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System-Based Technique to Evaluate the Risk of Self-Excitation of Synchronous Machines

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SUMMARY

Self-excitation of synchronous machines is a phenomenon that imposes a risk to the equipment especially in the islanded hydro generation and electrically in close proximity with the HVDC converter stations. Filters and shunt capacitors at the converter stations are considered major contributors to this phenomenon. The risk must be analyzed and preventive measures must be implemented to avoid self-excitation interactions between HVDC converter stations and synchronous machines. Two approaches would be considered for the self-excitation risk assessment:

- A straightforward approach of preventing/eliminating self-excitation is to assess the status of synchronous machines, filters, capacitors and other relevant components in the system to determine the level of risk. Although this method will not be practical for the systems with a large number of variables and operating conditions, this method is ideal for islanded systems (by HVDC) with a collector system of generators feeding the rectifier stations. Manitoba Hydro Northern Collector System is an example of a system of this nature.
- Another approach would be a continuous monitoring of the conditions for the inception of self-excitation in real time. While considered technically complicated and computationally expensive to implement, the self-excitation risk must be identified with a reasonable margin prior to the risk so that sufficient time is available to take actions to avoid the risk. Then the actions must be taken quickly to disconnect system elements such as filters and capacitors that contribute to the risk.

The latter method requires real-time assessment of the conditions and thus needs fast and sophisticated techniques for the evaluation. Electromagnetic transient simulations (EMTDC/PSCAD) have been commonly used in the past to analyze the risk of self-excitation. These simulations provide sufficient details of the variations of the system quantities to analyze the risk; however, this type of simulation and the analysis cannot be performed fast enough to implement in real-time. Therefore, a quick off-line assessment method considering the former approach would be beneficial to the operator, especially in dealing with unexpected system conditions.

In this paper, a system-based elimination technique based on short-circuit impedance calculations is used to identify the risk of self-excitation at generators' terminals for Manitoba Hydro Northern Collector System (NCS). This technique provides the use of a computationally inexpensive system-based index to evaluate the risk of self-excitation due to frequency excursions post HVDC system events. The proposed technique results are verified using the system transient simulations utilizing phasor domain software tools.

KEYWORDS

Self-excitation; HVDC; harmonic filters.

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INTRODUCTION

The phenomenon of self-excitation in synchronous generators imposes a high risk of damage to the generators' exciters and the equipment connected to the network [1]. It is a major concern in the operation of an HVDC system having nearby generating stations that feed the power to the converter stations. The number of generators connected to the network, the size of the filters and reactive support equipment connected at and around the converter stations are the key factors in this phenomenon.

Low order harmonic instability at converter stations is another concern in changing system conditions. It is known that second harmonic instability will lead to converter transformer core saturation.

Daily operations of HVDC systems involve adjustments to the HVDC power transfer to deal with the changes in demand of system loads and tie line transfers. Therefore, it is common that operators deal with a range of HVDC transfers between minimum and maximum operation limits daily. These operations involve shutting down and/or starting up synchronous generators to adjust power in-feed to HVDC schemes. It also involves adjustments to the number of filter banks connected, to keep the harmonic levels within acceptable limits. Thus, assessment of the risk of self-excitation is required to ensure safe operation.

Evaluation of the risk of self-excitation is usually carried out using electromagnetic transient simulations in EMTDC/PSCAD type software [1]. These simulations provide detailed simulation results showing the variations of the system quantities. From the operator's point of view, quick decisions are to be made on the adjustments to the system, assuring a safe operating condition with respect to the risk of self-excitation. Therefore, a method to perform a quick assessment is very useful, especially in dealing with unexpected system conditions. This paper describes the application of the impedance-based technique to analyze the risk of self-excitation.

SELF-EXCITATION PHENOMENON

A. Background

The self-excitation phenomenon in a synchronous machine is a condition that develops uncontrolled field flux in the machine and results an extremely high voltage across generator terminals that can damage the generator equipment and also the equipment connected to the network.

Self-excitation is possible when significantly large shunt capacitors are connected to the network around the point of interconnection of the synchronous machine. This condition leads to a capacitive resultant impedance seen at the generator terminals. The risk of self-excitation is determined by the following factors:

1) Capacitive reactive power support in the vicinity of the generator station
2) Machine synchronous reactance
3) Speed regulating characteristics of the turbine-governor
4) Voltage regulating characteristics of the exciter

Self-excitation can occur both in hydro and thermal generating units. Typical self-excitation occurrences are classified into two categories:

- Immediate self-excitation: The conditions of self-excitation resonance are satisfied at power frequency impedance conditions.
- Non-immediate self-excitation: The conditions of self-excitation resonance are satisfied in a frequency excursion in the system.

B. Relationship between Machine Parameters and Self-Excitation

The phenomenon can be explained using machine d-axis and q-axis flux dynamics. When the generator load is inductive, the q-axis flux component does not exist. The q-axis flux component appears when the generator load is resistive or capacitive. The d-axis flux is controlled by the exciter of the machine. Thus, in a transient situation, the d-axis flux decay depends on the d-axis time constant and the exciter time constant while the q axis flux decay depends only on the q-axis time constant. The d-axis and q-axis time constants (T_d and T_q) are given in Equation (1) and Equation (2), respectively.

$$T_d = T_{d0} \cdot \frac{X_C - X_d'}{X_C - X_d} \qquad \text{Equation (1)}$$

$$T_q = T_{q0} \cdot \frac{X_C - X_q''}{X_C - X_q} \qquad \text{Equation (2)}$$

where,

- X_C is the capacitive reactance seen at the machine terminal
- X_d is the d-axis synchronous reactance of the machine
- X_q is the q-axis synchronous reactance of the machine
- X'_d is the d-axis transient reactance of the machine
- X''_q is the d-axis sub-transient reactance of the machine
- T_{d0} is the d-axis open circuit time constant
- T_{q0} is the q-axis open circuit time constant

In a self-excitation resonance condition, the d-axis flux will be controlled by the exciter but the q-axis flux is uncontrolled. Consequently, the resultant machine flux will be uncontrolled resulting in uncontrolled terminal voltage at the machine.

When the d-axis time constants are positive, any sudden change in the field flux will be damped. When the time constants become negative, the field flux builds up exponentially, causing system voltage to rise. The time constants can become negative when the network equivalent reactance seen at the generator terminal is capacitive. Table 1 explains the situations when the capacitive loads in the system are large enough that the system equivalent reactance is capacitive and falls below X_d.

Table 1: Risk of Self-excitation and Machine Dynamics during a Transient Event

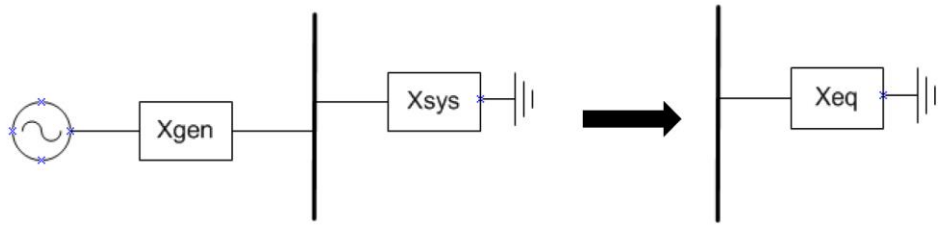
Xc<Xq	**Xq<Xc<Xd**
Td<0, Tq<0	**Td<0, Tq>0**
• d-axis flux increase • Exciter attempts to control the flux • Damping is not sufficient • Field current oscillations • Negative field current attempts	• d-axis flux increase • Exciter attempts to control the flux • Damping is not sufficient • Field current oscillations • Negative field current attempts
• q-axis flux increase • Uncontrolled q-axis flux and resultant machine flux increase • Uncontrolled terminal voltage rise	• q-axis flux is damped
• Risk of self-excitation • Immediate inception of uncontrolled voltage in a transient event	• Risk of self-excitation • negative current capability of the exciter helps to delay the inception of uncontrolled voltage in a transient event

Evaluation of Immediate Self-Excitation based on Impedance Index

The criteria for the evaluation of the risk of self-excitation can be simplified in terms of the Thévenin equivalent impedance (X_{eq}) at the generator terminal, which is the parallel sum of the system impedance (X_{sys}) at the generator terminal with the generator impedance (X_{gen}), as shown in Figure 1. The variation of the system equivalent reactance at resonance frequency is shown in Figure 2. Theoretically, the reactance will be very high (infinity) at the resonance frequency.

In practical terms, the operating conditions too close to the resonance must be avoided, allowing a safe margin. This margin can be introduced in evaluating the equivalent reactance. For the purpose of allowing a margin to self-excitation, the equivalent reactance greater than 1 pu allows a reasonable margin for the risk of self-excitation.

A synchronous generator with a higher reactance will reach self-excitation with a lower number of filters. Therefore, the use of the largest applicable machine reactance in the evaluation allows a conservative margin to the risk of self-excitation. The unsaturated synchronous reactance is the largest applicable reactance in the dynamics of a synchronous machine and was used to represent the machine reactance (X_{gen}).



$$X_{eq} = \frac{-jX_c X_{gen}}{-X_c + X_{gen}}$$

Xgen : equivalent synchronous reactance of the generators connected at POI bus
Xsys: equivalent system reactance excluding the power plant at POI bus
Xeq: Thévenin reactance of the system including the power plant at POI bus
When Xsys is capacitive (Xsys<0 and Xsys=-Xc),
To avoid self-excitation, Xgen must be less than Xc.
Therefore, -Xc + Xgen < 0
Thus, Xeq must always be greater than zero to avoid self-excitation.
Theoretically, there is a risk of self-excitation, if Xeq is zero or negative.
The criteria below is extablished by considering a safe margin to the self-excitation resonance.

Thevenin's equivalent impedance at a generator terminal must be inductive and less than 1 pu for the safe operation without a risk of self-excitation.

This criteria is applicable to assess the immediate self-excitation at power frequency.

Figure 1 : Criteria to Assess the Risk of Immediate Self-Excitation

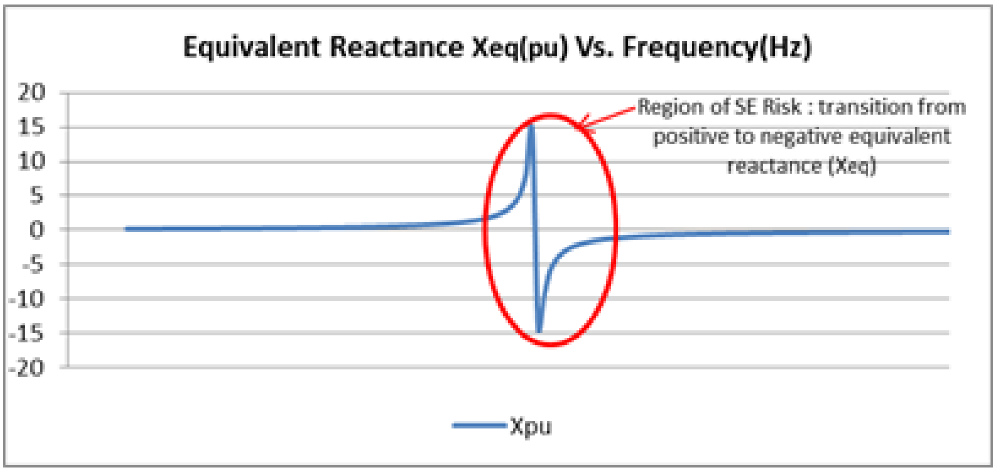


Figure 2: Variation of Equivalent Reactance with the System Frequency

Evaluation of Non-Immediate Self-Excitation using Critical Frequency for Resonance

Critical frequency (f_c) for self-excitation is defined to account for non-immediate self-excitation due to frequency excursions in the system.
The equation (Equation (3)) for the critical frequency (f_c):

$$f_c = f_0 \cdot \sqrt{\frac{X_{c0}}{X_{g0}}} \qquad \text{Equation (3)}$$

where,

- f_0 is the nominal frequency of the system
- X_{g0} is the equivalent inductive reactance of the generating station
- X_{c0} is the equivalent reactance of the system and the connected filters

There is a risk of self-excitation in a contingency event when the possible maximum frequency excursion (f_{max}) due to the event is greater than the critical frequency (f_c) for self-excitation [2]. Typically, this risk is common in the power plants feeding the HVDC schemes that have many filters connected, and frequency excursion is high in an event such as HVDC converter block.
This criterion was applied to the Manitoba Hydro System in a simplified way to avoid complexity without compromising the risk of self-excitation. Each generating station was considered to be isolated with the closest converter station filters as the worst scenario. The critical frequency for self-excitation (f_c) was calculated for the number of generators connected at the generating station with the number of filters at the converter station. These critical frequency values were compared with a known/pre-determined value of a frequency excursion that would likely to occur in a typical load rejection. The minimum number of generators that must be connected to avoid the critical frequency lower than the known frequency excursion were determined for a given number of filters connected. This minimum generator rule was used to prevent the non-immediate self-excitation in Manitoba Hydro Northern Collector System Generators in preparing start-up/shutdown procedures of generators.
Beyond this simplified method, these criteria can also be applied to assess the risk of self-excitation for real-time operations of the system such as generator startup/shutdown and HVDC power/filter adjustments.

Impedance-Based Comprehensive Criteria for the Assessment of Self-Excitation

An operating condition of the system carries a risk of self-excitation if at least one of the following criteria is true:

1) Equivalent network reactance at one or more generator terminals is capacitive and the value is less than the d-axis synchronous reactance of the machine.
2) Equivalent system reactance at one or more generator POI buses is capacitive. In order to allow a safe margin to avoid the operating condition close to the self-excitation resonance, the high values (>1.0 pu) of inductive equivalent reactance are also considered not acceptable.
3) Generator field current is crossing from positive to negative in a contingency event.
4) Generator terminal voltage increases without control in a contingency event.

Items 1 and 2 above are applicable in evaluating the risk of self-excitation for system conditions in the power-flow analysis platform using the impedance technique, and items 3 and 4 are applicable in transient simulations in power system stability analysis platforms. It should be noted that common bulk transmission planning practices, such as avoiding thermal overloading post N-1 events and reactive power absorption by synchronous generators, are followed.

Results of the Application and Verification of Impedance Technique

The impedance criteria recommended in this paper require only a regular power flow analysis program or a power system modelling program that is capable of performing Thévenin impedance calculation of a given node/bus. The simple criteria can be verified using dynamic simulations comparing criteria 3 and 4 that require a dynamic simulation platform.

A. Scenarios and Contingencies for Simulation and Analysis

Three scenarios given below were used in order to verify the impedance criteria 1 and 2 in the previous section and validate against criteria 3 and 4.

- Scenario 1: Violation of criteria 1 and criteria 2 with capacitive network reactance
- Scenario 2: No violation of criteria 1 and 2

Figure 3 shows a simplified schematic of a typical HVDC collector system with three hydro power stations in close vicinity to HVDC stations modelled for the calculations and simulations in this study. All transmission paths between generating stations contain three circuits in all scenarios. The differences between scenarios are the number of generators connected at each station and the HVDC loading, and therefore the capacitors connected at the HVDC stations. The self-excitation risk is prominent when a small number of generators are in-service; therefore, the HVDC loading is low in the selected cases with violations.
The self-excitation is triggered due to a switching action or a contingency in the system. A contingency situation that results in tripping of HVDC schemes was simulated to analyze the risk of self-excitation in the above scenarios. Impedances were calculated for each scenario and evaluated against criteria 1

and 2. The simulation results were assessed against criteria 3 and 4. The results of these assessments were used to validate the criteria statement given above.
Figure 4 and Figure 5 show the transient simulation results for Scenario 1 and Scenario 2, respectively. The tripping of the HVDC scheme resulted in the frequency excursion reaching 72 Hz. The type of system events that result in marginal frequency excursions that trigger the self-excitation phenomenon for the vulnerable generating units/harmonic filters combinations. As it can be seen, the system frequency excursion has triggered the self-excitation phenomenon for Scenario 1. The in-service generation units will be exposed to sudden and sharp voltage rise post the tripping of the HVDC scheme event. The generation units/HVDC filters configuration associated with Scenario 2 didn’t violate criteria 1 or criteria 2. Scenario 2 simulation results showed no risk of self-excitation phenomenon.

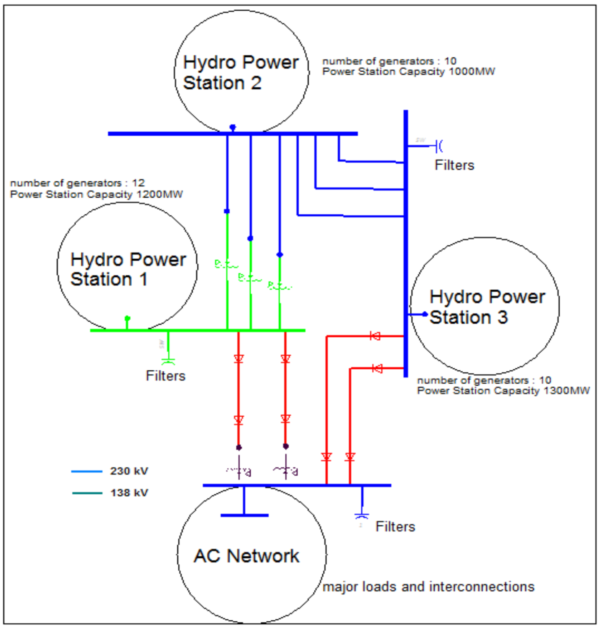


Figure 3: Simplified Schematic Diagram of the DC Collector System

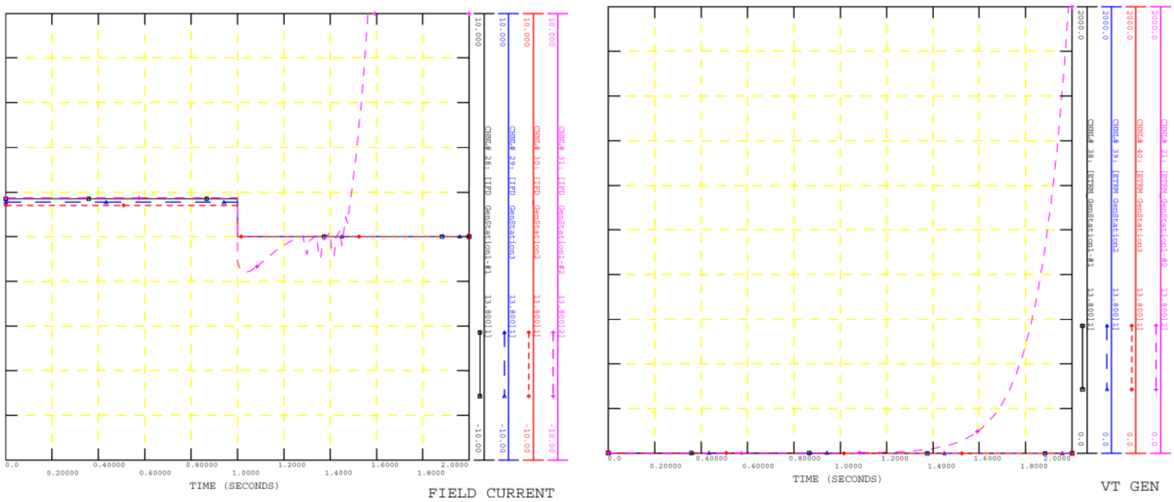


Figure 4: Generators’ Field Currents and Terminal Voltages – Scenario 1

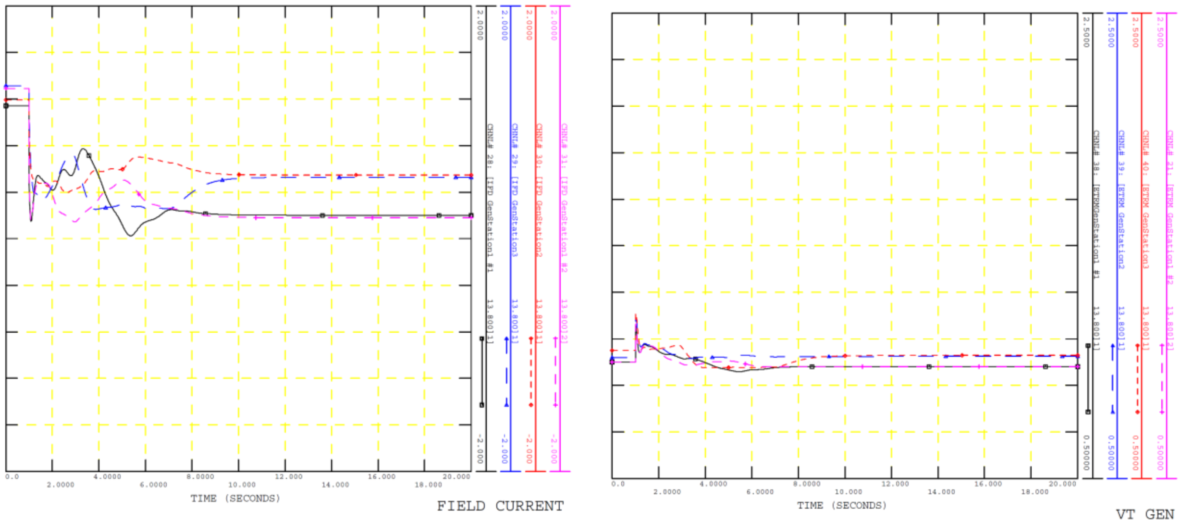


Figure 5: Generators' Field Currents and Terminal Voltages – Scenario 2

B. ***Real-time Assessment of the Risk of Self-Excitation***

System operation planning follows the operating procedures under normal operating conditions. However, the emergency conditions or the situations away from normal conditions force system operators to make quick decisions on the system configuration without compromising the safety of the equipment. Frazil ice conditions of cascaded generating schemes (northern Manitoba hydro generation units), unexpected outages of transmission elements, etc. are some examples of these situations. A real-time risk assessment for self-excitation can play an important role in these situations. The technique discussed above will enable a quick analysis considering the status of the transmission elements, consider changes to be performed, and obtain the assessment in a few seconds prior to the switching operations.

The overview of the idea of implementing the self-excitation risk assessment is illustrated in Figure 6.

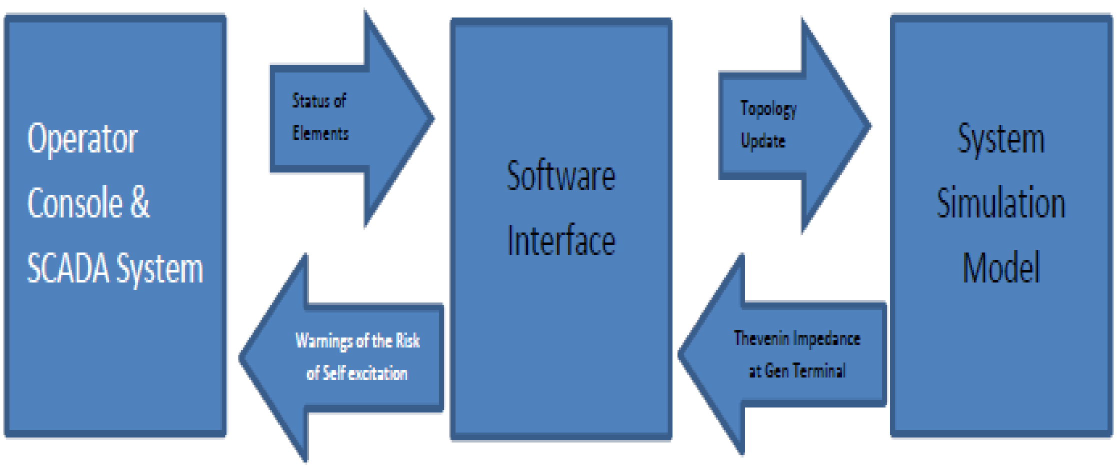


Figure 6: Concept of Real-Time Assessment of Self-Excitation

The calculation involved in the assessment mainly requires the equivalent impedance of the system at the generator terminal. The equivalent Thévenin impedance of the system at a given bus can be calculated in the PSS®E fault analysis module. Therefore, the calculation of the equivalent impedance can be performed with only topology updates of the system model.

The calculated system impedance is analyzed for the self-excitation risk (immediate and non-immediate) in the software interface and communicates the result to the operator console.

This concept can be implemented by having the following components linked with the operator console/SCADA system:

- Simulation model in PSS®E
- Software interface between simulation model and operator console/SCADA display
- Computer hardware for the simulation model and the software interface
- Data links between software interface/computer hardware and the operator console/SCADA display

These assessments are proven to be computationally inexpensive and capable of supporting real-time power system operation (energy management system - EMS).

Conclusion

This paper provided detailed background discussion for the self-excitation phenomenon (associated with generating units' HVDC filters in islanded generation collector systems) and system conditions that may trigger its occurrence, and associated risks. Although detailed electromagnetic transient modelling would be considered for predicting this phenomenon, a computationally inexpensive system-based technique was developed and applied to provide risk-free generating units/HVDC filters combinations (topologies) considering HVDC tripping schemes. The provided technique is fully capable of supporting the system operators for real-time energy management purposes.
The proposed technique was verified through transient simulations that showed no risk for the generation units/HVDC filters that passed through the evaluation criteria that used the system-based technique. The failed generation units/HVDC filters combinations (based on the system-based technique/criteria) have clearly demonstrated the occurrence of self-excitation phenomenon post HVDC tripping scheme events and consequent system frequency excursions.

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