

Transient Phenomena Analysis and Protection Evaluation in an Industrial Power System

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Abstract-- Various catastrophic incidents and tripping events that have taken place in the electrical power system of an oil and gas plant in Libya have initiated the investigation of electromagnetic transient related phenomena in this site. A field survey was initially performed for this purpose. In addition, advanced measurement devices were installed in critical substation locations in order to monitor various routine switching operations that would help to properly model the electrical network under investigation in an Electromagnetic Transients Program (EMTP). On February 7th, 2010, a plant blackout occurred twice while the monitoring process was still in progress. Post-mortem analysis of the blackout event has been performed using both EMTP and protection coordination software, based on the received oscillographs and measurements data. The analysis, as well as the simulations and the derived results are presented in this paper. Corrective measures were proposed to address both the transient phenomena and the protection issues in this site.

Index Terms--Blackout, EMTP, industrial power system, overvoltages, protection system, transients.

I. NOMENCLATURE

“NE, SE, S, NW” refer to the North-East, South-East, South and North-West 34.5 kV overhead line respectively.

“Main Transformer” defines the 3.75 MVA, 60 Hz, 4.16/34.5 kV, Dyn1 power transformer at the sending end of every overhead line.

“Well Transformer” defines the 350 KVA, 60 Hz, 34.5/2.3-1.919-1.15 kV power transformer feeding the submersible motors at the wells.

“Main Fuse Set” defines the three single-phase fuses set installed at the 34.5 kV side of every main transformer thus providing the main protection of the overhead line.

“Well Fuse Set” defines the three end tower single-phase fuses at the well branches.

II. INTRODUCTION

VARIOUS catastrophic incidents and tripping events have occurred in the power system of an oil and gas plant in Libya. The frequent tripping of the 34.5 kV overhead lines supplying oil production wells, the overvoltages experienced and the failure of a number of surge arresters, in combination with other influential factors such as the

original design and configuration of the electrical network, have given rise to the need to investigate electromagnetic transient related phenomena in this site.

Power system simulations have been performed in an Electromagnetic Transients Program (EMTP) for this purpose. A field survey was initially performed. In addition, advanced monitoring devices were installed in critical locations in order to record controlled switching operations. The actual performance of the power system, as recorded by the devices, was used in order to adjust the computer simulation model of the electrical network, so that the responses and simulations obtained from the computer model during various events are as close as possible to the actual ones.

On 7th February 2010, a plant blackout occurred twice while the monitoring process was still in progress. Post-mortem analysis of the events leading to the first blackout has been performed. Again, the recorded measurements have been utilized to validate the model used in the analysis.

Different cases studies have been simulated in order to propose corrective measures dealing with the problems that show up during the power system operation. It is shown that transient phenomena like the ones experienced will be eliminated in future if the proposed measures are implemented.

The next section describes the power system under investigation and presents its existing protection system. Section IV deals with modeling aspects and provides the exact methodology followed to retrieve an accurate representation of the examined electrical network. In Section V a detailed description of the blackouts happened on 7th February 2010 is given together with the findings of the post-mortem analysis of the events. Section VI deals with the corrective measures that are proposed for this power system and Section VII presents case studies that verify these solutions.

III. POWER SYSTEM CONFIGURATION

A. Description

The site under investigation has its own 4.16 kV gas turbine power generation plant (shown with blue at the left hand site of Fig. 1) which consist of five 3.125 MVA natural gas turbine generators divided into two groups that operate in parallel. One more generator is available but normally out of operation and a new one will be added for future needs. The total generating capacity is currently 14 MW at site conditions.

The 480 V distribution system (shown with black color in Fig. 1) is being fed through 34.5/0.48 kV step-down transformers directly from the generator buses. It supplies mainly the auxiliaries of the generating plant and the indus-

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trial processes consumptions.

Four 34.5 kV overhead lines (shown with green color in Fig. 1), namely North-East, South-East, South and North-West, supply through 4.16/34.5 kV step-up transformers a number of oil and water source well sites that are located in the desert. All of these transformers are star-delta connected, with the ungrounded delta winding on the 34.5 kV side. This, presumably, is an original design choice since the system was built, intentionally providing an ungrounded system for high service continuity.

To meet the Electric Submersible Pumps (ESP) supply requirements, the voltage level at each well site is reduced to 2.3/1.919/1.15 kV (depending on the ESP's motor nominal voltage) through a step-down transformer. The current maximum total load of this site is approximately 7.5 MW.

B. Protection System

Most of the main electrical equipment is protected with unit protection schemes (eg. generators and transformer circuits are provided with differential protection) for fast fault clearing. Overcurrent and earth fault relays are also provided on these circuits (generators, transformers and 4.16 kV feeders) so that in case the unit protection fails to operate, the backup protection isolates the faults without disrupting the healthy part of the system. In addition, undervoltage protection is provided at some generators and transformers.

Moulded Case Circuit Breakers (MCCB's), Miniature Circuit Breakers (MCB's) and fuses are used on the 480 V circuits. As regards the 34.5 kV transmission system, every overhead line is protected by three single-phase expulsion fuses installed at the sending tower end (secondary of main transformer). A set of three single-phase expulsion fuses installed at the primary of every well transformer is used to protect the transformer and the motor cable as a unit. The ESP motors are protected with fuse contactors, thermal overload and undervoltage protection.

For the overcurrent and earth fault relays on the 4.16 kV overhead line feeder circuits, appropriate 600/5 current transformer (CT) sets have been used. At the South line, however, a 300/5 CT is used. The 3.75 MVA transformer at this line has a full load current of 520 A at 4.16 kV. This means that this CT will be saturated even for prolonged full load operation of this circuit.

It should be noted that although the generators are resistively grounded, the neutral point of all the main overhead line transformers at this site is solidly grounded on the 4.16kV side. On the 34.5kV side the windings are delta connected. This way high service continuity is achieved because, if one earth fault occurs, any earth fault current will be limited and very low, no tripping of ESP motors or other equipment will take place and the production will continue. In the meantime the earth fault may be traced and rectified. However, any phase-ground fault at the overhead lines will not be detected and cleared by the protection devices at the 4.16 kV.

To conclude, protection relays and circuit breakers are installed only at the generators and the 4.16 kV feeder panels, while the overhead lines and the well distribution circuits are protected only by single-phase fuse sets.

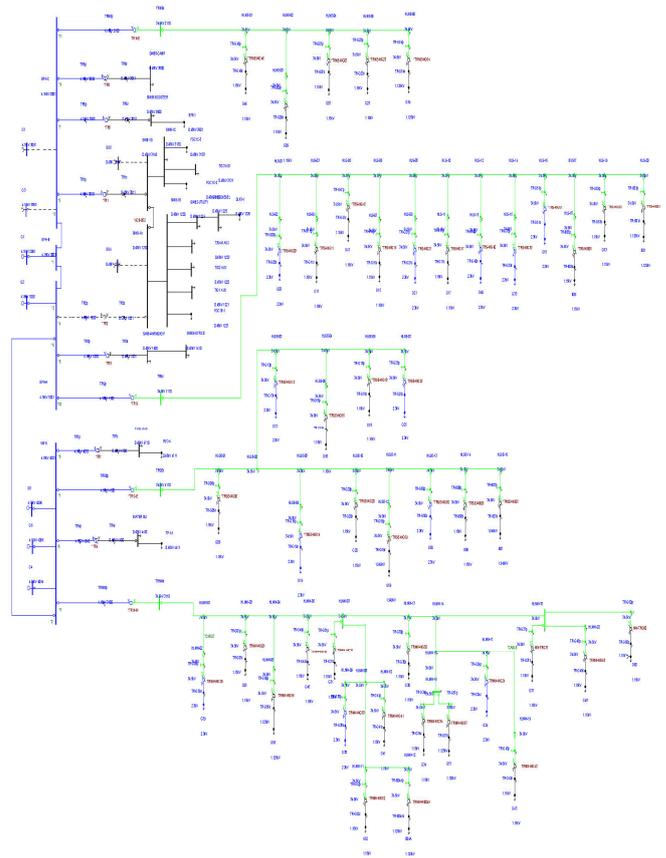


Fig. 1. Complete electrical network.

IV. SYSTEM MODELLING METHODOLOGY

A. Overhead Lines Switching Operations Procedure

Dranetz-PX5 monitoring devices were installed in the four 4.16 kV overhead line panels of the field substation in order to record various controlled switching operations that were agreed between the ZOC personnel and PROTASIS SA.

No any other measurement point was available as regards the overhead lines, so the devices were sensing current and voltage from the current and voltage transformer respectively of those panels. That means that current and voltage was measured on the low voltage (4.16 kV) side of the overhead lines' main transformer, not exactly giving an accurate record of the 34.5 kV part of the network.

The switching operations procedure was the same for all the overhead lines and was followed in the order described next:

- The circuit breaker at the 4.16 kV overhead line feeder circuit was manually tripped. After its opening, all the ESP motors at the wells were automatically disconnected due to undervoltage protection.
- The circuit breaker was manually closed. The entire line including the main transformer and the transformers at the wells was energized.
- Phase-A of the main fuse set was opened manually.
- Phase-A of the main fuse set was closed manually.
- The motors were being connected one after the other.

B. Equipment Modelling

Lines: Coupled pi-equivalents have been considered as all the overhead lines and cables that show up in the single line diagram of Fig. 1 are of relatively short length.

Transformers: The typical simple model has been used, where R and L of the transformer are considered as obtained by the Z% and the X/R ratio of the transformer nameplate. This model is based on the combination of three single-phase transformers, including the saturation effect but not including coupling inductances between the windings. In general, this model compromises the accuracy of the transient simulation with the ease of calculation, when little information about the transformers is known. However, a more detailed transformer representation based on the accurate magnetization curve and the real core configuration would be more useful for transient studies [1]. Note that real transformer core saturation characteristics were not known. However, saturation has been taken into account using non-linear magnetic representation characteristics retrieved from the simulation analysis performed in EMTP.

Load: A parallel R-L model is placed at each point where load is connected. Load provides damping and it must be taken into account in transients studies related with circuit breaker closing. On the contrary, heavy load conditions are the worst from a circuit interrupting point of view.

Sources: Equivalent sources like the ones used in protection studies have been used for the transients evolving in the time scale of a few milliseconds (switching operations). On the contrary, in the blackout analysis described later a complete generation representation has been used taking into account generators, automatic voltage regulators (AVR) and governors.

Switchgear: Circuit breakers and fuses have been modeled as ideal switches. The switching instant is important. For example, transformers saturate for zero point-on-the-wave closing, but cable energizing transients are worse for 90 degrees closing. Differences in the closing instants of the three phases have been taken into account.

C. Model Validation

The switching records from the Dranetz-PX5 devices were used to fine tune the model of the electrical network used in the EMTP, in order to better represent its transient response.

It should be noticed again that the real core saturation characteristics of the transformers, which play an important role on the transient analysis, were not able to be provided from the field personnel. However, the non-linear magnetic representation of the transformers has been approximated to some extent from the simulation of the performed switching operations.

In specific, numerous simulations of the circuit breaker and main fuse Phase-A closing operations at every line have been performed in order to retrieve similar waveforms with the recorded ones. Factors playing an important role during such energizing operations have been taken into account. For example, differences in the closing instants of the three phases have been considered - the closing instants in the simulation correspond to the actual ones relative to the voltage waveform.

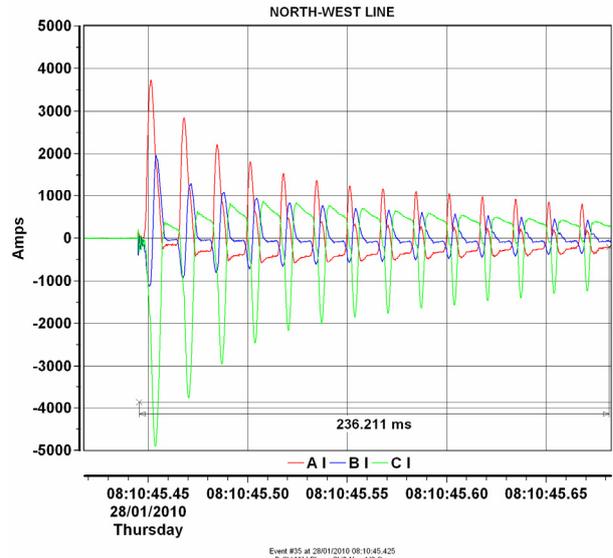


Fig. 2. Measured inrush current at North-West line

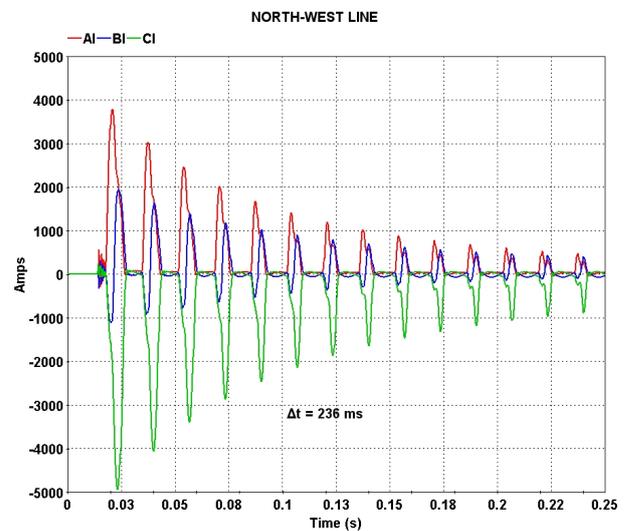


Fig. 3. Simulated inrush current at North-West line

The following assumptions were also made in the analysis without affecting the accuracy of the results:

- The magnetic hysteresis of the transformers core was neglected.
- The residual flux was not explicitly considered.

Note, however, that despite the fact that a detailed simulation approach was followed, the core saturation properties of the transformers are only quantitatively approximated from the EMTP analysis since a lot of parameters cannot be arbitrarily assumed [2], [3].

Some indicative results from the fine tuning process are presented next. Fig. 2 depicts the inrush current measured from the Dranetz-PX5 device at the CT location (4.16 kV panel) during the energization of the NW line. This current represents not only the inrush current of the main NW transformer but also the inrush of all the well transformers with the motor loads disconnected.

This was a great problem for the simulation in the EMTP because a systematic trial and error tuning of the saturation characteristics of all the transformers was needed in order to obtain the same inrush current.

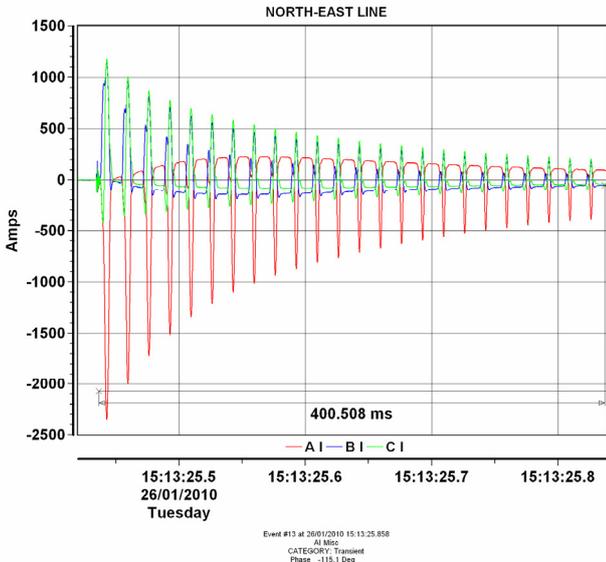


Fig. 4. Measured inrush current at North-East line

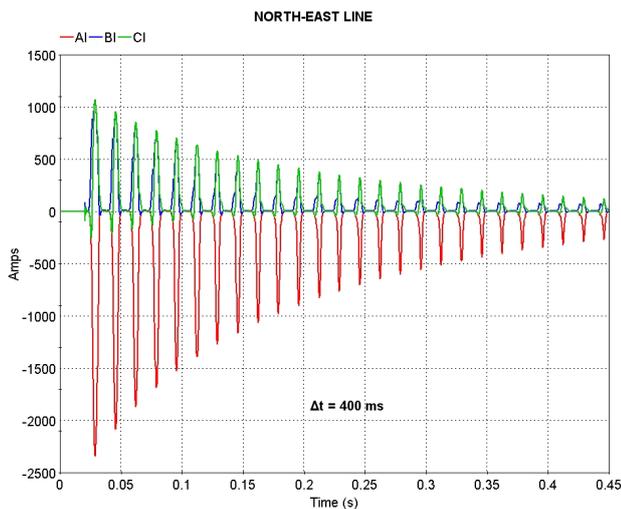


Fig. 5. Simulated inrush current at North-East line

Fig. 3 shows the corresponding inrush current retrieved from the simulation. As explained earlier, this current refers to the energization of the NW line considering all the well transformers connected and all the motor loads disconnected. One can see the similarity in the measured and simulated waveforms.

In Fig. 2 an offset of the Phase-A and Phase-C currents can be also observed, in contrast to the simulated waveform (Fig. 3). This is due to the CT saturation. The large and slowly-decaying dc component of the inrush current is able to saturate the CT even if the magnitude of the current is comparatively low. When saturated, a CT introduces certain distortions to its secondary current [4]. Moreover, the current in the supplying line is a sum of the inrush currents of all the transformers together, somewhat like a kind of a series “sympathetic inrush”. This has also an impact on the observed offset.

Fig. 4 and Fig. 5 illustrate the actual and simulated inrush currents respectively for the energization of the NE line. Similar responses have been obtained from the monitoring and simulation of the energization of the other two overhead lines.

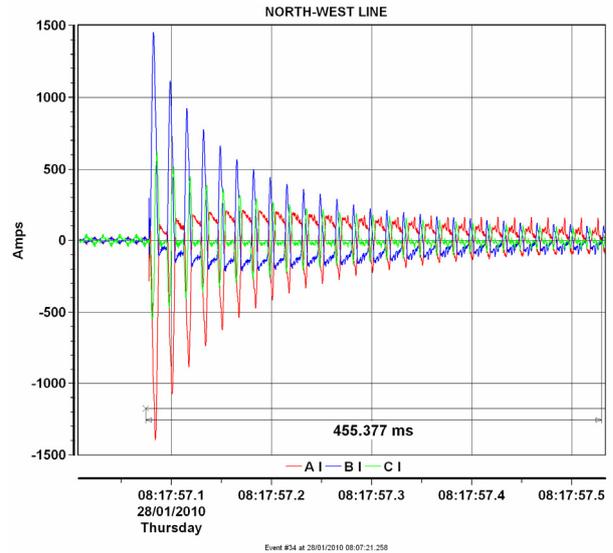


Fig. 6. Actual current during main fuse phase-a closing

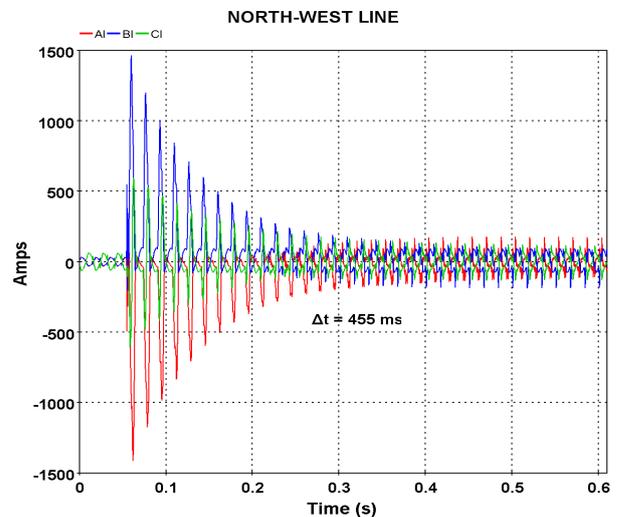


Fig. 7. Simulated current during main fuse phase-a closing

In Fig. 6 and Fig. 7 the Phase-A closing of the main fuse cutout in NW line is shown. Again one can see the similarity between the actual and simulated response.

The recorded current flows prior and after the closing of Phase-A fuse, when only transformers were connected at the overhead lines without any load, helped estimating the parameters of the magnetizing branch of the transformers. It should be noted that the operation with one phase open, results to a highly distorted current waveform.

The opening of the circuit breakers and fuses is not essential for fine-tuning the network model because the current interruption depends on the arc nature and the subsequent clearing mechanism. In addition, a reignition-restrike was observed in some cases, which makes the clearing mechanism even more complicated.

As a conclusion, the model of the electrical network used in the EMTP has been represented in such a way that it is appropriate to study switching transient phenomena in this site.

V. BLACKOUT EVENTS

A. First Blackout

The plant experienced two blackouts on February 7th, 2010, both appearing after a sequence of complicated events. A little information was given about the causes of the incidents from the field personnel, only the consequences had been reported. However, the monitoring devices that were installed for the recording of the switching operations at the overhead lines provided helpful information.

Repeated simulations of a large combination of fault locations and types both in EMTP and protection coordination software have been performed, based on the gathered information. According to the simulations and the reports, the following sequence of events is supposed to have led to the blackout.

The initial cause of the first blackout seems to have been a three-phase fault at the secondary (low-voltage side) of the G19 well transformer connected on the SE overhead line (referred as “1st Fault” in Fig. 8). Before this fault is cleared, an internal one-phase-ground fault at B06 well transformer in the same line followed (“2nd Fault” in Fig. 8). The latter fault caused the blowing of two single-phase fuses at the primary of the neighbor G06 well transformer. This is justified due to the earth returning path provided by the grounding of the star connected primaries of the B06 and G06 well transformers, having in mind that all other primaries of the well transformers at that line have a delta connection. Moreover, down hole equipment at well G06 was found without any problem indicating that the blowing of the fuses was not caused from a fault at this well. Some time later two single-phase fuses at well B06 blew, followed by the blowing of all three fuses at well G19. The melting of these exact fuses is in confirmation with the field personnel report.

After all these catastrophic incidents, the SE line continued to operate under an extremely unbalanced state. Note that a permanent current unbalance existed in the SE line prior the event (in steady state condition). Such conditions lasting for a sufficient period of time seems to have initiated surge arrester failures. This should be the most possible reason for the overcurrents that occurred after the clearing of the faults. Since it is not clear what caused these overcurrents they are characterized in this text with the general term “fault conditions” (see Fig. 8). Further analysis about this phenomenon will be presented in the next paragraph.

Phase-B blowing of the SE main fuse set followed as a consequence of that “fault conditions”. After that, the line seems to have been evolving in a ferroresonance state (shown with circle in Fig. 8). Ferroresonance is responsible for a chaotic response of the currents and voltages [5] and so was it at the line. The voltage and current distortion initiated the operation of the protection relays in the substation. The undervoltage trip of the circuit breaker at the primary of the 4.16/0.48 kV North Transformer resulted in a generators auxiliary equipment failure causing the generators to be disconnected. After this, the whole site was driven into a blackout.

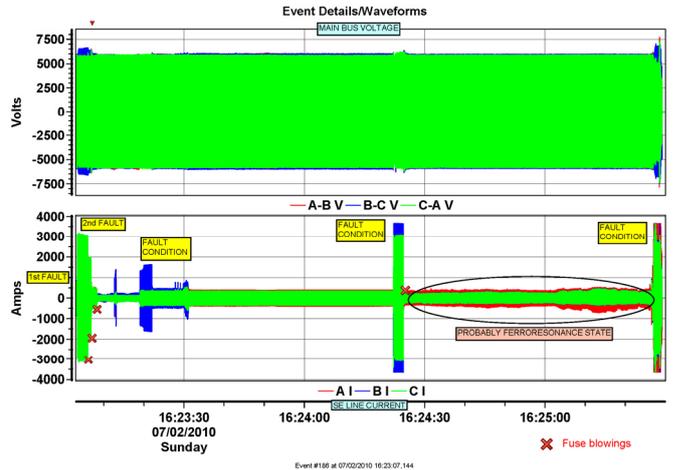


Fig. 8. Whole sequence of blackout events

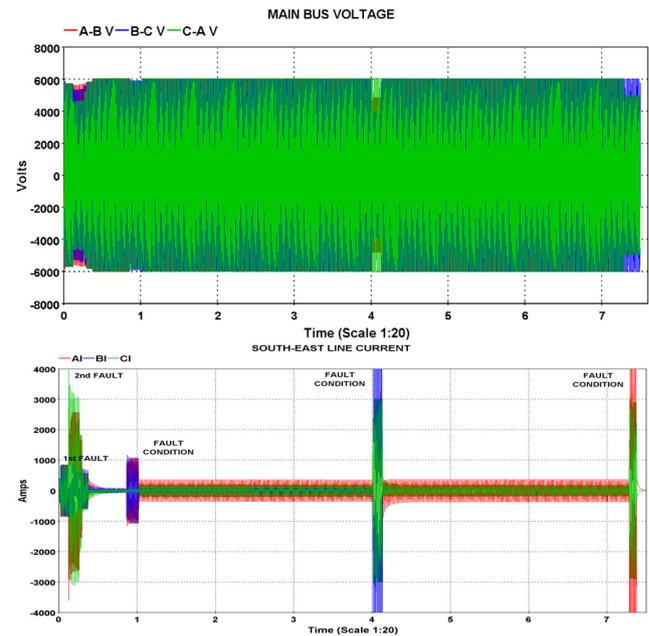


Fig. 9. Simulated sequence of blackout events

Fig. 8 depicts the whole sequence of events as recorded from the Dranetz-PX5 instruments located in the SE feeder panel. Again, notice that voltage and current are measured on the low voltage side (4.16 kV) of the line. That means that overvoltages appearing in the 34.5 kV part of the line could not be recorded.

B. Post-Mortem Analysis of the First Blackout

The complete sequence of events that led to the first blackout of the power system was simulated in the EMTP software. Since the cascaded events were lasting for about 2.5 minutes, a complete generation representation has been used in the analysis, taking into account generators, automatic voltage regulators (AVR) and governors' action.

Fig. 9 illustrates the whole sequence of events as obtained from the simulation. One can compare Fig. 8 with Fig. 9 to show the similarities, despite the fact that some events (instant spikes) happened actually cannot be reproduced. Keep in mind that the simulated waveforms are time scaled.

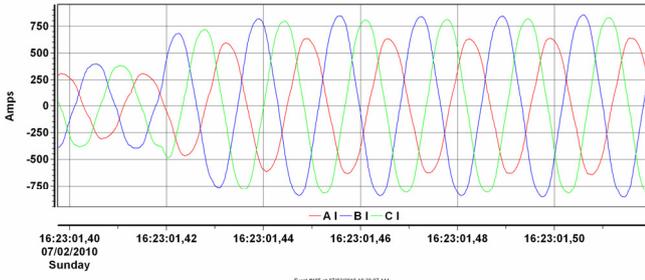


Fig. 10. Recorded fault at G19 well transformer (1st Fault)

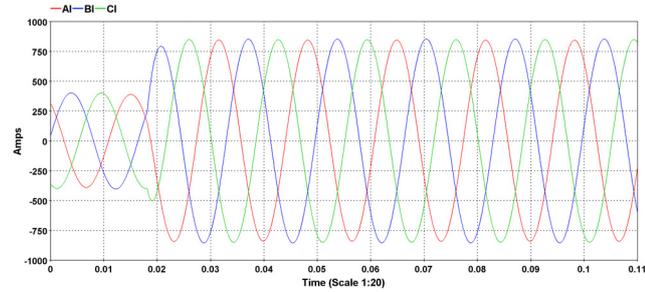


Fig. 11. Simulated fault at G19 well transformer (1st Fault)

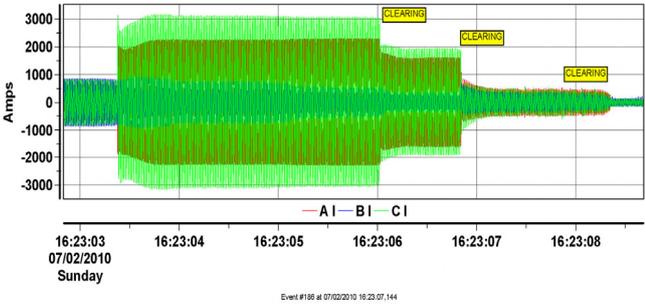


Fig. 12. Fuse blowing at G06, B06, G19 wells (record)

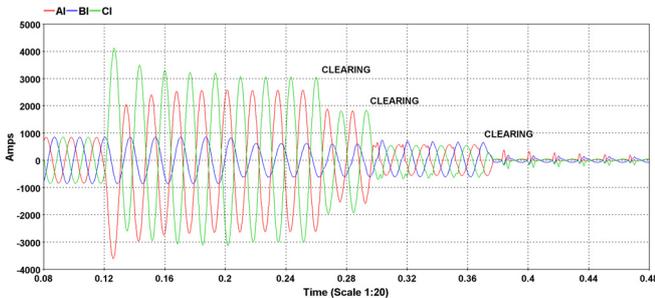


Fig. 13. Fuse blowing at G06, B06, G19 wells (simulation)

The current unbalance observed at the SE line during the steady-state operation (Fig. 10) has not been reproduced in the simulations (Fig. 11). Attempts to do so caused other problems affecting the accuracy of the simulation. In specific, a resistor connected in series with Phase-A caused an artificial damping of the fault currents and subsequent voltage rise on the other phases. On the other hand, a power unbalance on the ESP motor loads cannot be justified for technical reasons. It is still unclear what caused this current asymmetry. Hence, symmetrical steady state conditions have been finally assumed.

Fig. 12 and Fig. 13 show the fault-clearing sequence achieved through the blowing of the single-phase fuses at the wells G06, B06, G19, as recorded and simulated respectively.

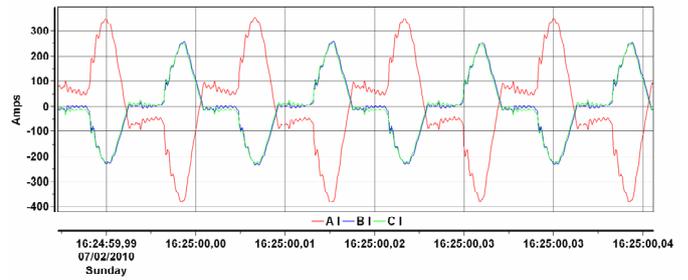


Fig. 14. Recorded state prior last fault condition

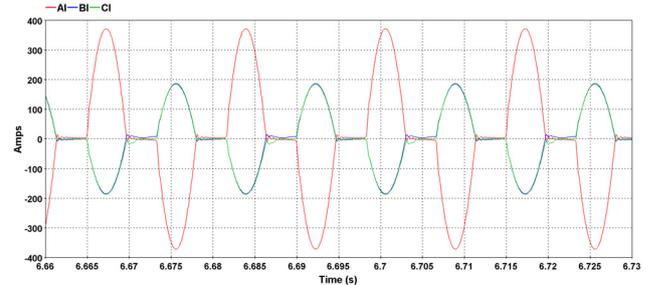


Fig. 15. Simulated state prior last fault condition

The final stage of the ferroresonance state could not be exactly simulated. However the simulation (Fig. 15) clearly indicates such a condition.

Ferroresonance is justified under the conditions existed that day:

- SE overhead line experienced a continuous current unbalance during all the examined time period.
- Sequential faults occurred at different instances and places that day, leading possibly to undesired overvoltages all over the line circuit.
- SE overhead line was left totally ungrounded after the blowing of the fuses at the G06, B06 well transformers that were grounded in their 34.5 kV side.
- SE overhead line operated under a highly asymmetry, especially after the main fuse Phase-B blowing. In addition, a lightly loaded system remained after all those disconnections.
- The surge arresters are old and inappropriate for a 34.5 kV ungrounded network. Rather they are chosen for a grounded 34.5 kV electrical network. It is understood that, after being subject to many overvoltage stresses over the years, their capability may have weakened.

The undervoltage tripping of the North Transformer circuit breaker is justified as one can see the voltage collapse at the last stage of the incident (Fig. 16 and 17). Keep in mind that the VT measures the voltage at the main 4.16 kV bus.

A critical question raised from the above analysis was how the “fault conditions” could be explained. Normally, when ferroresonance occurs in the lines, the overvoltage will be clamped by the arrester and the current will flow through the arrester. The heat caused by this current has to be transferred from the arrester to the environment. If the rate of heat dissipation is less than the rate of heat production, the temperature of the arrester will rise continuously. If the temperature rises above the temperature limit, the arrester will be permanently damaged [6], [7].

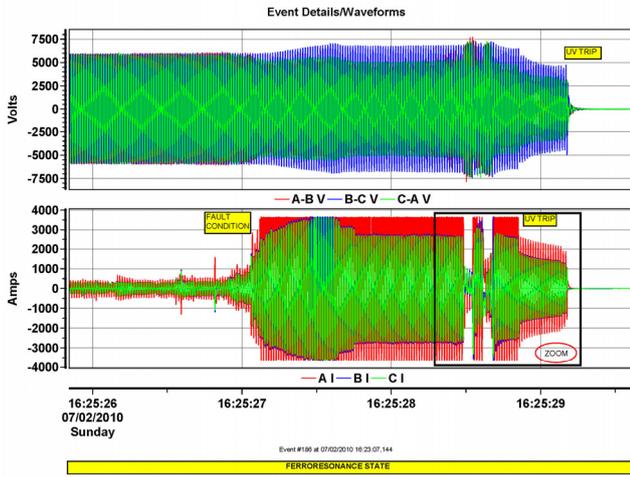


Fig. 16. Ferroresonance state in SE line currents

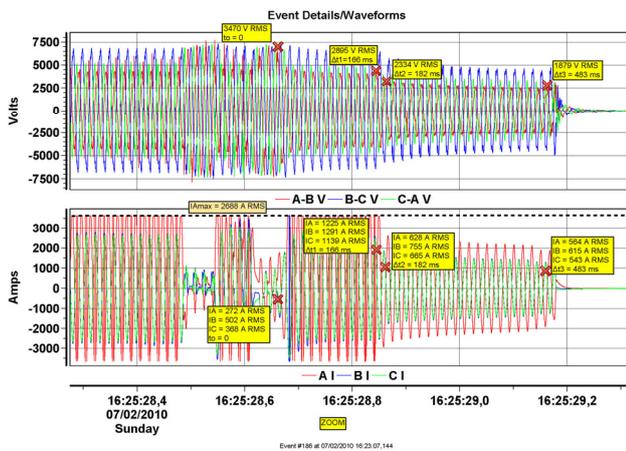


Fig. 17. Chaotic response (Last stage figure enlargement)

In some cases of ferroresonance, the damage does not occur but the current-voltage characteristic of the surge arrester will change. This defective arrester will lose its ability to block the current at the operating voltage level. Therefore when the phenomenon is completed and ferroresonance disappears, large current will flow through the defective arrester which can cause rapid overheating. Melting of the metal terminals, arc and explosion will follow.

Therefore, if the surge arresters at some points are damaged during single-phase switching operation, it is safe to assume that ferroresonance occurs during switching. However, if the single-phase switching operation is completed without any incidents but the arresters damage at few seconds later, it is very likely that the arresters are defective (from the ferroresonance during switching) and are destroyed by large current at the operating voltage level.

Under those specific conditions existing that day in the SE overhead line and in accordance with the aforementioned explaining, surge arrester failure is also justified.

C. Second Blackout

The second blackout was initiated from a fault occurring on 19:38 at the underground cable feeding G39 well transformer on the NW line. As a result, Phase-A cable pothead was burnt leaving the interrupter panel open. Actually, an evolving fault situation at NW line was recorded from the Dranetz-PX5 devices.

South line tripping followed three minutes later, while NE and SE lines did not trip. However, an unexplained voltage collapse starting on 19:42 drove the system into a blackout.

Next, system restoration procedures were initiated and all generators were run up one by one as reported from the field personnel. SE and NE lines were energized through the generators re-connection. S and NW lines did not have the time to be reconnected because an unexplained event at NE and SE lines caused a second system blackout.

A second restoration procedure followed. Again SE and NE lines were energized through the generators re-connection. The system restoration continued with the NW and S lines energization and the restarting of all the disconnected motor at the wells.

It should be noticed that the events recordings did not fully comply with the field personnel report for the second system blackout.

VI. PROPOSED CORRECTIVE MEASURES

A. Transient Phenomena and Protection Issues

The investigation showed that the examined power system has equipment specifications and system configuration that makes it prone to transient overvoltages.

The delta connection in the 34.5 kV secondary of the main 3.75 MVA transformers feeding the overhead lines, in conjunction with the variety of different power transformers connections at the wells (delta or star on the 34.5 kV primary winding), creates a complex and inconsistent 34.5 kV network configuration. Under specific circumstances the same line can be totally ungrounded or grounded only at some well transformers. Totally ungrounded networks are particularly vulnerable to overvoltages and similar transient phenomena.

There is no capability for simultaneous three-phase switching at the overhead lines either under fault or intended switching conditions (single-phase fuse blowing/reconnection). Operation with one or two phases open makes the network susceptible to ferroresonance.

Specific system conditions (unloaded well transformers, disconnected ESP motors, disconnected parts of lines) constitute a combination of system parameters under which transient phenomena (like ferroresonance) are possible to appear.

The core magnetization characteristics of the power transformers at the overhead lines seem to be such (for example steep enough) that ferroresonance or other transient phenomena are possible.

The unfortunate sequence of switching operations weakened the strength of the power system elements, such as transformers, surge arresters, cables etc. making faults even more frequent. In addition, old protective equipment (relays, CBs, CTs, VTs etc.) accuracy has been affected after many years of being in service continuously and subjected to faulty conditions repeatedly.

The solid grounding of the neutral point of all the main overhead line transformers on the 4.16kV side provides high service continuity. Indeed, if one earth fault occurs, any earth fault current will be limited and very low, no tripping

of ESP motors or other equipment will take place and the production will continue. In the meantime the earth fault may be traced and rectified. However, due to delta connected 34.5kV side windings, any phase-ground fault at the overhead lines will not be detected and cleared by the protection devices at the 4.16 kV.

B. Proposed Countermeasures

It is proposed that all the overhead lines should be washed as insulators contamination could give rise to air insulation breakdown and subsequent development of overvoltages throughout the system.

In addition, there should always be some load present on the overhead lines while being switched in. Load will damp (to some extent) the overvoltages appearing during the overhead line energizations. Note, however, that the more load is present the higher will be the inrush current.

The old surge arresters are stressed due to frequent operation and inappropriate for a 34.5 kV ungrounded electrical network. According to manufacturers' guides [8], surge arresters in a 34.5 kV delta ungrounded network should have a 36 kV rating (MCOV 29.0 kV) instead of the 30 kV (MCOV 24.4 kV) rating the great majority of the installed arresters have now. The latter rating is justified only for a grounded 34.5 kV electrical network. However, replacing all the installed 30 kV surge arresters with new ones without dealing with the common in ungrounded networks problem of overvoltages appearance and possible ferroresonance, only partly gives a solution. Such a measure would minimize surge arresters damage (the causality) but the possibility of ungrounded network operation with one or two phases open (the cause) would still exist.

As long as uninterruptible operation of the overhead lines is requested under ground-fault conditions, simultaneous three-phase switching of the main fuse is not suggested. Otherwise, three-phase switching of the main fuse should be of high priority. Moreover, simultaneous three-phase switching of the fuses at the end towers of the wells should be considered critical, in order to eliminate operation with one or two open phases in large parts of the line. The circuit breakers should also be tested for correct operation.

A permanent solution facing together transient and protection problems is the replacement of the 3.75 MVA, 4.16/34.5 kV, Dyn1, star-delta transformers at every overhead line with transformers that have a star-grounded connection in the secondary (34.5 kV) winding. The selection of a delta-star transformer (YNd11 connection) has the following advantages:

- Overvoltages will be extinguished (maximum phase-ground voltage is restricted to 19.92 kV).
- Ground-fault currents in the overhead lines will be increased to higher magnitudes, so that ground faults will be earlier recognized and cleared from the fuses.
- Ground-fault currents will not be reflected on the primary side (4.16 kV).

The selection of transformers with a star-grounded connection both on the primary and secondary winding (YNyn0 connection) leads again to overvoltages extinction (maximum phase-ground voltage is restricted to 19.92 kV). However, the latter selection has the following disadvantages:

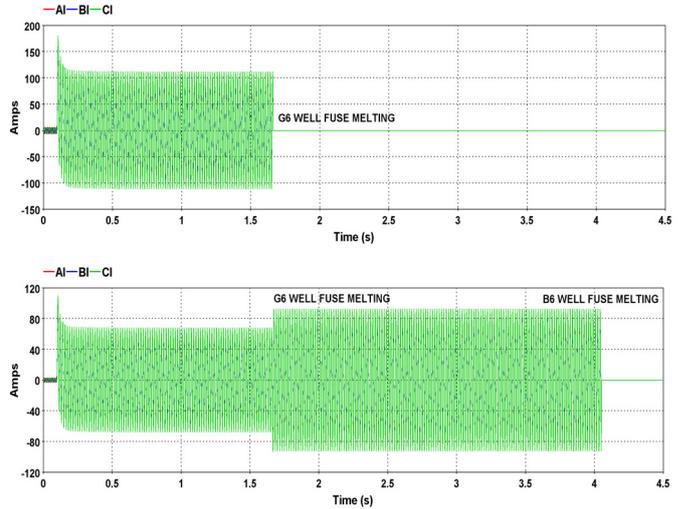


Fig. 18. Current flow through G06 and B06 well fuses

- Ground faults in the overhead lines will be directly sensed in the primary side (4.16 kV) of the main transformer needing more complex protection coordination.
- Ground-fault currents in the overhead lines will be lower than that appearing for an YNd11 connection.
- In case of a complete ungrounded 34.5 kV network (all primary star connected well transformers out of operation), a one-phase-ground fault will not be sensed and cleared from the main fuse.

An enhancement of the overall protection scheme can be achieved with the installation of circuit breakers instead of fuses at the 34.5 kV secondary of the overhead line main transformers. This solution will utilize the high reliability and speed of modern digital protective relays and circuit breakers, thus providing higher protection coordination flexibility which will improve the operation of the complete electrical network.

VII. CASE STUDIES

In this section the implementation of selected corrective measures are examined for different configurations of the power system.

A. One-Phase-Ground Fault at the SE Overhead Line

1) Existing Network Configuration

First, the existing configuration of the electrical network is considered, so that the 4.16/34.5 kV main transformers at the overhead lines are of star-delta connection (Dyn1). A one-phase-ground fault on the SE line bus "HLSE-01" is simulated. The following sequence occurs (see Fig. 18):

- All three phases of G06 well fuse set melt 1.56 s after the fault occurrence.
- All three phases of B06 well fuse set melt 3.95 s after the fault occurrence.

After those blowings, fault current is reduced to such a low magnitude (normal value) that the main fuse does not sense and clear the fault (Fig. 19). Thus, overvoltages that appear will become permanent. Steady-state phase-to-ground overvoltages of approximately 1.7 pu will be observed at all well locations of the line (Fig. 20). The magnitude of these overvoltages in conjunction with their duration can prove dangerous for the existing surge arresters.

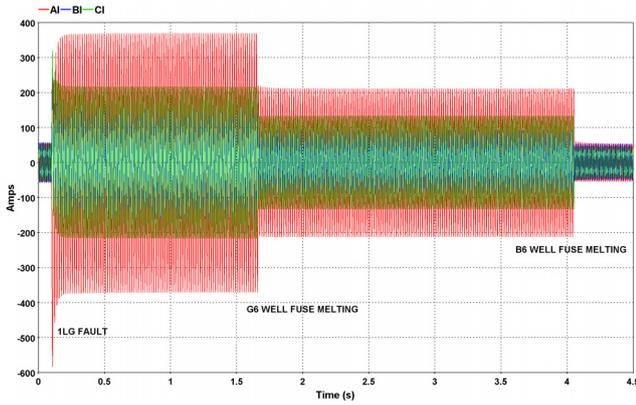


Fig. 19. Current flow through SE main fuse (Dyn1)

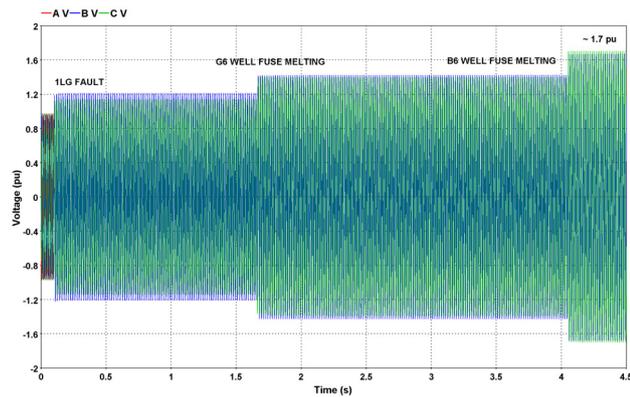


Fig. 20. Phase-ground voltages at SE main transformer secondary bus (Dyn1)

2) Selection of YNd11 Transformers

The same fault scenario is simulated assuming that all the 4.16/34.5 kV main transformers at the overhead lines have delta-star connection and are solidly grounded at their neutral (YNd11). It is further assumed that the new transformers' impedance is the same as the impedance of the existing ones.

A Phase-A to ground fault on bus "HLSE-01" will now be cleared 0.58 s after the fault occurrence through the blowing of Phase-A cutout of the SE main fuse. One can see in Fig. 21 that the current that flows through the main fuse is much higher than that sensed from the same fuse in the previous case (Fig. 19).

Fig. 22 shows the voltage response at the SE main transformer secondary bus (main fuse location) for this case. As can be seen the voltages retain normal magnitudes (not higher than 1 pu) for all the examined time period. This is also true for the voltages at all the SE line well locations.

3) Selection of YNyn0 Transformers

Next, a star-star connection (YNyn0) with solid grounding at both neutrals is considered for all the 4.16/34.5 kV main transformers at the overhead lines. Again, it is assumed that the new transformers' impedance is the same as the impedance of the existing ones.

The same Phase-A to ground fault at bus "HLSE-01" is simulated. Now, fault currents flowing through the main fuse (Fig. 23) are lower than that (Fig. 21) with the transformers having an YNd11 winding connection. The total melting time for Pole-A of the main fuse is 0.98 s.

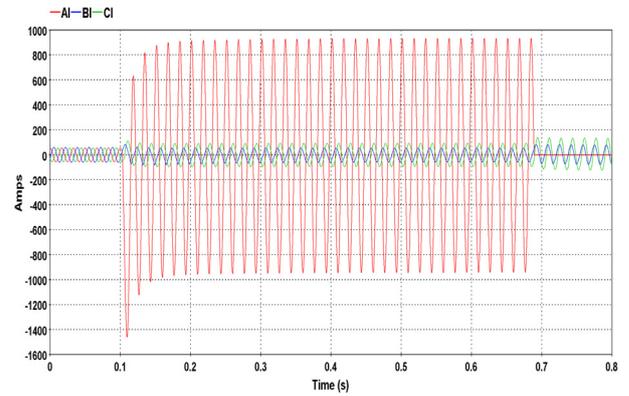


Fig. 21. Current flow through SE main fuse (YNd11)

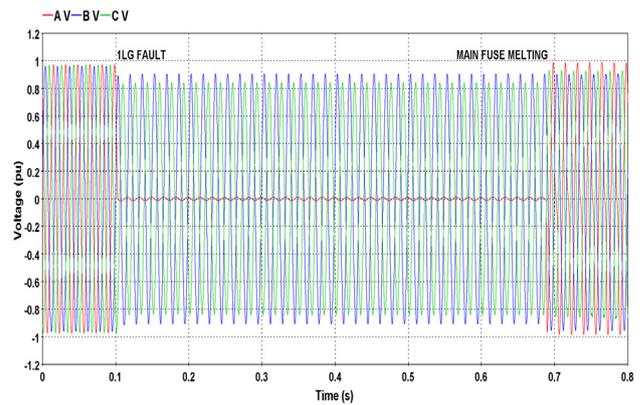


Fig. 22. Phase-ground voltages at SE main transformer secondary bus (YNd11)

Fig. 24 shows that an overvoltage in the order of 5-6% is observed for this case at the secondary bus of the SE main transformer. This is also true for the voltage magnitudes at all the SE line well locations.

As a conclusion, the replacement of the existing overhead line main transformers with new ones having an YNd11 winding connection is the most recommended solution against transient overvoltages. In addition, a protection coordination improvement will be achieved for ground faults at the 34.5 kV network.

B. Single vs. Three-Phase Switching

A one-phase-ground fault at the G06 well transformer primary bus "TRG06p" is simulated. For the existing configuration of the electrical network (main transformers are of Dyn1 connection), Phase-A of the end tower well fuse will blow 0.15 s after the fault occurrence. This single phase switching will produce permanent Phase-A to ground overvoltages of about 1.2 pu (Fig. 25).

If a three-phase switching disconnecter-fuse assembly would exist in the G06 well end tower, the simultaneous three-phase switching would prevent overvoltages such as the previous ones. This is clearly shown in Fig. 26.

As a conclusion, simultaneous three-phase switching of the overhead line fuses can eliminate the overvoltages at the 34.5 kV network.

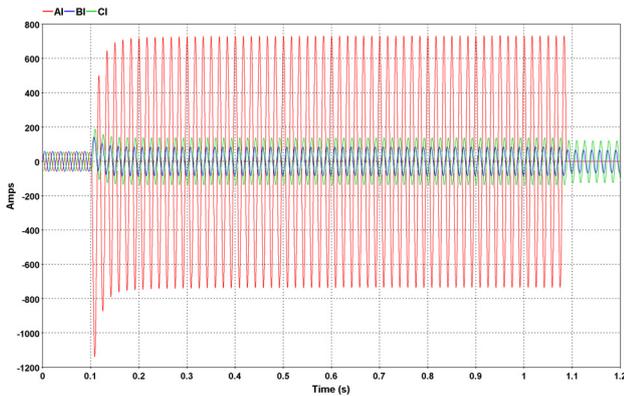


Fig. 23. Current flow through SE main fuse (YNyn0)

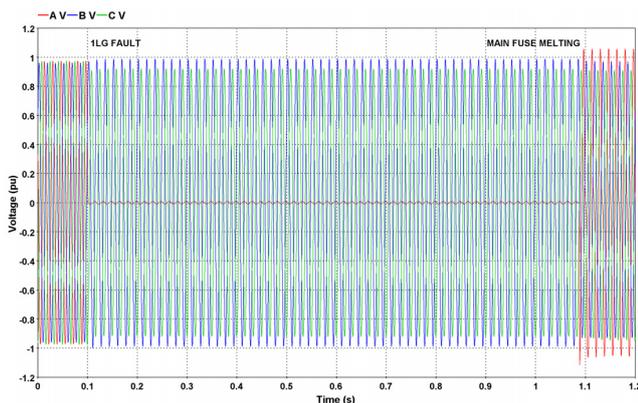


Fig. 24. Phase-ground voltages at SE main transformer secondary bus (YNyn0)

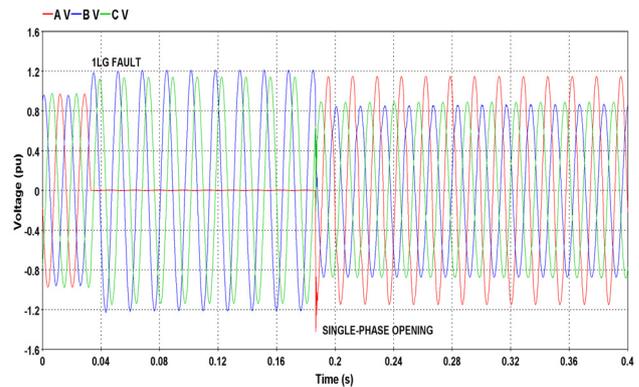


Fig. 25. Phase-ground voltages at SE main transformer secondary bus (single-phase switching)

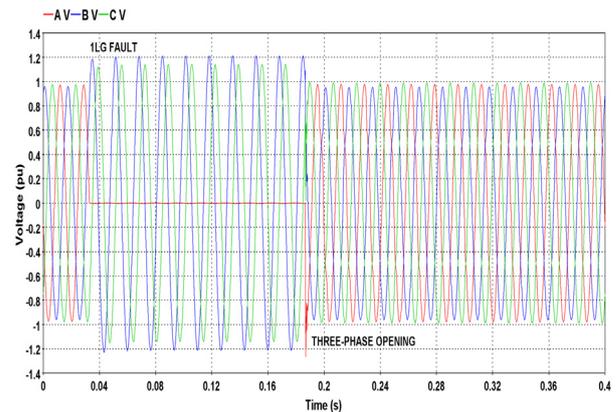


Fig. 26. Phase-ground voltages at SE main transformer secondary bus (three-phase switching)

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IX. BIOGRAPHIES

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