CIGRE-106 **2019 CIGRE Canada Conference**
Montréal, Québec, September 16-19, 2019

Generator Failure Forensic Simulations Study, Lessons Learned

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SUMMARY

Hatch Client had a failure of a 60MVA generator in their system. The client decided to conduct an investigation of the event in association with Hatch Ltd. This paper presents a step by step generator failure forensic analysis performed in PSCAD. In addition, a road map, in which the level of detail modelling of each equipment, is presented. To study the incident, detailed simulation of the power system in Electro Magnetic Transient (EMT) environment was required. PSCAD software was used to investigate the effect of synchronous condenser (SC) transformer switching on the client power system. A PSSE .sav file was setup to replicate the AC network at the time of the incident. To convert the PSSE model to PSCAD software, E-Tran software (Version 5) was used, and the entire power system was imported into the PSCAD software. To evaluate the accuracy of the PSCAD simulation, the steady state results of the detailed PSCAD model was benchmarked against the PSSE power flow and short circuit results. Once the system is converted in PSCAD, the neighboring transmission lines were replaced with a frequency dependent line model to replicate the effect of transformer energization in more details.

Although the recorded data for the voltage and current during the incident were provided to Hatch, no data regarding the transformer remnant flux during the transformer energization was available. Hence, the closest results for the transformer energization were achieved by iterations. To speed up this process, multirun components were used and transformer remnant flux for various breaker opening times were determined.

The system was modelled in PSCAD and the simulations included a replica of the event which led to the failure of the generator and determined what voltages this generator unit would have experienced during the incident. The early investigation indicated that this failure would have resulted from the energization of a SC transformer in the neighboring bus. It is evident that the point on wave (POW) device associated with the SC transformer was incorrectly programmed and may have caused an excessive voltage deviation and/or unbalances at the generator buses.

This paper covers the effect of SC transformer switching with the wrong closing sequence and then looks at the impact of the SC transformer switching on the client power system assuming the breaker switching is correctly synchronized.

The results indicate that the generated inrush current during the SC transformer switching caused a substantial voltage drop at the generator stations. In conjunction with this voltage drop, there was a high harmonic/unbalanced current in the SC transformer bus which could have contributed to the tripping of the machine. Furthermore, unbalanced current could cause premature aging or damage to the rotors of these machines.

Those conclusions were reported to the client along with recommendation to verify the differential protections of the generator (and other nearby machines) to avoid similar situation

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to occur again. The client needs to ensure that the installed synchronous condenser POW devices are monitored to confirm that they are in fact configured correctly.

KEYWORDS

Point of Wave, Transformer Energization, Generator Failure, EMT studies, Protection Coordination

I. Introduction

Most literatures advise that transformer inrush current can reach up to 10 times the transformer rated current and it will have a high harmonic content during this period [1]. In [2], the effect of high inrush current during energization of a 60 MVA transformer at the generator terminal is investigated. The mitigation solution was to use the second harmonic component in the differential current of the relay to distinguish transformer energization from the internal generator fault conditions. In this paper, the aim was to investigate the effect of inrush current generated during the large transformer energization on a generator 16 km away from the generator and investigate the effect of the operation of point on wave (POW) devices to mitigate the problem. In addition, the step by step procedure and assumptions that can be made for this type of study are presented to assist the reader in carrying out similar studies.

II. Power System Configuration

benchmarked against the PSSE power flow and short circuit results.

illustrates the relevant power system where the generator is located almost 16km away from the transformer. The actual power system that was modeled in PSCAD consist of more than 300 buses of various voltage levels (230 kV, 66 kV, and 13.8 kV).

III. Power System Modeling in PSCAD Software

A detailed simulation of the power system in Electro Magnetic Transient environment was required. PSCAD software was used to investigate the effect of synchronous condenser (SC) transformer switching on the power system.

A PSSE .sav file was setup to replicate the AC network at the time of the incident. To convert the PSSE model to PSCAD software, E-Tran software (Version 5) was used and the entire client power system was imported into the PSCAD software. To evaluate the accuracy of the PSCAD simulation, the steady state results of the PSCAD model were benchmarked against the PSSE power flow and short circuit results.

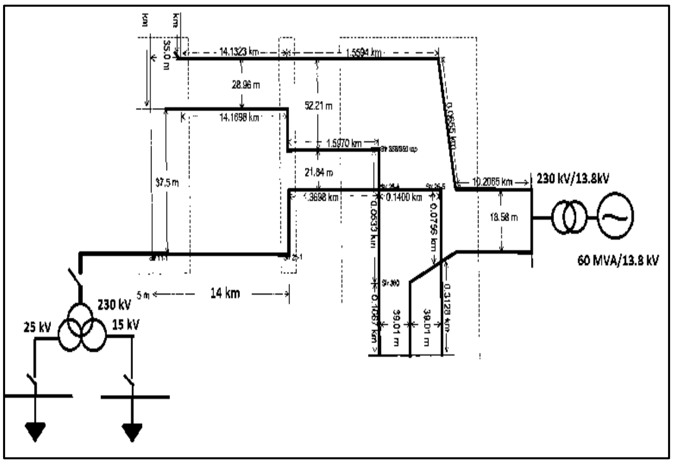

Figure 1 Power System Configuration

a. Transmission line modeling

E-Tran software imports the transmission lines into PSCAD software as a Bergeron line model. Although the Bergeron line model is suitable for steady state studies where the frequency is constant [3], this model does not represent the transmission line parameters with regards to various frequencies which is required for transient studies.

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To improve the accuracy in modelling of the incident, the Bergeron line models (PSCAD line representation using E-Tran conversion tool) for all 230-kV lines connecting the SC bus, and nearby substations, were replaced with the frequency dependent line models. This model accurately represents the behavior of transmission lines over a frequency range.

b. Transformer modeling

E-Tran imports the transformers from PSSE to PSCAD assuming all transformers are Y-Y grounded configuration. All transformers connected to 230-kV and generator station, 66-kV, were replaced by their detailed models based on the transformer datasheet. By changing the Y-Y to Y-Delta, the voltage angle of all the voltage sources at the delta side needs to be adjusted accordingly.

c. SC transformer breaker POW modeling

In this study, the aim is to investigate the effect of the introduced error in the SC breaker POW relay on the generator. To achieve this objective, the POW algorithm has been modelled in PSCAD. Note that the relay has not been modelled explicitly but rather the relay functional behaviour was implemented in PSCAD. Each phase of the breaker was closed individually as required during transformer energization.

d. Generator dynamic modeling

To investigate the effect of high transformer inrush current on the neighbouring generator, the generator was modelled in detail considering the dynamics of its governor and exciter. The input parameters are imported from the PSSE .dyr file.

IV. Investigation on Available Data During the Incidence and Transient Studies

In common practice, the B phase voltage is selected as the reference signal for a POW device. Once the voltage crosses 0 (from negative to positive), the B-phase breaker closes after a 90° phase shift (the minimum current is following through the B phase). Subsequently, the A-phase and the C-phase will close with a delay associated to 540° phase shift as follows; L2 closing angle +90°, L1 closing angle +540°, L3 closing angle +540°.

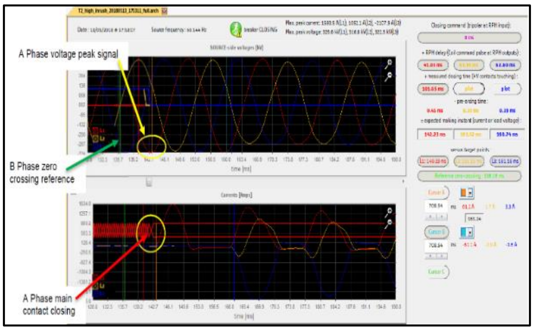

Figure 2a. Extracted voltage and current at the transformer terminal from the relay

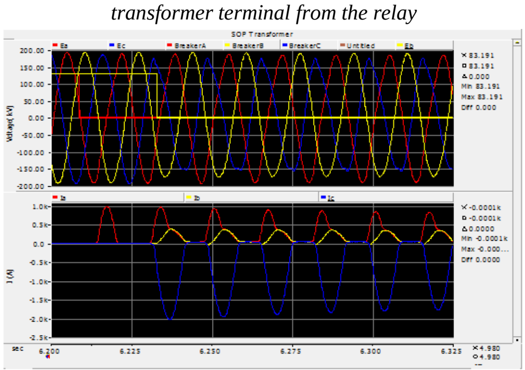
Figure 2b. Generated transformer voltage and inrush current during energization

This closing sequence ensures the transformer generates the minimum inrush current during the energization. According to the available information of the POW operation during the energization, the closing sequence of the breaker (A phase and B phase) were swapped.

Hence, during the first transformer energization, the following sequence was programmed for POW operation: L1 closing angle +90°, L2 closing angle +540°, L3 closing angle +540°.

With regards to this error, after the B-phase voltage zero crossing, breaker A phase was closed first. According to the report, “The result was 2100 amps current on the B phase”. The extracted voltage and current from the relay are shown in Figure 2a.

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A. PSCAD transformer energization simulation

For the PSCAD simulation, the same breaker phase closing was used with the same error introduced as follows: L1 closing angle +90° (4.17 ms + random error), L2 closing angle +540° (25.00 ms + random error), L3 closing angle +540° (25.00 ms + random error)
A random error of +1.91 ms for phase A, -4.2 ms for phase B, and +3.7 ms for phase C has been added to breaker switching time to more accurately replicate the behaviour of the breaker. No data regarding the transformer remnant flux during the transformer energization was available. Hence, the closest results were achieved by iterations. Multiple run features in the Master/Slave environment in PSCAD is used to determine the closest remnant flux. More data from the Master/Slave simulation can be found in [4]. Various transformer remnant flux and breaker time random errors were considered for each phase of the transformer. Figure 2b depicts the closest result achieved in PSCAD simulations for transformer inrush current during energization. As shown in Figure 2b, the results were closely matched with the recorded data from the relay.

B. The effect of transformer energization on the generator bus voltage and power output

Following the transformer energization and the appearance of high inrush currents, the SC transformer 230-kV bus experienced a voltage drop down to 0.93 pu (~10% voltage drop). Figure 3a shows the voltage drop at SC transformer 230-kV bus. This voltage drop is also seen at the generator 230-kV bus which the voltage also dropped to 0.93 pu (~9.5% drop). As shown in Figure 3b, following the transformer energization, at the generator 13.8 kV terminal, the voltage dropped to 0.925 pu (~5% drop). This voltage drop resulted in a sudden variation in the generator power output as shown in Figure 3c. The variation in power indicates a sudden force applied to the generator mechanical shaft during the SC transformer energization.

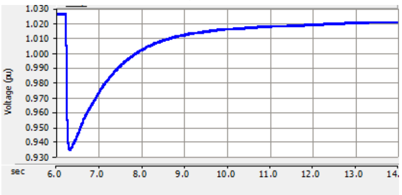

Figure 3a.3 Voltage drop at the SC transformer and the generator 230 kV

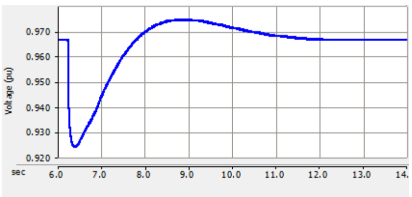

Figure 3b.2 Voltage drop at the generator 13.8 kV terminal

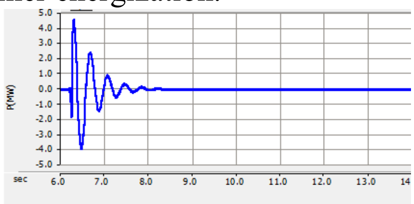

Figure 3c. Generator power output variation

V. Discussion on the findings

Given the weakness of the AC system at the time of the transformer energization, a substantial voltage dip was observed at the SC transformer and the generator buses. The voltage dip should still be within the capability of the machine as the machine did not go into an overvoltage.

C. Effect of harmonic on the generator

During the energization of the SC transformer, a large portion of the inrush current was supplied from the generator which is rated for 60 MVA. During the initial inrush, the current flows from the bus into the transformer being largely supplied from the close-by generators (due to the weak system).
Figure 4 show the currents (instantaneous, RSS, DC current, and harmonic content) of the generator. It is evident that the generator saw a high level of harmonics and a large negative sequence current. Past experiences and references have shown that generator differential protections are very sensitive to these types of currents [1] and [5].

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This negative harmonic component induced a double-frequency current on the surface of the rotor, the retaining rings, and field windings of the rotor. These currents have the potential to increase the temperature of the rotor and may damage the machine if operated continuously.

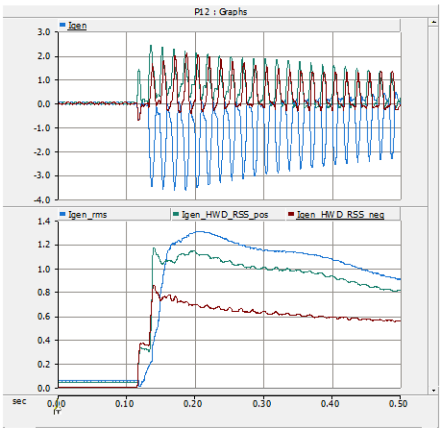

Figure 4. Instantaneous, RSS, DC currents at the generator terminal

VI. Transformer energization with corrected POW closing sequence

The effect of the SC transformer energization on the power system is investigated. It is assumed that the transformer has no remaining flux and the breaker closing sequence has been corrected. The same power system as used in the previous case is used with proper transformer breaker switching function implemented. Figure 5 shows the inrush current in all phases was significantly reduced.

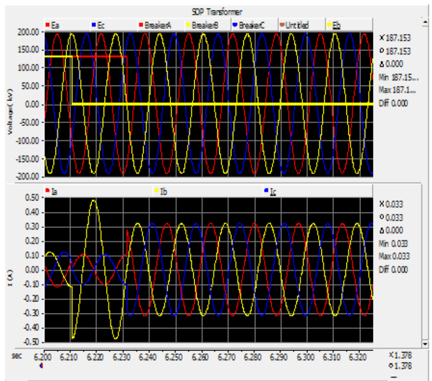

Figure 5. Generated transformer voltage and inrush current during energization with corrected POW closing sequence

VII. Conclusion and recommendations

This study covers the effect of SC transformer breaker switching with the wrong closing sequence and then looks at the impact of the SC transformer breaker switching on the client's power system assuming the breaker switching is correct.

The transformer energization event has been studied in detail using PSCAD. The PSSE .raw file for the time of the incident was used and the entire power system was imported in PSCAD software for EMT studies. Relevant components near the transformer and the generator were replaced with their detailed models.

The updated power systems were benchmarked against the provided PSSE .sav case. Power flow and short circuit results were matched between PSCAD and PSSE. The 60MVA generator was replaced with its detailed dynamic model. The SC transformer relay function was duplicated based on the POW function.

The PSCAD simulation results indicate that the generated inrush current during the SC transformer switching caused a substantial voltage drop at the SC transformer and the generator stations. In conjunction with this voltage drop, there was a high harmonic/unbalanced current at the generator terminal which could have contributed to the tripping of the machine. Past experiences and references have shown that the generator differential protections are very sensitive to these types of currents. Furthermore, an unbalanced current could cause premature aging or damage to the rotors of these machines [1].

It is recommended that the differential protecting the generator terminal (and other nearby machines) be reviewed to ensure this type of trip does not occur again. Furthermore, system operators need to ensure that the remaining SC POW are configured correctly.

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