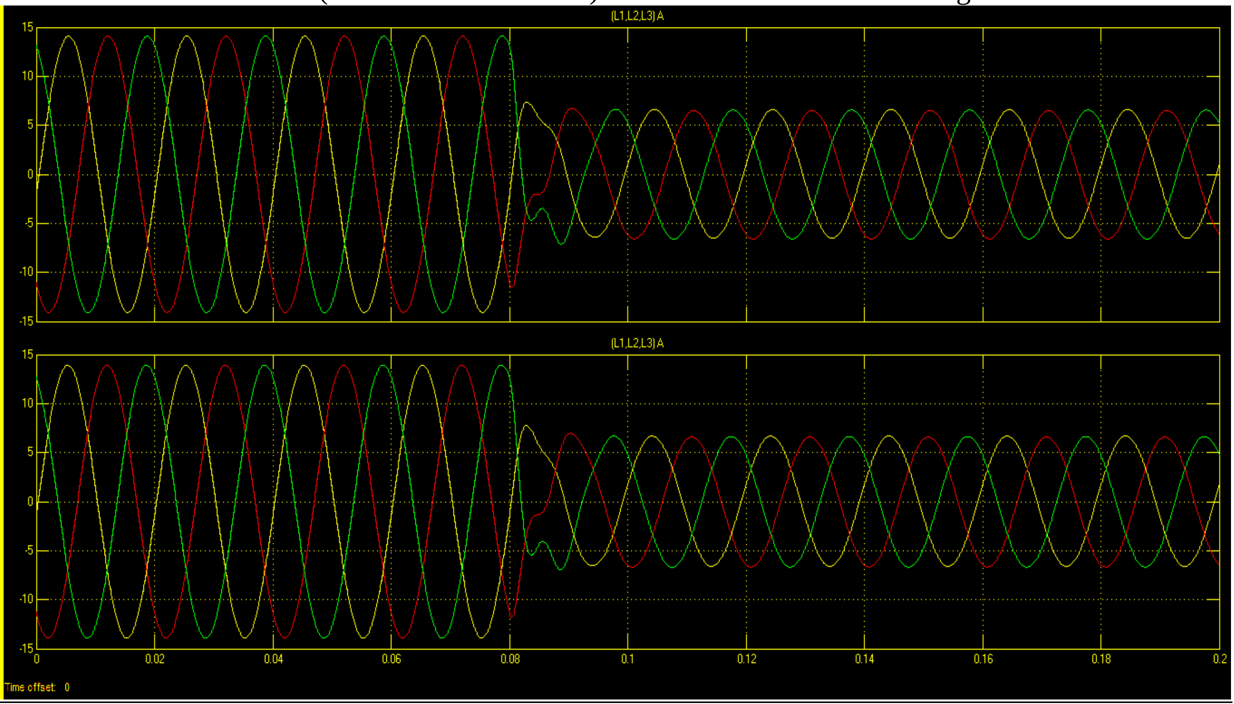

Figure 19. 2: The behavior of the system due to Coordination Disorder at the 2012 numbered circuit-breaker (broken circuit-breaker) in Keban Transformer Switchgear Center. Undesired load-shedding case due to the broken circuit-breaker. Upper plot denotes Line 3 and Bottom plot shows the current waves of Line 2.

A low oscillation is observed at 380 kV bus bars in the center due to the coordination disorder (Fig. 20).

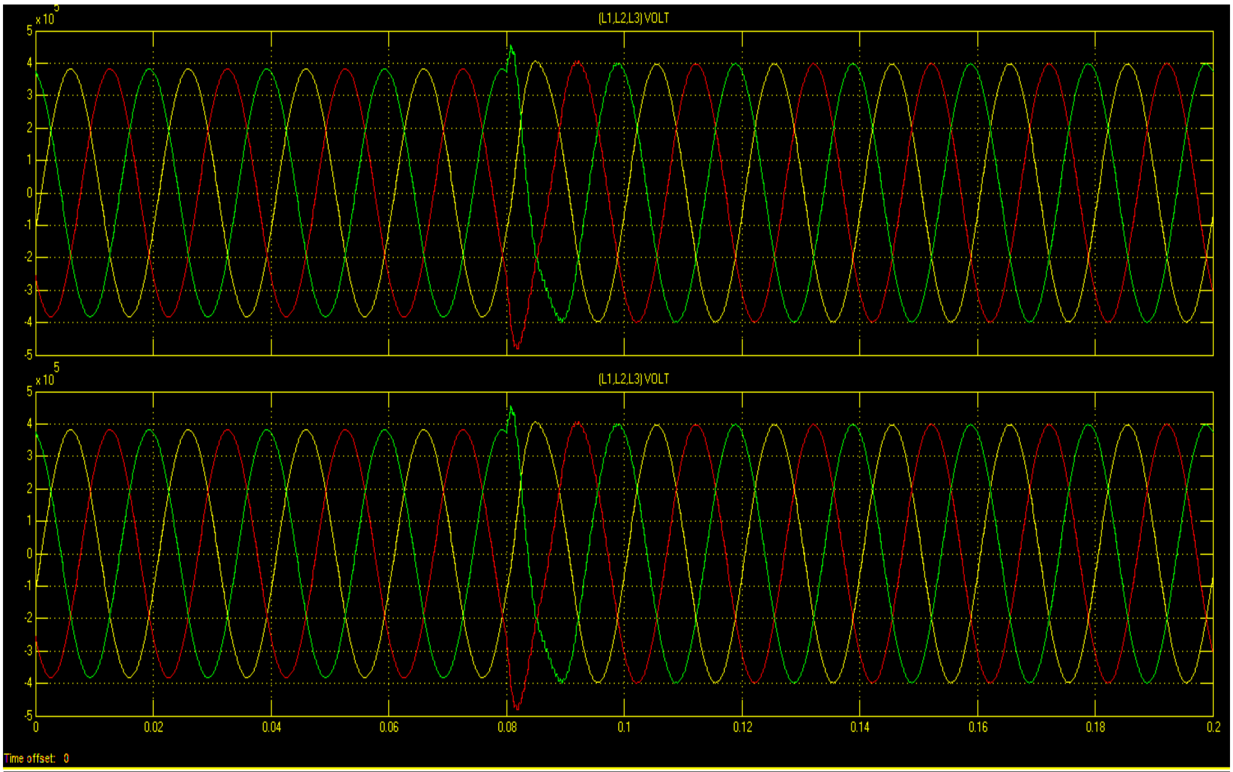

Figure 20: Voltage fluctuations in fiders due to Coordination Disorders at the 2012 numbered circuit-breaker in Keban Transformer Switchgear Center. Upper plot denotes Line 3 and Bottom plot shows voltage waves of the Line 2.

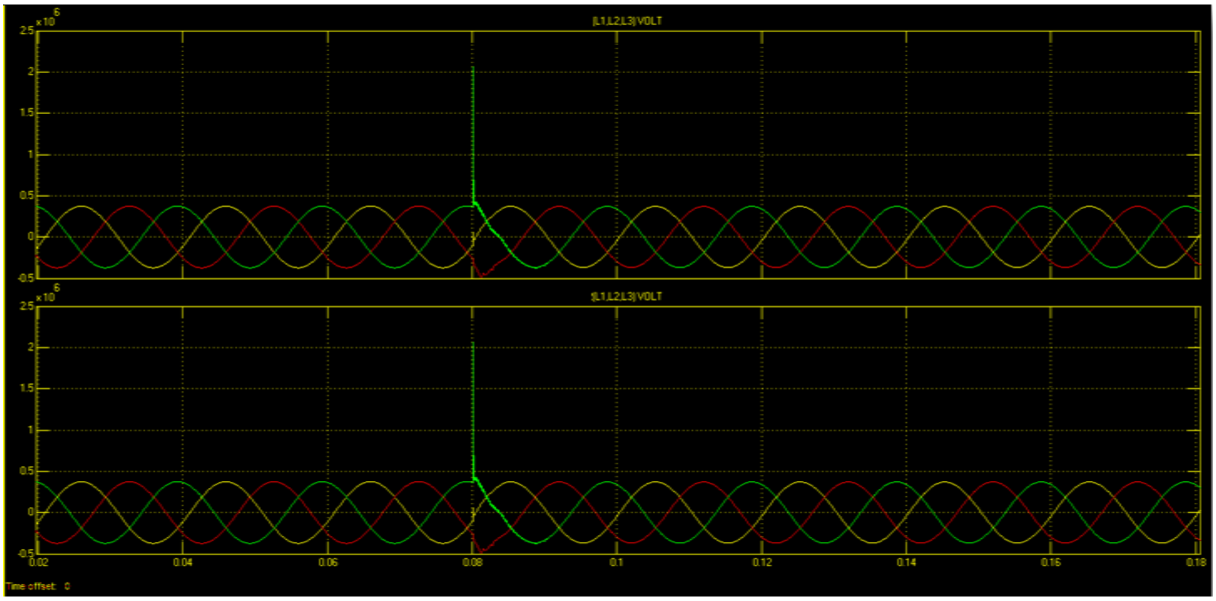

Figure 21: The Voltage Fluctuations of 380 kV fiders in the case of all circuit-breakers switching-off in the Keban Transformer Switching Center. Surge-voltage occurs. Upper plot denotes Line 3 and Bottom plot shows voltage waves of the Line 2.

Due to a major fault occurrence at all circuit-breakers in Keban Substation, all of the circuit-breakers are switched-off and internal overvoltage occurs (Fig. 21). This type of voltage is the inductive character. When this error occurs, in order to damp this overvoltage, series compensation units must be commissioned urgently.

As a result of the fault analysis obtained in numerical modeling study implemented with ***Matlab^{TM}/Simulink***, it can be observed that the voltage is at the desired level (Fig. 18. 2.) unlike the current waveforms (Fig. 18. 1.). There is nothing affecting the voltage waveform. RL filter circuit is designed to ensure the balance of the current waveform.

4. Conclusion and Discussion

In this study, the power flow and the short circuit analysis of the power transmission network were implemented by modeling the power system in the Simulink toolbox of MATLAB™ Software. Current, voltage, active and reactive power variations were obtained at transformer, transmission network and loads in the power system. By examining active and reactive loads of substations, the amount of power that should be added into the system were identified. In line with these data, the planning of the energy investment for this region can be intended in advance. Voltage drop in the power transmission lines and line losses can be detected by comparing the main bus voltage value. The variation of the input and output current level according to the normal operation conditions of the substations in the system were obtained at short-circuits analysis implemented in the simulation study. These currents lead to mechanical losses by generating a large magnetic forces and causing overheating in elements of the network. As a result of the short circuit analysis, the switch-off power of circuit-breakers can be determined and to improve the system stability necessary revisions are implemented. Moreover, relay coordination of the system can be achieved by determining the switch-off power of circuit-breakers and adjusting the relay settings used in the generation, transmission and distribution network. Since the fault trapping time of the circuit-breakers and the detection time of relays are on the order of 10 to 20 seconds, transient faults (occur in very short time periods) and their detrimental effects cannot be predicted in real power network systems. By the help of this transient study (implemented for 0.2 second), these type of faults can be observed and necessary precautions may be taken in advance. The most important benefits of modeling the transmission network in the computer are to be able to acquire the maneuvering and control settings in the real system with the database in the computer and by interpreting the problems according to the graphical and analytical results, to be able to provide opportunities to pre-intervention for the problems in the realistic systems. By this way, having an idea about the behavior of the system will provide us to produce solutions and take precautions against the worst-case scenarios.

Acknowledgments

The study has been supported by the Research Project Department of Akdeniz University, Antalya, Turkey. This study is a part of studies held by Akdeniz University Industrial and Medical Applications Microwave Research Center (IMAMWRC).

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