Subsynchronous Resonance Risk Assessment in Interconnected Power Systems

A thesis submitted in fulfilment of the requirements for the degree of
Master of Engineering

Nadia I. Yousif
B.Eng.

School of Electrical and Computer Engineering
RMIT University
January 2011

Declaration

I certify that except where due acknowledgement has been made, the work is that of the author alone; the work has not been submitted previously, in whole or in part, to qualify for any other academic award; the content of the thesis is the result of work which has been carried out since the official commencement date of the approved research program; any editorial work, paid or unpaid, carried out by a third party is acknowledged; and, ethics procedures and guidelines have been followed.

Nadia Yousif

31 January 2011

Acknowledgment

I would like to thank Dr Peter Graszkiewicz for his support and encourgement to complete this work. I also would like to thank Professor Ian Burnett and Laurie Clinton for the opportunity and coopration to resume and continue this research work. I also would like to thank my previous supervisor Professor Majid Al-Dabbagh for the opportuity to do this research and his support during his supervision period.

Many thanks to my family, especialy to my husband Aryan Dawood who is always there to support me progressing this work.

Finaly, I would like to dedicate this work to my late father who was looking forward to completion of this research.

Publications

[1] Nadia Yousif, and Majid Al-Dabbagh, ‘Time-Frequency Distribution Application for Sub-synchronous Resonance Analysis in Power Systems’, Power Engineering Conference Proceeding, 2005. IPEC 2005. The 7th International

[2] N. Yousif, M. Al Dabbagh, and P. Graszkiewicz (Australia),’ Continuous Non-linear Model of Series Compensated Transmission Line for Sub-synchronous Resonance Investigation’, Proceeding European Power and Energy Systems (EuroPES 2004)

[3] Nadia Yousif, and Majid Al-Dabbagh, ‘Sub-Synchronous Resonance Assessment Using Time Frequency Distribution Algorithm’, Australasian Universities Power Engineering Conference (AUPEC 2004), Brisbane, Australia

[4] Nadia Yousif, and Majid Al-Dabbagh, ‘Sub-synchronous Resonance Damping in Interconnected Power Systems’, Australasian Universities Power Engineering Conference (AUPEC 2002), Melbourne, Australia

Contents

Page number

Summary

Series compensation and high voltage direct current (HVDC) links, technically increase the viability of suppling remote areas by long loading transmission lines, or connecting new remote generation hub to the main network. Nowadays such technologies have become part of utilities' plans to increase power transfer capability between regions. This is usually due to lack of local reserve within a region under system wide contingencies or when there is redundancy of large unscheduled generation (usually in case of extensive wind generation during low demand durations).

Both series compensation and HVDC converters excite frequencies below the synchronous frequency of the system called subsynchronous frequencies. These frequencies will be seen as voltage and current components superimposed on the 50 Hz voltage and current signals. These components may excite tortional torque at the adjacent generator causing excessive voltages and currents, and damage to the generator–turbine shaft. Subsynchronous currents or voltages can also be generated in power systems as inter-harmonics emission from a distorting load such as HV high-capacity variable speed drives (VSDs). In other cases, a series resonance between the cables' capacitance and the transformer's inductance can occur, resulting in resonant frequency components. Under all these circumstances, there is a risk of SSR conditions. Subsynchronous resonance will become an important network condition to investigate when the new technologies are introduced in power systems.

The purpose of this research work will be to establish clear understanding of challenges and issues facing the power networks planning, in particular the SSR conditions. The thesis presents key characteristics of power systems and modelling considerations, which need to be taken into account for SSR assessment. Further, a good understanding of the general requirements and criteria for addressing SSR problems is established. Design requirements for HVDC links and series compensation to reduce the risk of SSR are presented.

A guide for power system elements representation for simulation studies is established. New modelling and simulation approaches for SSR analysis are proposed to overcome the difficulty of incorporating the discrete nature of the operation of Thyristor Controlled Series Capacitor (TCSC). A computation algorithm for eigenvalue calculation is developed based on Time Frequency Distribution (TFD) concept, by capturing the time variation of a frequency component.

The author considers the disproportion between the cost of mitigation solution and the cost implication of the risk of low probability condition such as SSR conditions. This disproportion led the utilities to underestimate the risk, thus increasing the system vulnerability to failure. The author identifies the need for further understanding of existing risk identification and assessment approaches. Two context are realised in SSR risk, firstly is the system states probability and the correlation with SSR risk, and secondly the relationship between SSR risk and the system's operating conditions.

A new technique is proposed to assess SSR risk. The technique propose to utilise the analysis tools and input data to assess SSR risk. The probability weighted cost implication of the SSR risk is estimated and compared with the cost of mitigation measure. This comparison will assist in the economical justification of the countermeasure. It is concluded that it is possible to optimise system's operating condition to achieve acceptable risk of SSR by quantifying a relationship between system's constraints and the system's operating conditions.

1. Chapter One - Introduction

1.1 Introduction

Transmission utilities plan to increase power transfer capability between regions due to lack of local reserve. Some other transmission projects intend to build long distance transmission lines to supply remote areas. Under such circumstance, it is becoming more economical to implement series capacitor or HVDC at the strategic links than undertaking other conventional network re-enforcement.

However, both series compensation and HVDC convertors excites frequencies below the synchronous frequency of the system. These frequencies will be seen as voltage and current components modulated on the 50 Hz voltage and current waveforms. These frequencies namely subsynchronous frequencies may excite tortional torque at the generator system causing excessive voltages and currents, and damage to the generator –turbine shaft if transient tortional torque occurs. The first and only case of SSR was experienced by a turbine-generator at the Mohave Power Plant in southern Nevada In 1970, and again in 1971, causing shaft damage that required several months of repairs on each occasion. This incident occurred following switching events that connected the turbine-generator with a series-compensated transmission line in a radial configuration.

The key objectives of this research work is to establish clear understanding of challenges and issues facing the power networks planning when considering SSR conditions. These issues include power systems characteristics and modelling considerations, planning requirements and criteria for addressing SSR problems, and risk identification and assessment approaches and their application to assess the risk of subsynchronous resonance in an interconnected system

In this chapter, the SSR and its implications are presented. A literature review is performed for SSR analysis and power system modelling and simulation. A review of applied and proposed countermeasures was also carried out. Further an outline of challenges and issues facing engineers when analysing SSR and planning mitigation measures, are discussed briefly. Overview of the thesis content and scope of work are presented.

1.1.1 Definition of SSR

Subsynchronous resonance is a power system condition under which the electrical network interacts with turbine–generator system at frequencies less than the synchronous frequency (50Hz). A disturbance near a series capacitor excites current or voltage components at the electrical natural frequency. The natural frequency of electrical network with series capacitor is $\omega_n = \sqrt{\frac{1}{LC}}$, where L is the inductance of the transmission line conductor and C is the capacitance of the installed series capacitor.

This component will be received at the adjacent generator's rotor as the complementary of the synchronous frequency (50-f_n). If this subsynchronous component at the rotor coincides with the frequency of the natural tortional mode of the generator-turbine mass, an oscillatory interaction between the generator system and the electrical network will occur which may cause damaging stress on shaft section of the generator-turbine system and excessive voltage and current at the electrical network.

1.1.2 Effects of SSR

The SSR have numerous physical and operational implications on power systems. The interaction between the network and the generator's system will results in torsional torque oscillation which may instantaneously damage the shaft system if the oscillation is significantly undamped. In other cases the tortional torque will cumulatively fatigue and age the shaft system which may result into unpredictable failure.

Subsynchronous frequency current or voltage component due to sustained torque interaction can result in excessive voltages and currents at the adjacent parts of the network which may result into forced damage to vulnerable network components.

Subsynchronous components can result into false operation of the conventional generator protection scheme such as overvoltage and over current protection, causing unwanted frequent tripping of base load generation units.

1.2 Literature Review

The first reported case of SSR was experienced by a turbine-generator at the Mohave Power Plant in southern Nevada, USA in 1970, and again in 1971[1, 2]. The incident caused damages to the mechanical system of a high pressure turbine unit that required several months of repairs on each occasion. This incident occurred following switching events that placed the generator in a radial configuration with a series-compensated transmission line. The two incidents were caused by tortional interaction which is one of three recognised types of SSR [2].

The IEEE SSR working group committee [3] provides clear definitions of the SSR and the three types of sub synchronous resonance including induction generation effect, tortional interaction and torque amplification.

The three types of SSR include the induction generation effect which is defined as the state of the self excitation of the synchronous generator at sub-synchronous frequency [4]. The sub synchronous frequency current or voltage component will produce magnetic motive force (mmf) rotating at the angular speed that corresponds with the sub synchronous frequency. As the rotor normally rotates at synchronous speed which is higher than the speed that corresponds with sub synchronous frequency, the machine will experience negative slip and hence induce sub synchronous component at the stator resulting into sustained sub synchronous currents and voltages at the generator. This effect can be detected by the effective resistance seen by the machine as a combination of network, generator stator and rotor resistance [5]. If that effective resistance is negative, the SSR problem is eminent. Figure 1.1 illustrates the effective resistance for SSR component.

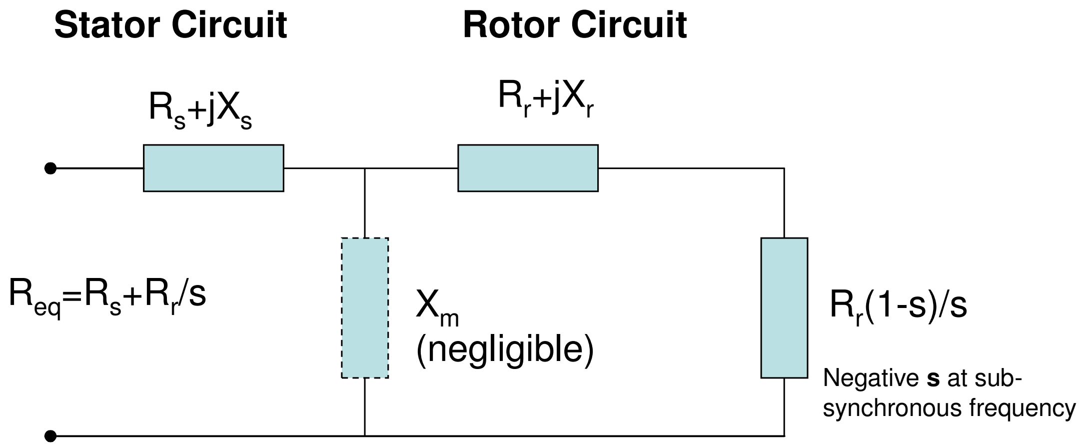

Figure 1.1 The equivalent resistance of the generator at sub-synchronous frequency

The occurrence of Induction generation effect can be excited by small disturbances during steady state, such as small change in systems conditions [1, 2]. Although there is no reported SSR condition caused by induction generator effect [2].

The impact expected from this type of SSR may not be significant; however this type may lead to tortional Interaction if not damped by the system. The implications of this type of SSR are sustained sub synchronous currents and voltages seen by the generator, triggering of tortional interaction, and false tripping of conventional protection schemes [3,4,5].

The second type of SSR is the tortional interaction which occurs when the sub synchronous component current produce induced subsynchronous torque [3,4]. If the mechanical natural frequency of the generator shaft segments is close to the frequency of the produce subsynchronous torque, a tortional torque oscillation will occur resulting in a twisting force on the shaft segments of the generator causing fatigue and damage to the shaft.

Third type of SSR as the torque amplification which is anticipated under system's transient conditions that can occur due to disturbances such as short circuit faults and sudden change in network configuration near series compensated network. The transient conditions for non-compensated networks will result into a transient dc current component which decays with time. For series compensated network, the transient dc current component will contain oscillation at frequencies equivalent to the natural frequencies of the network, refer to equation 1.1. [1,4]. The number of natural frequencies will depend on number of series capacitors installed in the network. Equation 1.1 presents the expression of the transient current expected at a redial compensated line [1].

$$i(t) = A\sin(\omega_1 t + \theta_1) + B \cdot e^{-\varsigma\omega_2 t}\sin(\omega_2 t + \theta_2) \text{.................................} 1.1$$

A is the amplitude of the fundamental current, B is the amplitude of the sub synchronous component, ω_1 is the angular fundamental frequency, ω_2 is the angular subsynchronous frequency, and ς is the damping ratio of the electrical system.

If these subsynchronous components coincided with the tortional modes of the generator's shaft system, tortional torque oscillation can occur, resulting into instantaneous damage and failure of the shaft system. Electromagnetic transient program are essential for quantifying the risk of SSR under such conditions.

Subsychronous oscillations were experienced in a 250 kV DC link system in North Dakota, USA [6]. One of the rectifiers was connected adjacent to a generating plant of two turbo generators. The rectifier control was a constant current control and constant voltage control. This control mode resulted in tortional interaction between the DC link control and the generator control causing subsynchronous oscillation, which was mitigated temporarily by reducing the power flows through the DC link.

There are number of factors when considering HVDC link interconnection including short circuit capacity of the interconnected systems and/or the interconnected generator(s), and the link thermal capacity [6]. The characteristics of power systems with imbedded HVDC link are further investigated in chapter two.

The risk of SSR was also identified in industrial systems with large HV Variable speed drives (VSDs) [8]. The subsynchronous currents or voltages can also be generated in systems as inter-harmonics emission from a distorting load such as HV high capacity VSDs. In other cases a series resonance between cables' capacitance and transformer's winding saturated inductance can occur, resulting into resonant frequency components [9].

With all these system characteristics, there is a risk of subsynchronous resonance and oscillation, if the subsynchronous component is produced near a generator with a shaft system that its natural frequency(s) coincide with the frequency of the produced subsynchronous components. Despite the risk, the network and the generator may present adequate damping of the oscillation. With such system characteristics a countermeasures may not be required to mitigate or prevent this interaction between the network component and the generator mechanical system. However, the risk of SSR may increase when any augmentation or system conditions change along the life time of the system. Two major developments were proposed including embedded HVDC sub-sea link and series compensation in Great Britain (GB) transmission system [10]. These developments were proposed to extend the power transfer capacity of the network which is expected to be constrained by the anticipated heavy penetration of renewable energy in GB transmission network. The relevant transmission utility focused on the risk exposure to the SSR when the two major re-enforcements are considered.

The SSR analysis can be implemented using various computer programs and software. However, there are three key methods include frequency scanning, eigenvalue analysis and time domain simulation [1,2,3,4].

The frequency scanning can be most practical and straightforward approach to study SSR by detecting negative equivalent resistance at the generator neutral and the percentage reactance dip of the equivalent impedance [10,11]. The increasing implementation of modern technology which introduces nonlinearity, offsets the actual frequency response characteristics of a power system [13]. A frequency dependent model for nonlinrear elements such as thyristor controlled series capacitor (TCSC) were derived in reference [14], which can be incorporated in the conventional frequency scan to determine system damping using the TCSC.

In this thesis, a phasor model for TCSC is derived which is dependent on the firing angle (α). The author illustrated the impact of the TCSC controls on the SSR using the proposed phasor model [15].

Frequency scan technique is proven to be the most effective method for preliminary identification of SSR risk and to handle large power system models. Most of the utilities have established their network models in PSS/E and DigSilent software tools

[16-17], due to their ability to handle big number of nodes. Frequency scan tool is available under most of these software packages under the harmonic analysis module. Accurate generator mechanical system is not required by this technique to identify the SSR risk.

The eigenvalue analysis involves mathematical representation of the dynamic behaviour of the system including generators' mechanical and electrical systems, networks and load characteristics in a compact state space model [1,18]. Each dynamic subsystem is represented as a partial linear state-space model in a common D-Q reference frame. The solution of the state space equations of the model represents the eigenvalues.

The linear state space model is represented as:

$$\overset{*}{x} = Ax + Bu$$

Then the eigenvalues are defined as the solution to the matrix equation:

$$\det[\lambda U - A] = 0$$

Where λ are called the eigenvalue. In Appendix A, a state space modelling and eigenvalue derivation was demonstrated

The determined eigenvalues will provide information about the expected electrical and mechanical oscillatory modes as the real part of the eigenvalue will represent the system damping and the imaginary part will represent the frequency of the oscillation. Solving the eigenvalues can be very challenging for large scale power systems.

Although, computational tools were developed to calculate the eigenvalues based on a modular structure offering a complete solution for large scale state space model [19]. Small-signal stability problems for large systems can be analysed around initial operating point in steady state *or* quasi steady state.

Electro-Magnetic Transients Program (EMTP) is a digital transients program developed and maintained by the Bonneville Power Administration (BPA) [20]. Earlier time domain simulation packages were available to investigate transients in electrical networks, then a program that can be run in EMTP environment was developed to investigate the interaction of network transients', the mechanical systems and controls of the coupled machines over a wider range of frequencies. These programs allow detailed modelling of machines and system controllers as well as transient faults, and other types of switching events such closing or opening circuit breakers.

Although frequency scan tools are still used to perform rapid risk assessment of SSR, while time domain simulation was used to quantify the risk under fault conditions [22]. Time domain simulation is most suitable for the study of torque amplification or transient torques. Long time simulations duration will be required to capture the SSR condition during steady state.

Despite that most of the research on SSR is still working on developing better study techniques, there is also focus on developing better measures and protection to provide safe operation of generators under SSR conditions.

Number of SSR mitigation solutions has been identified [23]. Some of the solutions were implemented (e.g., the static SSR filter at the generator connection), while others were shown to be effective only by mathematical simulation. The static SSR filters were best suited for addressing tortional interaction and torque amplification.

The series reactance and pole-face amortissuer winding were best suited to address Induction generation effect.

There is around 10% discrepancy between the estimated SSR modes' parameters from SSR studies and the parameters obtained from actual measurements

Means to measuring the tortional natural frequency were identified [24], the turbine-generator is equipped with sensors to detect torsional oscillations and spectrum analyser to provide direct readout of the frequencies during normal operation of the unit. There are toothed wheels equipment and reluctance pickups, optical sensors, and strain gauges. The readout can be during normal operation or during site or factory testing. Tortional oscillation decay can be measured by forcing a significant level of torsional oscillations by applying a transient event or by injecting a sinusoidal signal to the voltage regulator input, then measuring the decay after removing the driving force or after the oscillation is stabilised by the system.

Some utilities prefer to conclude SSR risk after in-service date, for most of the commissioned generation projects at Midwest USA [25]. SSR risk assessment that were done before in-service date, were incomplete or inconclusive, due to lack of detailed generator model data and uncertainty of assumptions made before in-service date. So the SSR risk were based on SSR verification site tests and or factory tests

Numerous utilities around the world are continuously reviewing the assessment process of SSR and the selection of countermeasures, as the implementation of series compensation and HVDC are becoming more common near generation connection points.

Most power utilities have planning criteria and market rules that enforce performance requirements with respect to impact of network modification to network stability including oscillatory conditions in general, however do not set specific performance and design requirements that address SSR conditions [26,27]. Some utilities follow a deterministic method to establish network planning requirements. While some other utilities choose to factor uncertainties in their planning approach by setting probabilistic requirements to drive the decisions on network investments, including those that address system stability problems [29].

1.3 Power System Challenges

This section aims to present some of the challenges that face network planners in maintaining network resilience. These challenges include providing quality and reliable supply to the customers at low cost, without compromising community welfare and the environment. These requirements will affect the way that power system problems and constraints are addressed.

Due to deregulation in financially challenging environment, the utilities lower their capital expenditure and have to put up with increasing operating expenditure. This has led the utilities to planning and operating parts of their systems at the limits, exposing the system to a critical level of risk of failure or loss of supply.

Deferral of capital expenditure makes the system more vulnerable to high impact-low probability event such as those caused by SSR. This disproportion between the cost implication of system failure and the overspending on network solutions is a challenge facing the utilities. Further, the lack of integration between the individual business systems and their asset management strategy has led to neglected opportunities or risks that could have an impact on network infra spending.

There is a need to understand the risk and the implications, and identify unconventional ways to quantify risk in order to better justify the network re-enforcements. In the following chapters, the author aims to establish a good understanding of risks in power systems, in particular under SSR conditions, and suggest a technique to quantify the risk for the purpose of economic justification of the proposed countermeasure.

1.4 Thesis Aims and Content

The purpose of this research work is to establish clear understanding of challenges and issues facing the power networks planning, in particular SSR conditions. The thesis discusses key power system characteristics and modelling considerations that need to be taken into account for SSR assessment. Further a good understanding of the general requirements and criteria for addressing SSR problems are established. In addition, the thesis aim to establish an understanding of risk identification and assessment approaches and how they can be applied to assess the risk of subsynchronous resonance in an interconnected system

In chapter two, a new view of some of the characteristic of the power system, in particular when studying SSR, is presented. A guide for power system modelling and representation for simulation studies is also given. New modelling approaches to deal with the non-linearity in power system, especially when analysing SSR problem are demonstrated

In chapter three, a phasor model of the TCSC reactance is developed and used for investigating the characteristics over a range of firing angles. A new application for Time Frequency Distribution (TFD) algorithm in SSR analysis is presented. A computation algorithm for eigenvalue calculation is developed based on TFD concept, by capturing the time variation of the frequency component. The technique is dependent on the information obtained from the time domain signal which can be obtained from non-linear simulation. A case study is presented to illustrate the implementation of the algorithm

In chapter four, a review of the existing planning criteria from various utilities is presented with reference to SSR assessment and performance requirements. Most of the utilities consider deterministic requirements to assess the system stability. The new proposed requirements include the design requirements for HVDC link and series compensation system that aim to reduce the risk of SSR. Probabilistic requirements for SSR system response are proposed based on probability and severity of contingency event.

In chapter five, the existing risk analysis techniques and their applications in power systems were reviewed and presented.

In chapter six, a new technique is presented to assess SSR risk and assist in the decision making of risk mitigation. The technique uses probability weighting of SSR risk to estimate the cost of the consequence as compared with the capital cost of the countermeasure. A quantitative relationship between the system's constraints and the system's operating conditions were realised for the purpose of optimising system's operating condition to achieve acceptable risk of SSR.

2. Chapter Two – Key Characteristics of Power Systems with SSR Condition

2.1 Introduction

A number of key characteristics of modern power systems are identified and presented in this chapter. These characteristics are discussed from SSR prospective to assist in better understanding of SSR risk and in making valid assumptions. The characteristics apply to modern technologies such as HVDC systems, series compensation and big shunt components at extra high voltage level.

In this chapter, a number of rules and guidelines for modelling have been established. The models for the key power system components are selected based on the frequency range. For SSR study, the frequency range is below the synchronous frequency of 50/60 Hz. A lumped positive sequence model is considered acceptable for line, transformer and shunt elements. More detailed representation is required for the study of the machine/generator including electrical, mechanical and control system.

Guidelines for model simplification without compromising system response validity are given.

2.2 Power System Characteristics and SSR

In this section, key characteristics of modern power systems are presented to further explain SSR condition. Case studies and examples are included to demonstrate some of these characteristics.

2.2.1 Transmission System with HVDC

Integration of embedded HVDC technologies to heavily meshed transmission systems with a substantial amount of conventional generation represents a technical challenge. Power transfer requirements are to be met without causing an adverse oscillatory interaction between the HVDC and the generator system.

The subsynchronous oscillations at the generator's shaft system can be modulated back as a subsynchronous component into the AC input voltage waveform to HVDC system, refer to Figure 2.1.

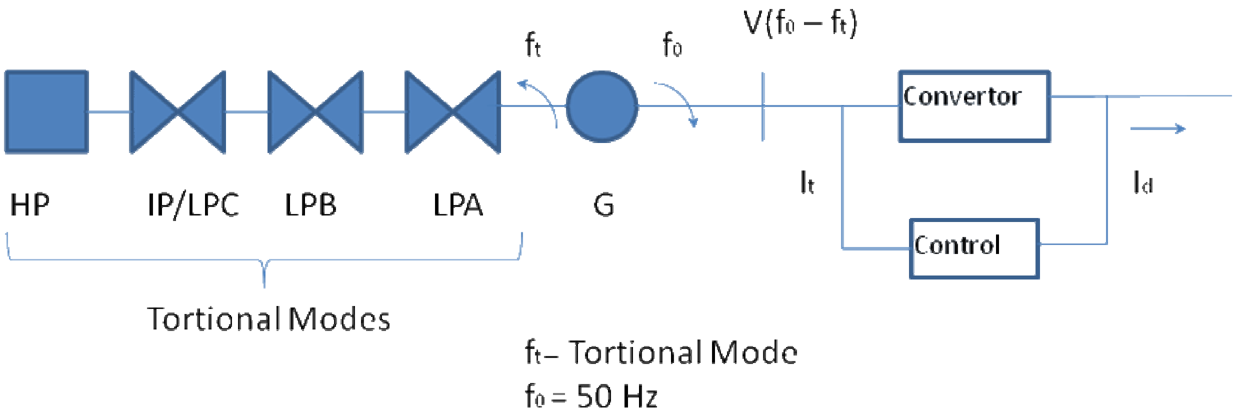

Figure 2.1 – Generator Interaction with HVDC control

This modulated voltage is impressed on the DC bus, causing shift in the firing angle similar to the same shift in the phase modulated voltage wave. This in turn changes the output direct current and voltage in a corresponding manner. This change is seen by the network as a swing in generator power, shaft speed and electrical generator torque at subsynchronous frequency. If the variation in triggering angle exceeds 90° the oscillation becomes unstable and the generator may lose synchronism.

2.2.2 Series Compensated Transmission System

In general, having a series capacitor in transmission system is a key indicator of SSR risk. However for system with certain characteristics, series compensation may not cause sustained SSR problem. These characteristics can be summarised as follows:

1) *High ratio of generator mass to turbine mass*, resulting in adequate modal damping and inertia. For example hydro units and wind synchronous and asynchronous units enjoy a high mass ratio compared with large thermal power plants. Steam generator units have small radius alternator driven by multi staged steam turbines.

2) *The series compensated line in parallel with uncompensated line*. The series compensated lines can extend their compensation levels to 70% without compromising SSR stability.

3) *Series Compensation level is maintained below 30%*. Any compensation level above 30% excites electrical natural frequency complementary of the of the shaft system's tortional mode which is normally lower than 15 Hz , refer to Table 2.1 and Equation 2.1

Table 2.1 Compensation Level and corresponding Natural Frequency

Compensation level (X_C / X_L)%	Electrical Natural Frequency (Hz)	Tortional Mode (50-f_n)
10%	18	32
20%	28	22
30%	32.6	17
40%	38	12
50%	42	8

$$\omega_n = \omega_o \sqrt{\frac{Xc}{X_L}} \quad ....2.1$$

where ω_n is the network natural frequency, ω_o is the system's frequency, X_C is the series capacitor reactance, and X_L is the reactance of the line.

However, operating the transmission system at compensation levels lower than 30% may not justify the installation of the series capacitor in a transmission line that experience continuous or sudden growth in power transfer levels. In other words, reducing compensation levels below 30% will constrain the transmission line far below its power transfer capability.

2.2.3 Transmission System with Shunt Reactors/Capacitors

Shunt capacitor bank, and the inherent shunt capacitance of a long transmission line or underground cable, excite natural frequencies above 50 Hz. Therefore the risk of SSR condition is unlikely. However, shunt reactors in systems with subsynchronous modes can impact these modes.

In a case study that involves a long 220 kV cable; inductive reactive compensation was installed in two intermediate stations along the cable to absorb the excessive charging, refer to Figure 2.2. The combination of the cable capacitance and the cable impedance resulted in numerous resonance frequencies. The shunt reactor switching (in and out of service) has a notable impact on the impedance spectrum at frequencies below 50 Hz. Figure 2.3 demonstrates the frequency scan of the cable impedance at the network connection point. For a couple of reactors switching scenarios, the impedance changes notably at frequencies below 50 Hz. If the network beyond the cable connection point excites subsynchronous frequencies, the cable system will show notably different characteristics for each reactor switching configuration. Therefore, shunt reactors should be considered carefully when performing SSR assessment.

Since shunt capacitance will only impact the impedance spectrum at higher frequency range (above 50 Hz), it can be neglected for SSR assessments.

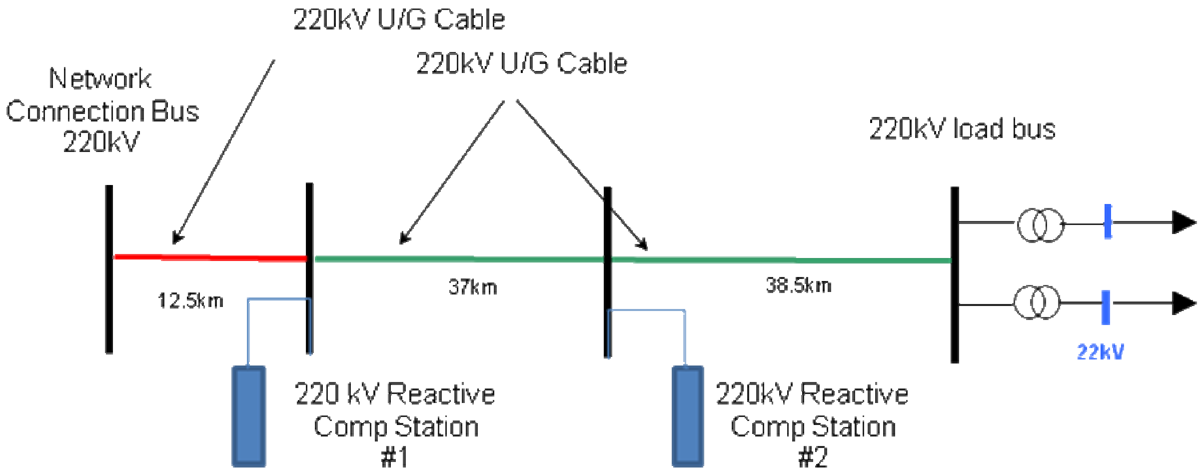

Figure 2.2 – 220 kV Cable System Configuration

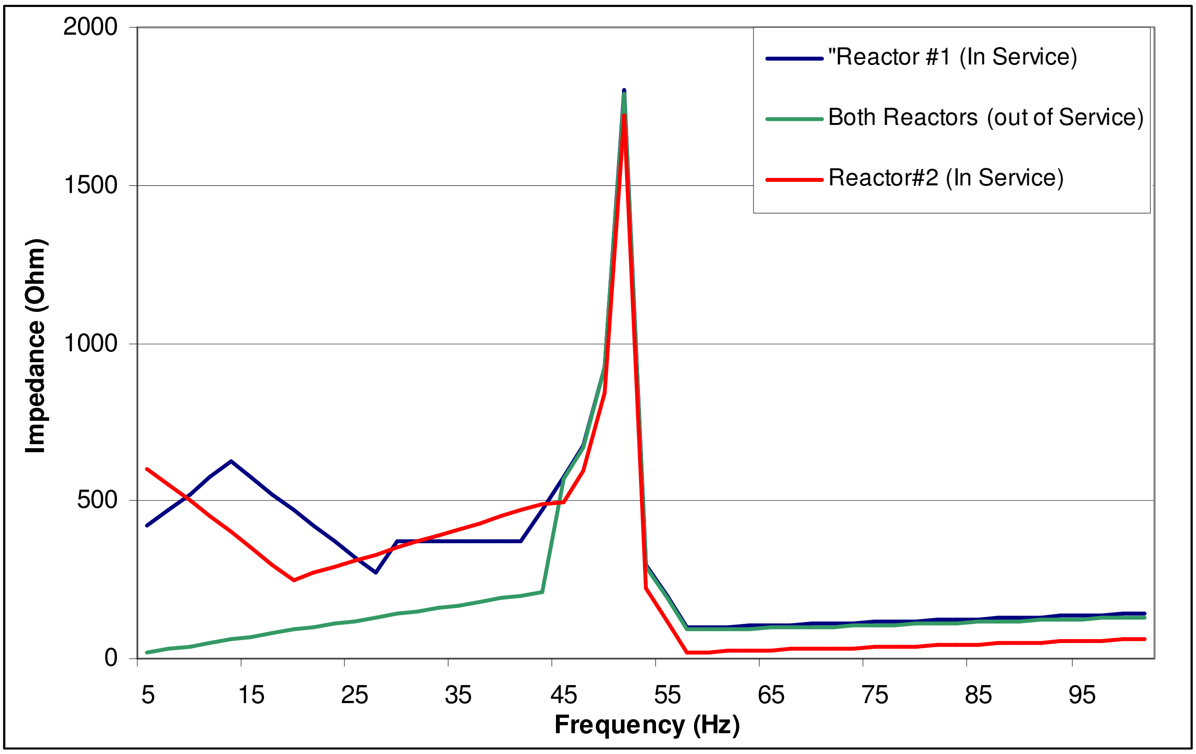

Figure 2.3 – Impedance scan for the 220 kV Cable at the Connection Point

2.2.4 Complexity of System Elements

Nowadays, utilities are more likely to be equipped with Flexible AC Transmission (FACT) systems that use power electronic technology for controlling their operation. FACT devices include Static VAr Compensators (SVC), Thyristor Controlled Series Capacitor (TCSC), Static Synchronous Compensators (STATCOM), Unified Power Flow Controller (UPFC) and Synchronous Series Compensator (SSC).

Due to recent developments in power electronics, the TCSC has become a viable replacement for the fixed series capacitors. The TCSC can offer flexible control of power flow, secure damping of power oscillation and in some case effective SSR suppression.

Due to the switching behaviour of these components, their detailed representation adds complexity to the representation of the overall system. Network analysis, especially SSR analysis, can become difficult when incorporating such components, due to the following points:

1) Difficulty to represent this in simulation and/or mathematical environment.

2) Complexity of the interface with the other conventional system components.

3) Detailed representation makes simulation running time longer.

These issues are addressed through proposing a new continuous model that is easy to incorporate and integrates well with the representation of rest of the system. Further, a new method has been developed to efficiently represent TCSC in time domain simulation environment (EMTP/ATP). In chapter three, the proposed continuous model and simulation method for the TCSC are discussed in details

2.3 Power System Modelling

In general, the time spent for running a simulation is a small percentage of the study time. Most of the time is spent constructing the models, obtaining the parameters for model's component and verifying and testing the components. This can be an iterative process. Further the developed model needs to be tested against actual measurements after commissioning the project, and then more model adjustment normally will follow. For large scale networks, it is important to establish a comprehensive model without compromising the validity of the actual representation and behaviour of the system studied. The author has found that the following factors are important to consider when modelling dynamic behaviour of power systems, in particular when considering the SSR condition.

2.3.1 Network Component Representation

In SSR studies, especially when considering the transient conditions, the most critical step in the construction of the study model is the determination of the model parameters. Table 2.2 provide a modelling guideline for selecting the appropriate representation of power components in power system studies including SSR studies. The selection of the representation is based on a frequency range of the phenomenon to be simulated, that varies from DC to several MHz [31].

The frequency ranges are classified into four groups as illustrated in Table 2.3 : low-frequency oscillations including SSR from 0.1 Hz to 3 kHz, slow-front surges, from 50/60 Hz to 20 kHz, fast-front surges, from 10 kHz to 3 MHz, very fast-front surges, from 100 kHz to 50 MHz [32]

Table 2.2 Power system components and the Recommended Representation

Frequency range	Power system components					
	Transmission Lines	**Insulated Cable**	**Transformer**	**Machine**	**Shunts**	**FACT (e.g TCSC)**
0.1Hz – 3kHz	lumped and constant parameters,	lumped and constant parameters,	Saturation effects, as well as core and winding losses	Detailed model of the electrical, control and mechanical system including saturation	Shunt reactors should be modelled for any frequency below 100 Hz, Shunt cap need to be modelled for above that range	Fixed compensation can be used, ignoring the piece wise behaviour of the power electronics
50Hz- 20kHz	Lumped and constant parameters,	Distributed parameters, including. Frequency-dependence of parameters	Core losses and saturation can be neglected. Coupling between phases is mostly capacitive.	The machine can be modelled as a source in series with its sub-transient impedance.	Shunt cap need to be modelled while shunt reactors can be ignored	the piece-wise behaviour of the power electronics is represented if relevant
10kHz- 50MHz	Distributed parameters, including. Frequency-dependence of parameters	Distributed parameters, including. Frequency-dependence of parameters	Core losses and saturation can be neglected. Coupling between phases is mostly capacitive.	The machine can be modelled as a source in series with its sub-transient impedance.	Shunt cap need to be modelled while shunt reactors can be ignored	the piece-wise behaviour of the power electronics is represented if relevant

Table 2.3 Power system Studies and the Associated Frequency Range

Frequency range	**Phenomena**	**Power system studies**
0.1 – 3 kHz	Low frequency oscillation	SSR studies Transient stability Small signal stability
50 Hz-20 kHz	Switching surge – slow front surge	Insulation Coordination Over voltage Protection
10 kHz-50 MHz	fast –front surge	Insulation Coordination Lightening protection, ferroresonance

2.3.2 System Simplification Guideline

For large scale systems, system simplification is essential to be able to perform simulations within the limited software capabilities, and acceptable running time. The following considerations need to be taken into account when modelling a simplified system:

1) Decide the system size taking into account the frequency range of the study. The higher the frequency range, the smaller the model studied. For high frequency transients such as lightning protection, all external systems should be replaced by a simple mono-component model. In the case of SSR simulation it is preferred to represent most of the system. However, for large scale system, it is suggested that the supply connection points (e.g load connection points) be replaced with an equivalent system
2) Minimize the number of components by removing the components that have negligible impact on the study results. For low frequency studies such as SSR, the line admittances and some shunt capacitive elements can be neglected due to their insignificant impact on the system representation at low frequencies.
3) Idealise the representation and parameters for some components when the system is too complex by using typical or nominal values. Sensitivity test can be performed to determine the range of the study parameters values that does not compromise the integrity of the model.

3. Chapter Three - New Modelling & Simulation Approach for SSR Analysis

3.1 Introduction

A mathematical continuous model of the TCSC is developed. The new proposed model facilitates the SSR analysis when considering the integration of TCSC model with the model of the rest of the system. A simulation method for TCSC is also developed to facilitate the representation of the TCSC in any time domain simulation tool without affecting result accuracy.

A new approach is developed to estimate eigenvalues for a complex and non-linear model without the need for linearization. The new method is based on the Time–Frequency Distribution (TFD) technique which is used widely in signal processing applications, such as speech recognition. The information on the frequency content and the time variation of the frequency contents were extracted from the time domain response of the study signal. The limitation of this method is that a time domain response of the non-linear system component to a transient disturbance is required. This time domain response can be a signal that is obtained from a logger record or from a simulation study.

3.2 Modelling and Simulation of TCSC

A new continuous model of the TCSC is presented in this section. Further a simulation technique is presented to incorporate the piece-wise behaviour of the TCSC in simulation tools such as Alternative Transient Program (ATP) and Power System Blockset /SIMULINK/MATLAB.

3.2.1 TCSC Operation and Piece Wise Behaviour

The principle of the TCSC is to control the reactance of the fixed series capacitor by controlling the current in the parallel inductor using two reversed thyristors, as shown in Figure 3.1. The effective value of the inductor varies with the conduction time of the thyristor; hence changing the level of series compensation.

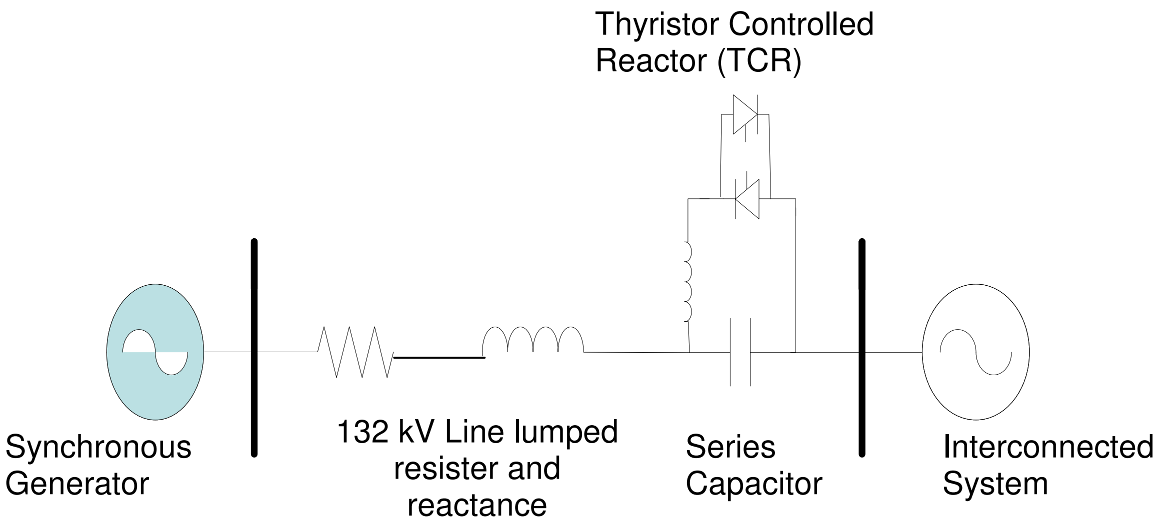

Figure 3.1 - Series compensated line with TCSC

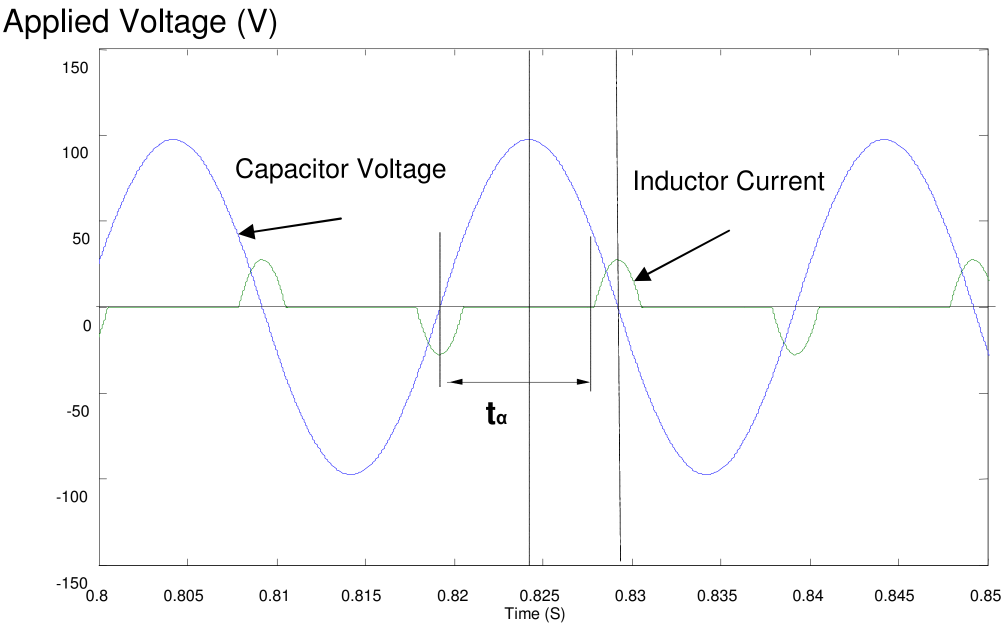

Figure 3.2 TCSC Operation

3.2.2 New technique for TCSC Simulation

A simulation technique is developed to simulate the actual TCSC piece-wise behaviour in a time domain simulation platform such as EMTP/ATP.

The technique is based on detecting the positive and negative peaks of the capacitor voltage as the thyristor conduction reference, refer to Figure 3.2. The peaks were detected by comparing the derivative of the voltage signal with zero as shown in Figure 3.3.

Once the signal generator receives a true command from the peak value detector, it will generate a pulse to trigger the thyristor with a time delay equal to t_α instant of conduction.

The thyristor firing angle ($\pi/2<\alpha<\pi$) is defined as the delay angle between the zero crossing of capacitor voltage and the start of thyristor conduction.

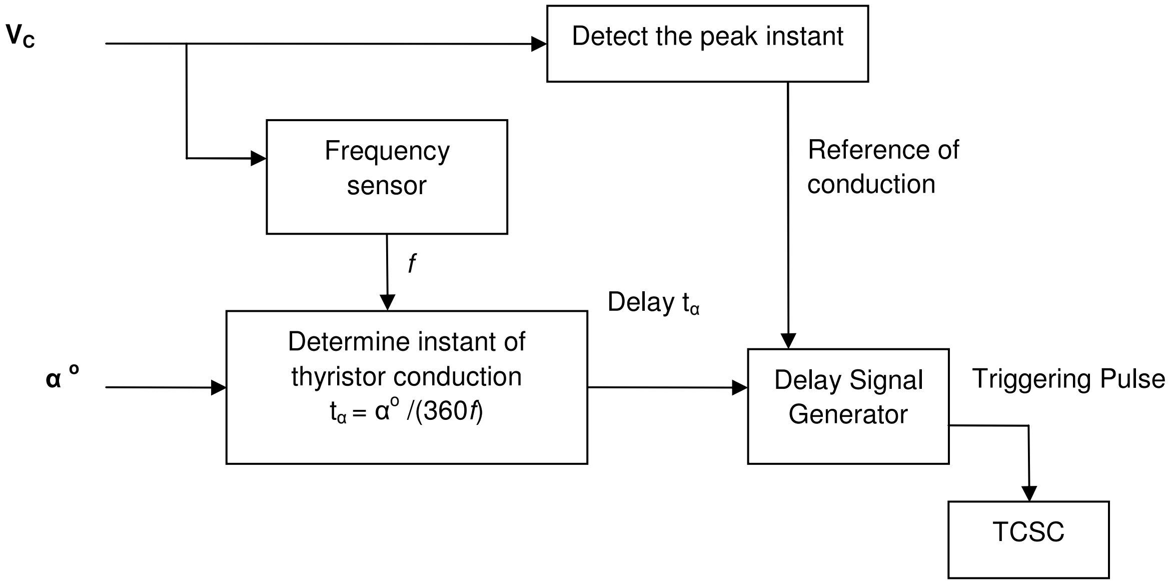

Figure 3.3 TCSC Simulation Technique

3.2.3 Continuous Model for TCSC

Due to the switching behaviour of TCSC, the detailed representation adds complexity to the overall system model. Network analysis and especially SSR analysis could be challenging when incorporating such components due to complexity of implementation in simulation tools. It is difficult to integrate the discrete model of the TCSC with the continuous model of the rest of the system.

The discrete inductor current is represented in equation 3.1. Appendix A illustrates the derivation of the instantaneous inductor current:

$$\begin{aligned} i_L &= \frac{\sqrt{2}\cdot V_C}{\omega\cdot L}\int_{\alpha}^{t}\sin(\omega\cdot t) \\ &= \frac{\sqrt{2}\cdot V_C}{\omega\cdot L}(-\cos(\omega\cdot t)-\cos(\alpha)) \end{aligned} \quad \text{...(3.1)}$$

Fourier analysis was applied to the inductor current to obtain the fundamental frequency component. Consequently, the r.m.s value of the fundamental component of the inductor current shown in Figure 3.4 is:

$$I_{L_1} = \frac{V_C}{\pi\omega L}\cdot(2\pi-2\alpha+\sin(2\alpha))\text{..............(3.2)}$$

Other harmonic components are to be neglected on the assumption that their values are insignificant.

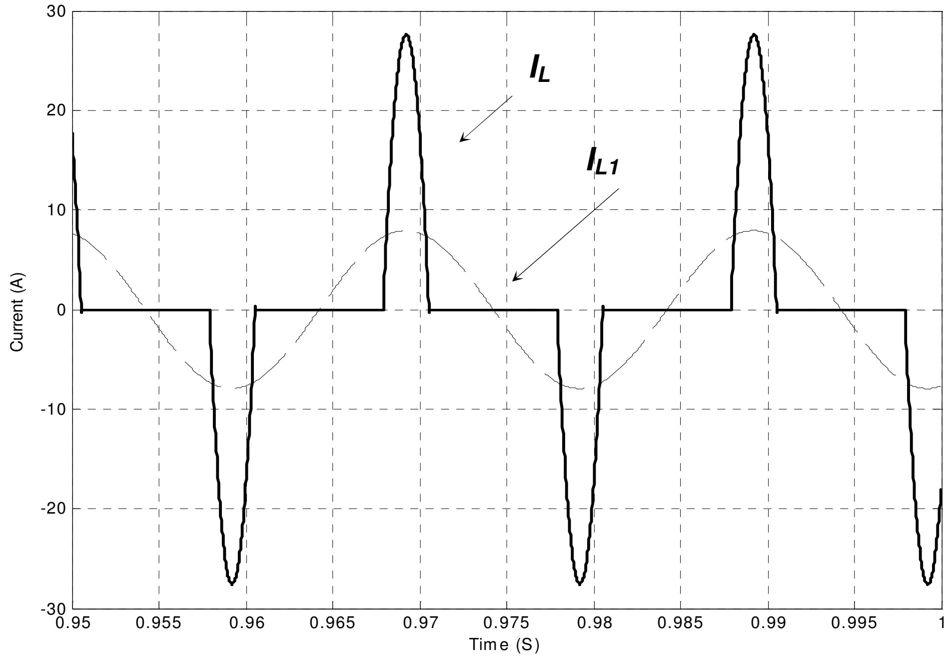

Figure 3.4 Current through the parallel inductor and its fundamental

The effective value of the inductance can be expressed as:

$$L_{eff} = \frac{V_C}{\omega I_{L_1}} = \frac{\pi \cdot L}{(2\pi - 2\alpha + \sin(2\alpha))} \qquad \text{............. (3.3)}$$

The reactance of TCSC would be:

$$X_{TCSC} = \frac{X_{L_{eff}} \cdot X_C}{(X_{L_{eff}} + X_C)} \qquad \text{..................... (3.4)}$$

The developed continuous model of TCSC impedance is used to test the frequency response of the TCSC reactance for a range of triggering angles ($\alpha = \pi/2 + \omega t_\alpha$),

Figure 3.5. shows the apparent impedance of TCSC with reactor inductance of 65mH and physical series capacitor with capacitance of 106 μF to provide 50% compensation of the line reactance.

The TCSC reactance changes from inductive to capacitive as the frequency increases. It is notable that the TCSC shows inductive characteristics for low subsynchronous frequency components and capacitive characteristics for frequencies around the synchronous frequency 50 Hz. For triggering angles between 112° – 158°, a series resonance is excited at subsynchronous frequencies. For this case, it is desirable to operate at triggering angle lower than 112°, to avoid the resonant conditions and maintaining the TCSC capacitance.

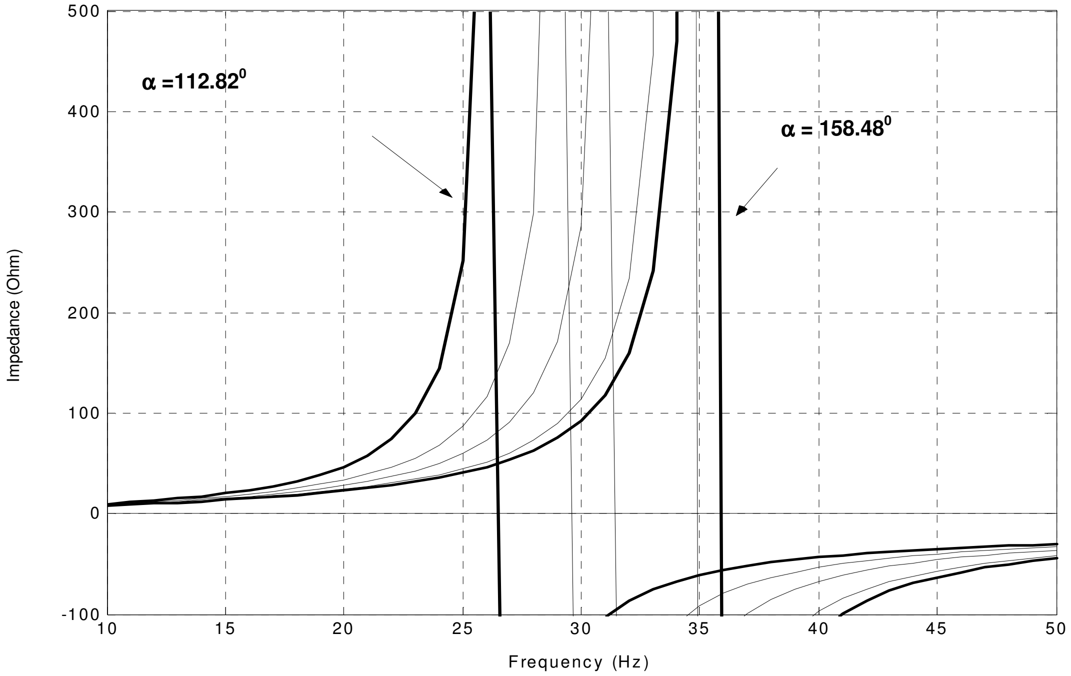

Figure 3.5 TCSC reactance characteristic for different values of α

3.3 New Analytic Approach using TFD Technique

A new application of Time Frequency Distribution (TFD) algorithm to SSR analysis is presented in the following section. Eigenvalues are computed from the information obtained from the TFD algorithm which extracts the frequency contents from the time domain signal.

A computation algorithm for eigenvalue calculation is developed by capturing the time variation of a frequency component. This technique is dependent on the information obtained from the time domain signal which can be obtained from a non-linear simulation. The benefit of this technique is that the oscillatory modes can be identified from the time domain response of the system to an applied fault. This approach will save the effort to model complicated system in state-space form.

3.3.1 Time Frequency Distribution Algorithm (TFD)

This algorithm reveals the time-frequency structure of the time domain signal. As shown in Figure 3.6, the principle of this algorithm is to perform the Fourier Transform on the studied signal to determine frequency information and then the signal is re-constructed using inverse Fourier transform to determine the corresponding time information.

In [33] a number of methods used for performing time frequency analysis is discussed. One of these is based on the Wigner-Ville distribution, which is known for its high-resolution image of the energy distribution over the time.

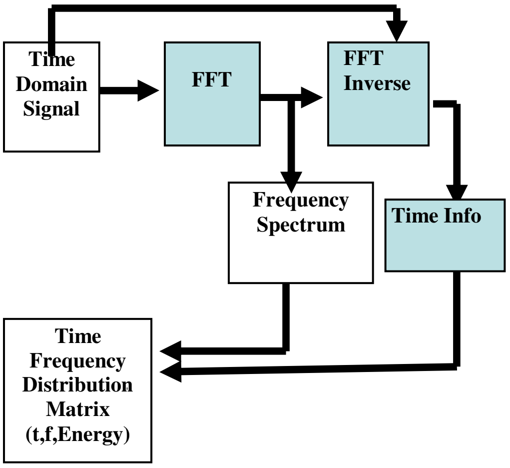

Figure 3.6 - Block Diagram Illustrating TFD Algorithm

The advantages of this method can be summarized as following:

- Easy to understand the relation between frequency and time. As for FFT, it is not sufficient to understand the behavior of the frequency content of the signal from the magnitude spectrum, and it is not easy to understand the time-varying nature of the signal using the complicated phase-magnitude relations.
- Another advantage of TFDs is that they are more resistive to noise than FFT, since they spread noise along the time-frequency plane.

3.3.2 Proposed Eigenvalue Computation Algorithm

It is assumed that the study time domain signal *g (t)* consists of the following N terms:

$$g(t) = \sum_{K=1}^{N} A_K e^{\sigma_K t} \cos(\varphi_K + 2\pi f_K t) \qquad \text{.................................3.5}$$

where σ_K and f_K in the following equation describes the outstanding eigenvalue:

$$\lambda_K = \sigma_K + j2\pi f_K \text{......................................3.6}$$

K refers to subsynchronous mode and in the following equation A_K is the amplitude constant for *K* mode. By having the amplitude proportional to the spectrum energy X (f_K , *t*) for mode *K*:

$$X_K(f_K, t) \propto A_K e^{\sigma_K t} \quad \text{.............................3.7}$$

The value of $X_K(f_K, t)$ was looked up from TFD matrix, for the identified subsynchronous frequency (f_K) and the time sample t_1 & t_2

$$\frac{X(f_K, t_1)}{X(f_K, t_2)} = e^{\sigma_K \Delta t} \qquad \text{.........................3.8}$$

$$\sigma_K = \Delta t \ln \frac{X(f_K, t_1)}{X(f_K, t_2)} \text{.........................3.9}$$

3.3.3 Case Study – Implementation of TFD

The system shown in Figure 3.1 was considered for this case study. A three-phase fault is applied at the source bus of the system for 2.5 cycles. The disturbed capacitor voltage is selected to be the study time domain signal as shown in Figure 3.7. The TFD algorithm is used to extract the time variable information around the frequency content of the study signal. Figure 3.8 provides the top view of 3D plot of the TFD matrix which represents the energy (V^2) with respect to time and frequency. It is clear from Figure 3.8 that the sub synchronous component is around 38 Hz, as at the specific frequency the X function trend can be established as shown in Figure 3.9 Based on the X values extracted from the established trend, the damping coefficient σ_K is derived.

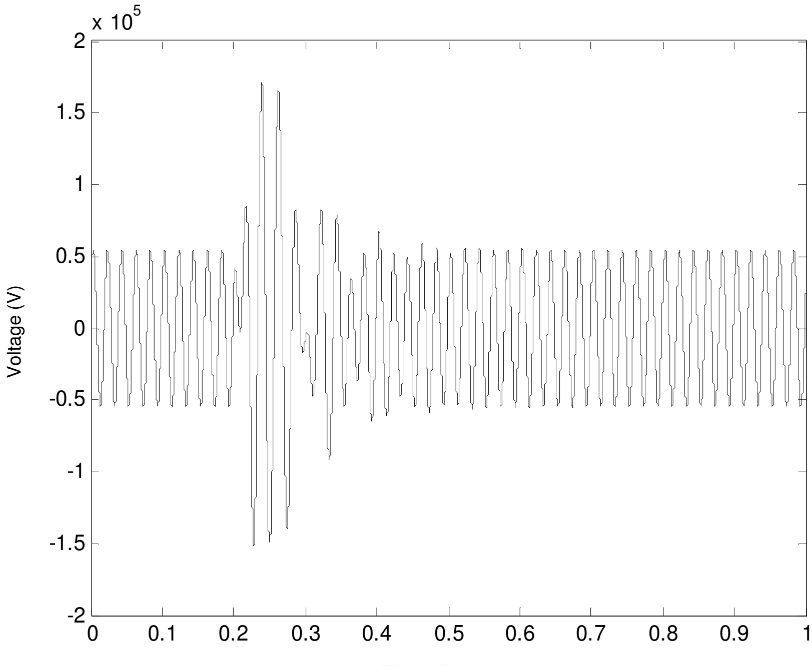

Figure 3.7 Capacitor voltage time response

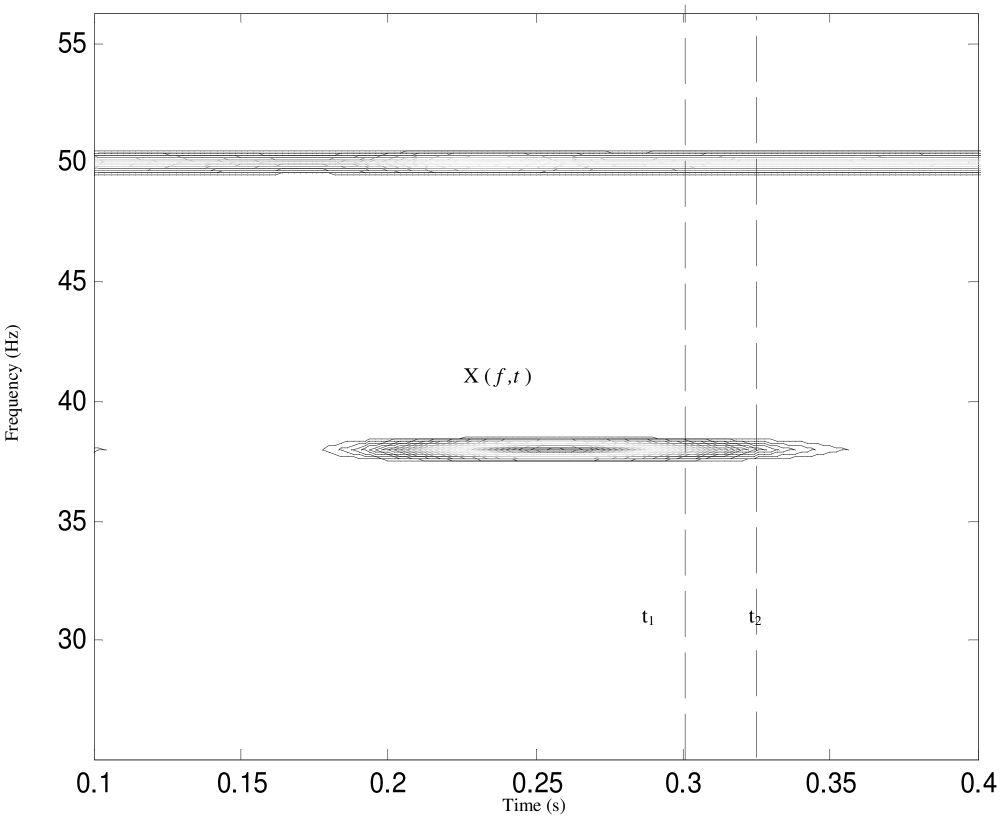

Figure 3.8 Time frequency distribution for capacitor voltage signal across TCSC

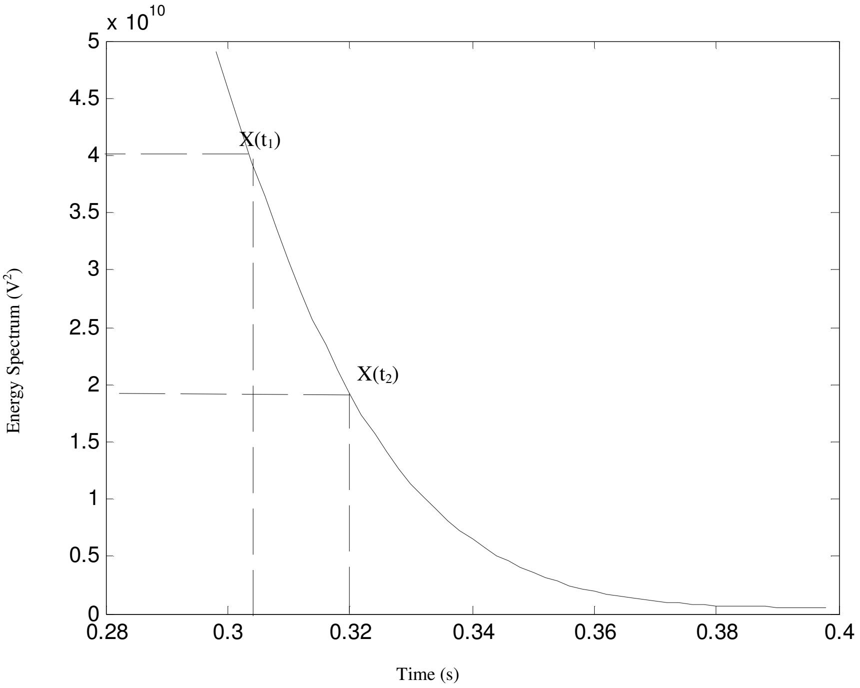

Figure 3.9: TFD spectrum energy versus time

This approach can be used to estimate eigenvalues for a complex and non-linear model without the need for linearization. However, the limitation of this method is that a time domain response of the non-linear system component to a transient disturbance is required. This time domain response can be a signal that is obtained from a logger record or from a simulation study.

4. Chapter Four – SSR Existing Technical Standards & Criteria

4.1 Introduction

Many utilities establish certain requirements and criteria for network development in order to maintain network reliability and security. Most of these criteria and requirements address capacity constraints. These criteria are not detailed enough to address network limitation such as SSR condition.

In this chapter, a review is performed for the existing planning criteria by different utilities including the Inter Regional Planning Committee (IRPC) of Australian Energy Market Operator (AEMO), PowerWater, Western Electricity Coordinating Council (WECC) and Western Power.

Some of these criteria include assessment standards, system performance requirements, information requirements for assessments, allocation of stakeholder obligations and responsibilities, and system design guidelines.

New requirements are proposed as design standards for developments that involve series capacitor and HVDC link. New requirements are proposed as SSR performance standards, some of these requirements are used for SSR risk assessment and quantification as shown in chapter six.

4.2 Review of Existing Planning Criteria

In this section, a review of some utilities' planning criteria is carried out, identifying any guidelines and requirements when addressing SSR condition.

4.2.1 Requirements for SSR assessments

PowerWater which is the electricity utility in NT, Australia, require SSR/SSO assessment for planning series compensation at a location with a low fault level (usually with source impedance higher than 1.0 pu)

The Inter Regional Planning Committee (IRPC) of Australian Energy Market Operator (AEMO) sets a requirements for SSR assessment when any augmentation involving either installation of a series capacitor or modification of the network near an existing series capacitor, is planned. The application of series capacitor in the Australian National Electricity Network is limited to the 330 kV interconnector between Victoria and NSW.

Western Electricity Coordinating Council (WECC), USA, sets in detail the requirements, obligations and guidelines of SSR assessment to the involved stakeholders. WECC requires the transmission utility to perform a valid SSR assessment before the in-service date of a new addition to transmission system at 200 kV or higher including series capacitor, HVDC rectifier terminal, or static var compensator (SVC) system.

The SSR assessment is also required when implementing a new switching practice such as high-speed auto-reclosing (e.g. reclosing after a delay of less than two seconds) and single-pole switching on a transmission line 200kV or higher, and connection of large fluctuating load greater than 100MW such as an ac electric arc furnace, rolling mill, cyclo-converter, or industrial drive, near a turbo-generator.

4.2.2 Performance Standards

One of the dynamic stability performance indicators is the damping of the electromechanical oscillations. The power system oscillations are caused by steady state changes or a contingency event such as changes in power transfer between regions, steady state voltage change, and sub-synchronous oscillations. The damping capability of the system is very important to assess the risk of instability of the system.

In general, Australian utilities including AEMO, Western Power and PowerWater define the requirements for oscillatory behaviour of system variables by setting the minimum damping requirements for any electromechanical oscillations resulting from any small or large disturbance. The minimum requirements is the damping ratio of the oscillation should be at least 0.5 rad/sec. For inter-area oscillation modes the requirement is defined by the halving time of the oscillation overshoot which should not exceed five seconds. If the oscillation does not comply with the minimum requirements corrective action plan would be required.

IRPC requires an initial assessment if the damping of the electromechanical modes is lower than 0.3 neper/sec.

4.2.3 Probabilistic Performance Requirements

The performance requirements stated in section 4.2.2 are deterministic requirements. These requirements are established based on worst cases contingency. Conservatively utilities still consider them for all types of contingencies.

The Western Electricity Coordinating Council (WECC) is one of the few transmission utilities that consider probabilistic performance requirements for transmission network planning.

The requirements illustrated in Table 4.1 are established based on the probability of contingency occurrence, however, these requirements may not address the SSR/SSO directly.

Table 4.1 – WECC disturbance – performance table of allowable effects on other systems. Courtesy of WECC

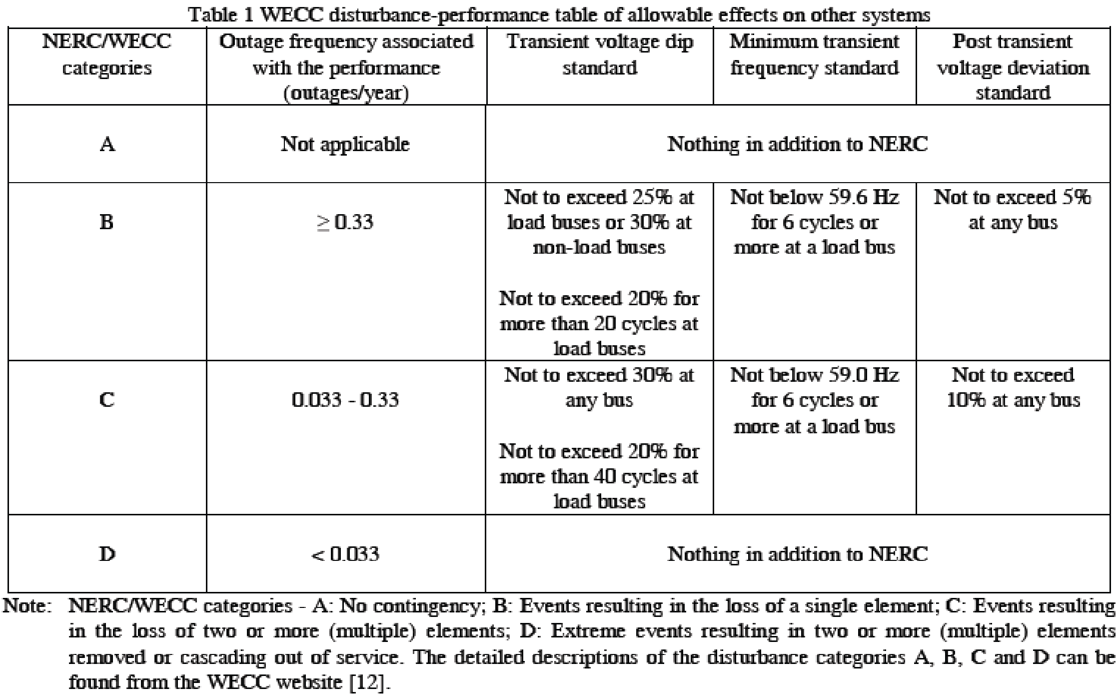

Table 1 WECC disturbance-performance table of allowable effects on other systems

NERC/WECC categories	Outage frequency associated with the performance (outages/year)	Transient voltage dip standard	Minimum transient frequency standard	Post transient voltage deviation standard
A	Not applicable	Nothing in addition to NERC		
B	≥ 0.33	Not to exceed 25% at load buses or 30% at non-load buses Not to exceed 20% for more than 20 cycles at load buses	Not below 59.6 Hz for 6 cycles or more at a load bus	Not to exceed 5% at any bus
C	0.033 - 0.33	Not to exceed 30% at any bus Not to exceed 20% for more than 40 cycles at load buses	Not below 59.0 Hz for 6 cycles or more at a load bus	Not to exceed 10% at any bus
D	< 0.033	Nothing in addition to NERC		

Note: NERC/WECC categories - A: No contingency; B: Events resulting in the loss of a single element; C: Events resulting in the loss of two or more (multiple) elements; D: Extreme events resulting in two or more (multiple) elements removed or cascading out of service. The detailed descriptions of the disturbance categories A, B, C and D can be found from the WECC website [12].

4.2.4 Obligations & Information Requirements

WECC requires, each generator owner to provide manufacturer data and/or results from field tests to the transmission planner, if a potential for a SSR condition is evident. The field test should provide and verify the frequencies and damping of the natural mechanical modes of the generating system as a function of the system loading.

For the transmission utility, who would be performing the SSR assessment, the following outlines the information requirements for the SSR studies:

- Updated model (built in PSS/E or DIgSILENT) of the transmission network under study
- Details of the proposed series compensation designs for the key circuits across the network interface.
- List of future defined system augmentations which may impact the powerflow across the network.
- List of possible new generation locations which may impact the study area during the agreed study periods;
- Load and generation dispatch scenarios for the study periods.
- List of credible contingencies which cause transient and/or voltage collapse problems on the network

4.3 Proposed Supplementary Standards

For the purpose of this research, the author realises the consideration of additional requirements to assess and manage the risk of SSR when planning the transmission network. These requirements include:

4.3.1 Design Requirements

The following requirements were developed for transmission network planning and design based on conceptual network analysis established during the research:

A) Series Compensation Design Considerations

1. It is recommended to design the series capacitor to compensate a transmission line up to 70% without compromising SSR stability, if it is connected in parallel with another line.

2. While for a radial series compensated line, it is recommended to design the series capacitor to compensate a transmission line up to 30% without compromising SSR stability. Compensation level beyond 30% result in natural frequency complementary of the natural frequency of the shaft system, refer to Table 2.1 and Equation 2.1

B) HVDC Link Design Consideration

1. This requirement is considered when HVDC is proposed to interconnect two independent sub-systems. The short circuit capacity ratio of the system at the connection point of HVDC is recommended to be between 70%-95%. Figure 4.1 and Equation

4.1 explain the recommended short circuit capacity ratio without compromising SSR stability.

$$UIF = \frac{MVA_{DC}}{MVA_g}\left(1 - \frac{SC_g}{SC_t}\right)^2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4.1$$

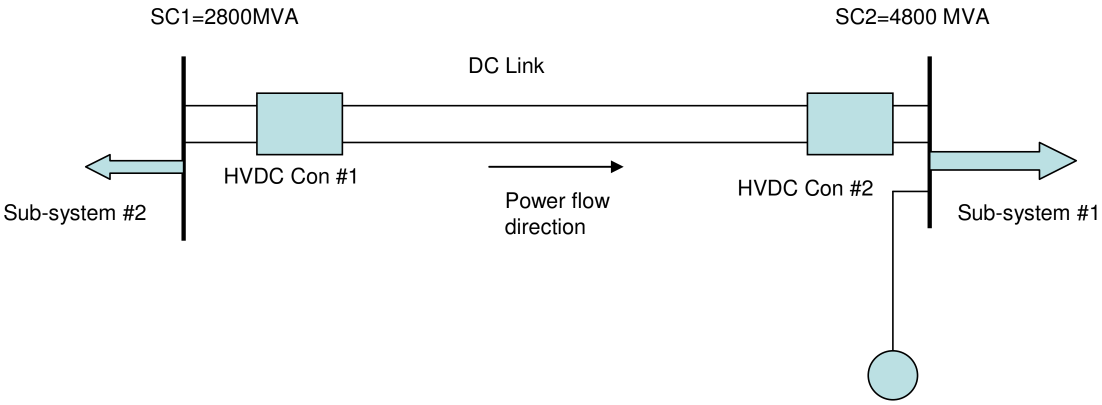

Figure 4.1 Short Circuit Ratio SC1/SC2 is around 70%

2. This requirement is considered when HVDC is proposed to connect remote generation with external system. The power transfer through the HVDC should be constrained to 10% of the generation capacity if the external network short circuit capacity is high (10 times the generation short circuit capacity). If the external network short capacity is low (2 times the generation short circuit capacity), the power flow is constrained to 90% of the generation capacity as shown in Figure 4.2.

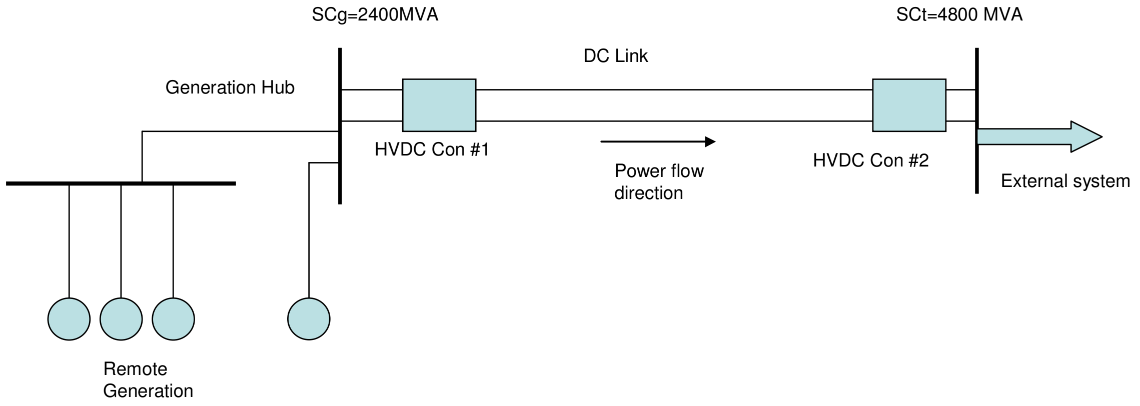

Figure 4.2 Power Flow is Constrained by SSR stability to 90% of the Generation Capacity

4.3.2 SSR performance indicator

The following indicators for assessing the system performance are introduced as supplementary indicators to address the risk of SSR. These performance indicators will be used later in chapter six to investigate new approach for assessing the risk of SSR.

1) If the resistance of the sub synchronous component of the equivalent impedance at the generator neutral point is negative, the risk of SSR problem is possible. The magnitude of the negative resistance is a reference to the growth rate of sub synchronous oscillations.
2) If the percentage reactance dip caused by sub synchronous resonance (percentage difference between the minimum reactance and the maximum reactance at the sub synchronous frequency) is higher than 5%, a subsequent tortional torque at sub synchronous frequency is likely. The severity of the transient torque caused by SSR transient torque is a function of both the percentage dip at sub synchronous frequency and the proximity of the sub synchronous frequency to the 50 Hz complement of the modal frequency. This percentage dip can be reduced by detuning the network equivalent capacitance through a series reactor.

4.3.3 Proposed probabilistic requirements for System Stability

The probabilistic requirements illustrated in Table 4.2 are proposed to assess system's capability to damp sub synchronous oscillation. The frequency of occurrence determines the probability weighting of the contingency which helps negotiating the worst case requirements. High impact low probability contingency have strict requirements

Table 4.2 Proposed probabilistic requirements for system damping

Contingency Type	**%Frequency of Occurrence (p.a)**	**System damping requirements**	
		Halving Time	**Rotor angle deviation**
N-2 Contingency (loss of two transmission elements)	0.01%	2 sec	90 deg
N-1 Contingency (loss of one transmission element)	0.1%	5 sec	180 deg
Generation trip (>400 MW)	10%	5 sec	180 deg
Bulk Load trip (>100 MW)	10%	10 sec	180 deg

5. Chapter Five – Risk Assessment Theory

5.1 Introduction

Power systems nowadays are becoming more complex and system risk cannot be fully avoided. Achieving zero risk in power system would be impractical or not feasible. However, system risk can be reduced to an acceptable level through planning, design, operation and maintenance activities.

At the present, SSR problem is perceived as highly undesirable but of low probability risk. Therefore SSR assessment using deterministic assumptions by considering the worst case scenario only, may lead to overestimating the risk. There are various events or conditions that trigger SSR problem, each event can have different probability weighting. The assessment of SSR risk under various probability weighted scenarios can be an effective way to address SSR problem.

In this chapter, risk analysis techniques and applications in power system are reviewed and presented. The deterministic and probabilistic context of SSR risk is outlined, to establish basis for discussing the SSR risk assessment in chapter six.

5.2 Definition of Risk

Risk in general can be defined either as the impact of a deviation from the expected. Risk can be characterised by reference to potential events and the consequences of an event and the associated likelihood (including change in circumstances and conditions). Risk can also address the impact of uncertainty on the outcome of a process [34].

Risk management can therefore be considered the identification, assessment, and prioritization of risks followed by coordinated and economical application of solutions to minimize, monitor and control the probability and/or impact of unfortunate events or to maximize the realization of opportunities [34].

5.3 Risk Assessment and Treatment

The following outlines the process of risk assessment and management as illustrated as well by Figure 5.1.

5.3.1 Risk Identification

Risk identification is represented by identifying the source of the problem and the event that triggers the problem. There are number of risk identification methods. One method identifies events that endanger a process or achieving project's objectives, while another method identifies the events that trigger undesired conditions or scenario.

5.3.2 Risk Assessment

This activity in risk management, involves understanding of the risk severity and possibility. A risk analysis and evaluation are carried out to quantify the risk and assist in making a decision for treating the risk for making further analysis.

Risk analysis involves consideration of triggers and sources identified for the risk, their consequences and the likelihood and severity of these consequences.

Assumptions and uncertainties in the information and inputs to the analysis are addressed at this stage.

Based on analysis results, an evaluation of the risk is conducted and decision can be made. The evaluation outcome and the decision making may not always lead to treatment of risk in any way other than maintaining existing controls or firming assumption for another analysis. Decisions like that will be influenced by the management attitude and the objectives and criteria of the process.

5.3.3 Risk Treatment

Risk treatment is a cyclical process of assessing the risk after applying treatment measures, deciding whether residual risk levels are acceptable, and assess the effectiveness of the treatment measure.

The options of risk treatment can include risk avoidance measures, remove the risk source, change the likelihood, change the consequence, and retain the risk by informed decision.

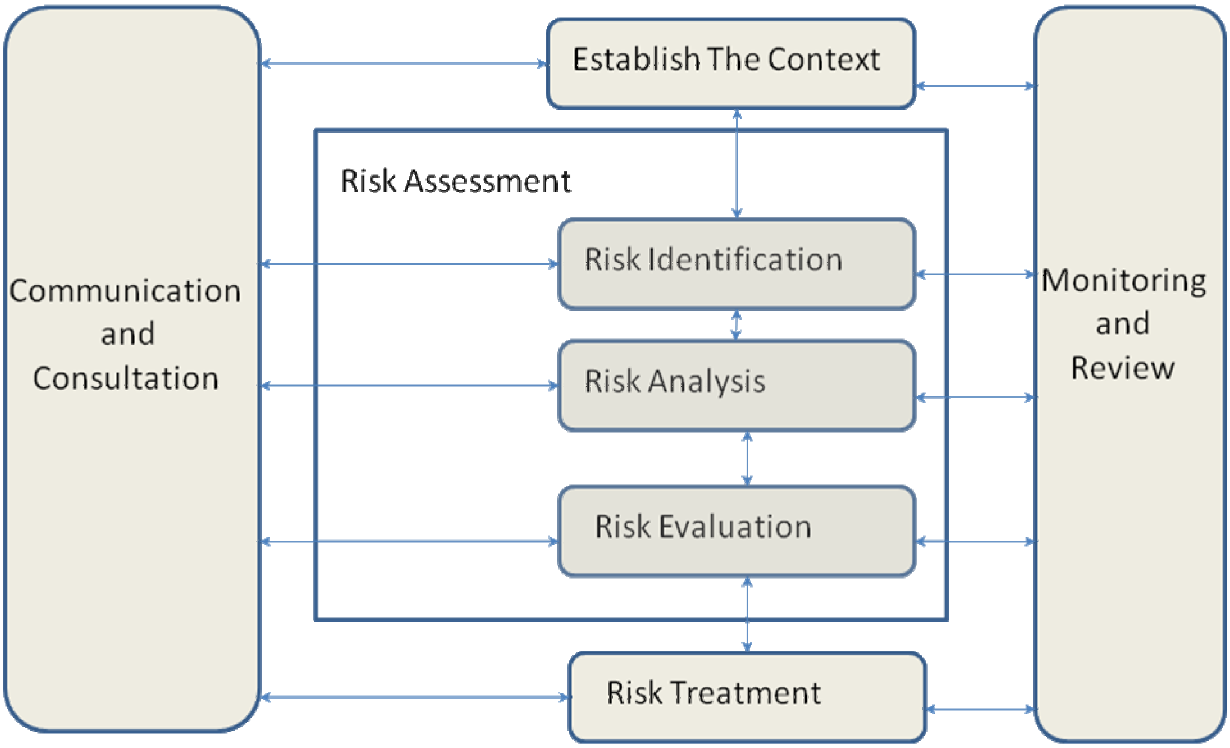

Figure 5.1 Risk Management Framework

5.4 Risk and Power System Planning

As a result of the deregulation of the electricity market and under competitive environment, some utilities tend to plan their networks with a level of risk, by considering the probability weighting of the contingency (N-1). Some utilities plan their networks with lowest risk possible by considering a worst case scenario in a deterministic approach.

Deterministic approach analyses the risk based on worst case scenarios to quantify the worst consequences at the highest possible value. However, deterministic approach may result in a conservative basis for overspent solution with no attempt to address the likelihood of the problem. Yet despite that, many organizations plans and operate using this type of approach due to its simplicity and its ability to address worst case risk.

5.5 Risk of SSR in Power Systems

Some power systems are inherently exposed to the risk of subsynchronous resonance when the central generation are located close to interconnector transmission lines. The constraints of the interconnector are generally defined by a transfer limits between the supply regions at which the system is barely stable.

Lack of reliable reserve capacity within a region may increase the need for power transfer between the regions. As the transfer between the regions will increase in the future, it will be more economical to implement series capacitor than undertaking network re-enforcement. Increasing the utilisation of series compensation will increase the risk of SSR occurrence. It is critically important for transmission utilities to perform detailed investigation of SSR risk when considering new installation of series capacitor or when any network re-enforcement or new connections is planned near the series capacitor installation.

At the present, SSR issue is perceived as high impact, but low probability risk. Most of the utilities and researches address the SSR problem by deterministic approach. The outcome of deterministic considerations may lead to over-investment in the mitigation solutions without taking into account the likelihood of other contingencies.

The SSR countermeasures with network solutions can be very costly, depending on the level of the problem and the level of mitigation they provide. As SSR condition is a probable condition, consideration of firstly, the probability of SSR events occurring and secondly, the consequence impact cost, are recommended to effectively make a decision in investing in countermeasure. This concept will be discussed in details in chapter six.

Other proposed solution is to optimise system variables (e.g compensation level, fault clearance times, generator control tuning etc) to reduce or avoid the risk of SSR. This concept is outlined further in chapter six

6. Chapter Six – New approach for SSR Risk Assessment

6.1 Introduction

A new strategy for assessing SSR is proposed which include two levels of risk assessments, qualitative and quantitative risk assessment. There three attributes to this strategy, the pre-event system states, test criteria and consequence/impacts.

The new proposed strategy can utilise the well know SSR analysis tools and their outcome in an explicit manner to provide a better basis for risk informed decision making in spending for SSR risk management and/or control.

This new strategy proposes a new application of new risk analysis theories to SSR assessment.

The strategy has two focuses. The first is a quantitative risk assessment of SSR instability in an interconnected system. The second type is an optimisation assessment which provides the missing link between the risk assessment outcomes and the appropriate level of risk control, by optimising operating conditions to mitigate the risk, e.g level of series compensation. This kind of assessment is applied by many transmission utilities nowadays to ensure system security and reliability when planning. This approach has been used for transient stability assessments including evaluation of associated operating parameters such as transfer levels between inter-areas, critical fault clearing time, generators controllers gain adjustment, etc.

Despite the uncertainties related to the result of such assessments, a list of proactive decisions can be produced and considered for another round of risk assessment.

6.1.1 Probabilistic Context in Power System's Stability

Deterministic stability criteria have been used traditionally in power system planning and operation for years. Under deterministic criteria, a system is planned and operated to withstand the most extreme system condition. Typically, in such worst case scenario an incredible contingencies such as three phase fault with critical fault clearing times and N-1 or N-2 post contingency scenarios, will be considered. The deterministic criteria have been widely and successfully followed for years in network planning.

However, in a deregulated environment and competition pressure, utilities also needed to adjust the power supply requirements based on customers' expectations which are described as low cost acceptable risk. These objectives can be fulfilled by planning the network with acceptable level of risk based on contingency probabilities.

There are two probabilistic contexts surrounding the power system stability in general:

1) System State Probabilities and Associated SSR Risk

The first can be defined by pre-event system state (network configuration, fault location, protection operation, etc) and the probability of occurrence. This context can be used effectively to quantify systems associated risks in a set of probability indices, taking into account the stochastic nature of the operating condition as well as system component. Identifying these probabilities will give a reasonable probability weighting of the state which leads to SSR instability. These weightings will be used in the consequence analysis to quantify the cost of the consequence/impact. The probability weighting of various system states will be more effective than considering a couple of worst case states for SSR risk assessment. As worst case states may result in onerous quantification of the impact that is unlikely, and it could lead to unnecessary spending (i.e high cost of a countermeasure) or ineffective operation of transmission network (i.e reduce the transfer levels, by-pass existing series compensation).

2) Optimisation of System's Operating Conditions

The second context is realised through a stochastic relation between system state and the system stability. This relation helps to better understand the link between the risk and the consequence. Optimised operating conditions to achieve acceptable risk can be converged at a lower cost, although this could subject the system to operate closely to its constraints. Effective SSR risk control can be achieved through utilising this concept.

6.1.2 SSR Risk Assessment

At the present, SSR is assessed using deterministic approach. When considering SSR, the planning and operation of the transmission system are still based on deterministic assumptions and considerations. The need for SSR countermeasures were decided based on worst case system conditions. Implementing countermeasures to address this kind of risk may not be economically justified by some utilities or generator proponents.

There is a need to determine the justification of the expenditure by performing further risk analysis considering three main factors which are required to be understood and established. These factors include probability of pre-event state of the system/condition, test criteria and the expected consequence/impact. A new strategy was developed to incorporate these three factors to estimate the risk of SSR instability and facilitate a well informed decision of how the risk should be addressed.

6.2 Proposed New Strategy for SSR Risk Assessment

A new strategy was proposed to assist effective structuring of the inputs and the outcomes of SSR analysis, and achieving a meaningful risk assessment. The new strategy involves the following factors:

6.2.1 Pre-event System's State

The state can either be stochastically selected using their probabilities of occurrence. Using the "worst-case" approach to define the system state, may not cover the system critical point because of non-coincidence of network constraints, and other factors. Therefore a probabilistic model is needed to represent probabilities of the system state.

The system states are identified based on the following functions:

Operational function: A short time horizon is considered (hourly, daily or seasonally); few key operating conditions will be selected to pick a system state, including:

a) Network switching modes, load levels, and generation levels

b) Disturbance type, location and duration. This could include network switching event, fault event, step load change event, or a change in system's configuration

Planning function: a long time horizon up to 5 years will be considered. The amount of system state seems enormous, although only few strategic variables such as network configuration change due to future augmentations and demand growth will be considered.

Protection and control operation settings including system protection operation sequence and duration during and after fault clearance, and any possibility of deviation in control settings such as generator AVR controls, SVCs control, series compensation control, generator tripping, etc, can be included to tag the system states and their probabilities.

6.2.2 System State Probability Modelling

The probability modelling for the system state will include a discrete probability distribution of the system conditions, with each level of system factors having a probability value or state. Based on each system state, the power-flow cases will be developed compatible for SSR analysis.

The state sampling approach described in **Appendix B** can be used to randomly establish system states and their probability of occurrence.

6.2.3 Risk Test Criteria

To identify the risk, number of test criteria is required. The criteria can be for two stages. First stage is a qualitative criterion for risk identification. The second is a quantitative criterion for risk quantification.

The two stages of the criteria test are summarised as follows:

<u>Stage One – Qualitative Test – test of the outcome of Frequency Scanning</u>

There is a risk of SSR resonance if the Sub-synchronous resistance of the network equivalent impedance as seen from the study generator neutral, is less than the negative rotor resistance.

Stage Two – Quantitative Test – test of outcome of Eigenvalue & Time Domain Simulation

- *C1 – Network Resistance:* Test of network resistance, high negative network resistance indicates a risk of sustained SSR oscillation.
- *C2 – Damping of SSR mode:* If the negative damping at SSR oscillation mode (n) is 80% of the mechanical damping of the generator-turbine, a risk of SSR instability is possible.

  $\Delta\sigma_n$ =80% of $\sigma_{n(\text{gen-turb})}$

  $\Delta\sigma_n$ is the negative damping of SSR oscillation and σ_n is the generator-turbine mechanical damping for mode n.
- *C3 – Reactance Dip:* If the reactance dip of the equivalent impedance at SSR frequency is equal or greater than 5%, risk of Torque Amplification is high.
- *C4 – Oscillation halving time:* If the halving time of the peak of the SSR oscillation (i.e the time duration from the peak and half of the peak) is greater than 0.5 seconds, a high risk of SSR instability is indicated.

For effective testing, it is proposed to combine the criteria based on the input and the analysis tools. For example, test criteria C1 and C3 are testing outcomes from frequency scanning while criteria C2 is testing outcome from eigenvalue, and criteria C4 is testing outcome of time domain simulation. To combine these criteria, the following logic algorithm is proposed:

C = (C1 or C3) and (C2 or C4)

This algorithm suggests that it is essential to perform frequency scanning and either time domain simulation or eigenvalue analysis. If C equates to zero that doesn’t mean there is no risk, it actually means either inaccurate calculations or misleading system states. If C equates to 1, a consequence (generator trip due to vibration detection, overvoltage trip) is identified and evaluated.

6.2.4 Consequence Analysis

The consequence cost (e.g loss of revenue, restarting cost, etc) is weighed by the probability of the system states that results in C=1. If the probability weighted cost is lower than the mitigation cost, it will be more economical to do nothing with acceptable risk of SSR otherwise mitigation measure should be implemented. Due to unforseen changes in system state, risk of SSR may increase or decrease over the time, resulting in impact cost higher than the cost of the mitigation. Therefore, it is important to run this assessment periodically, every 5-10 years.

6.2.5 Implementation of the proposed strategy

In this section, the implementation of the new strategy is presented. The implementation includes two levels of assessments, the qualitative assessment and the quantitative assessment. The implementation style proposed will enable effective evaluation of the SSR by managing the flow of the network data and the utilisation of SSR analysis tools.

Figure 6.1 shows the implementation of the SSR assessment strategy and the flow of the input data and outcomes.

The assessment under the proposed strategy can be performed at one generation node at a time, in particular a node that is adjacent to strategic interconnectors with series compensation.

After running the frequency scan, the resistance and reactance at frequencies in the sub-synchronous range will be tested by Stage One criteria. If tested satisfactory, the risk index is set very low against that system state without performing state probability weighting. If tested non-satisfactory, then another stage of analysis and testing will be performed on the system state and the preliminary outcomes of the frequency scan.

Meanwhile, a probability weighting of each system state is estimated using either of the three probabilistic weighting methods [35]:

1) **Monte Carlo** which involves a random simulation method to model a wide range of system states,

2) **Frequency-Duration method.** This method uses the anticipated frequency and duration of system states, based on historical data in discrete scenarios.

3) **Billinton method,** the probability of a range of possible system states is derived from the expected probability of forced and planned outages. This method is relatively simple to apply, but does not take into consideration of

the frequency and duration of ‘abnormal’ events and uncertainties of future augmentations.

The consequence impact/cost is estimated based on the cost of the lost revenue (due to generation tripping) and the probability weighting of the system state causing the SSR event. Other impact/costs can be identified by reduction of transfer levels to avoid or mitigate SSR risk levels.

Other extreme impacts such as permanent failure of the generator and fatal cascading failures can have a huge cost. Although, the probability weighting of these impacts can be very low, the weighted cost can still justify mitigation measure. There are other factors that can contribute to the probability of the SSR occurrence apart from the system state. These factors are more to do with generator vulnerability to permanent failure (e.g aging, lack of maintenance) and vulnerability of the network to cascading. The consideration of such factors and extreme impacts are outside the scope of this research work.

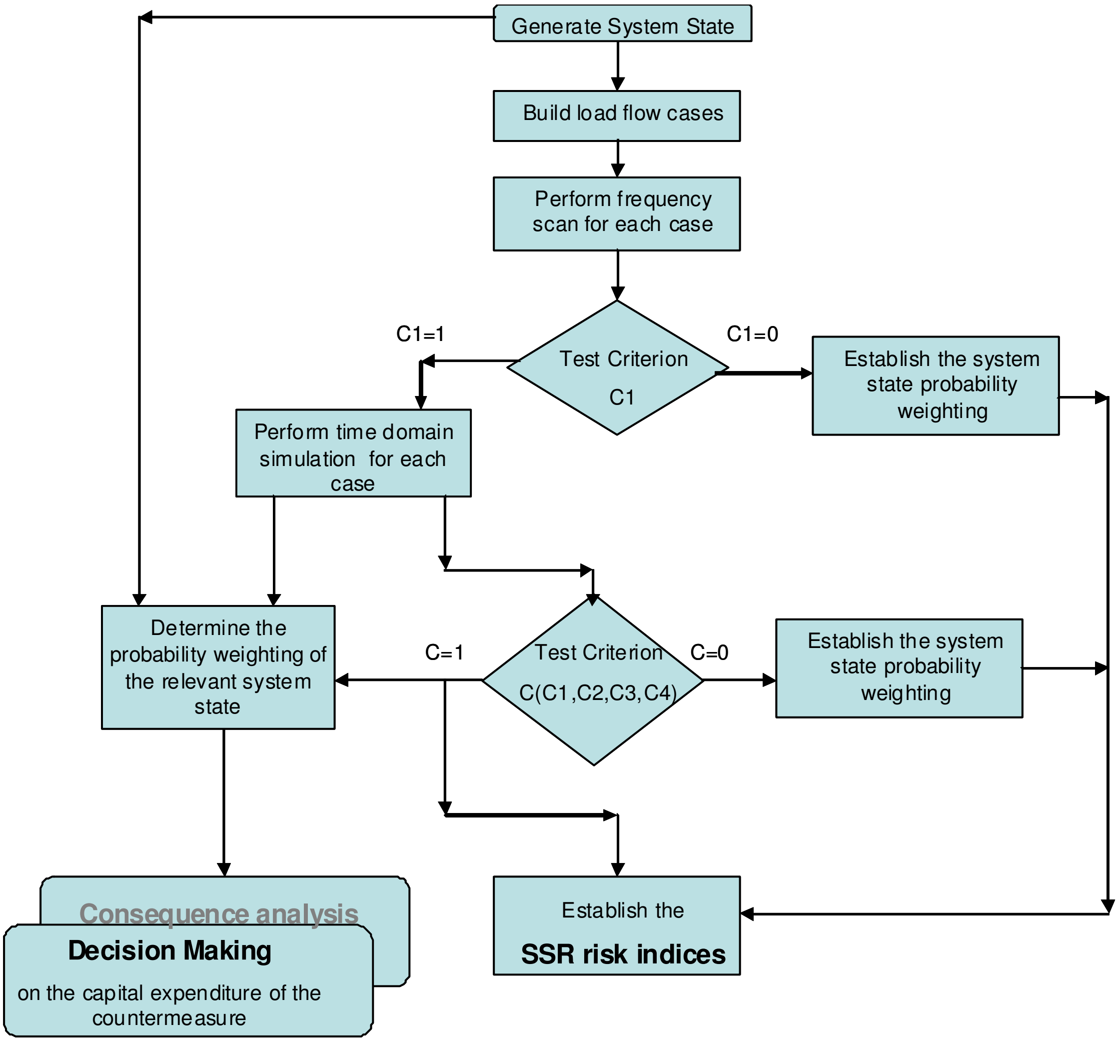

Figure 6.1 – SSR Probabilistic Risk Assessment Procedure

6.2.6 Case Study #1 – Centralised Generation

This actual case study is to demonstrate the SSR risk assessment for centralised generation or any other system that are vulnerable to cascading failure. The actual system of this case study is shown in Figure 6.2. The system includes a series compensated interconnector (interconnector #1) between two independent power systems in Area1 and Area 3. Another interconnector (Interconnector #2) between Area 3 and Area 2 is present. The constraint in interconnector #1 are defined by the transient stability limits of 500 MVA. Area 3 will be the focus of this case study, as the SSR impact is expected to be clearer in Area 3.

The credible contingency that defines the constraint in interconnector #1 is a two phase to ground fault near the interconnector.

The centralised generation include a group of generation plants connected to a collecting system. There are two key switching modes at the centralised generation to manage fault levels namely R0 and R1. There are six key base cases; each case set a level of demand (light, medium and high), generation and import/export through interconnectors. Figure 6.3 presents the detail of the generator plants connection configuration. The generation collector network 220 kV is connected to the rest of the power system through one key bus HWTS 500 kV.

Simple assessment

For this case study, a simple assessment can be performed at HWTS 500 kV, by applying frequency scan at HWTS 500 kV. Figure 6.4 illustrates the frequency spectrum of the network impedance at HWTS 500 kV. Although a few SSR components were detected, it is required to compare the impedance parameters with specific generator parameter. For the purpose of this simple assessment, the nearest generator bus was selected namely LYPS 22 kV#1. The rotor resistance of this generator should be at least lower than the network resistance at the corresponding SSR frequency.

This simple test, however assess only one configuration as a system state, but it is a qualitative indicator of the risk.

If a negative equivalent resistance at the rotor was evident, SSR risk is eminent. For such case, with centralised generation, the impact cost is extremely high. Tripping couple of generators due to SSR, may cause cascaded tripping of the generating system and hence a major blackout. Therefore, it may be meaningless and time consuming to do further risk assessment and probability weighting of the risk to justify a proposed countermeasure such as damper winding, generator control tunning, etc.

There are operational countermeasures, such as re-tunning the generator controls, the optimisation technique discussed in section 5.4 will be helpful to manage and control the risk of SSR without compromising system stability.

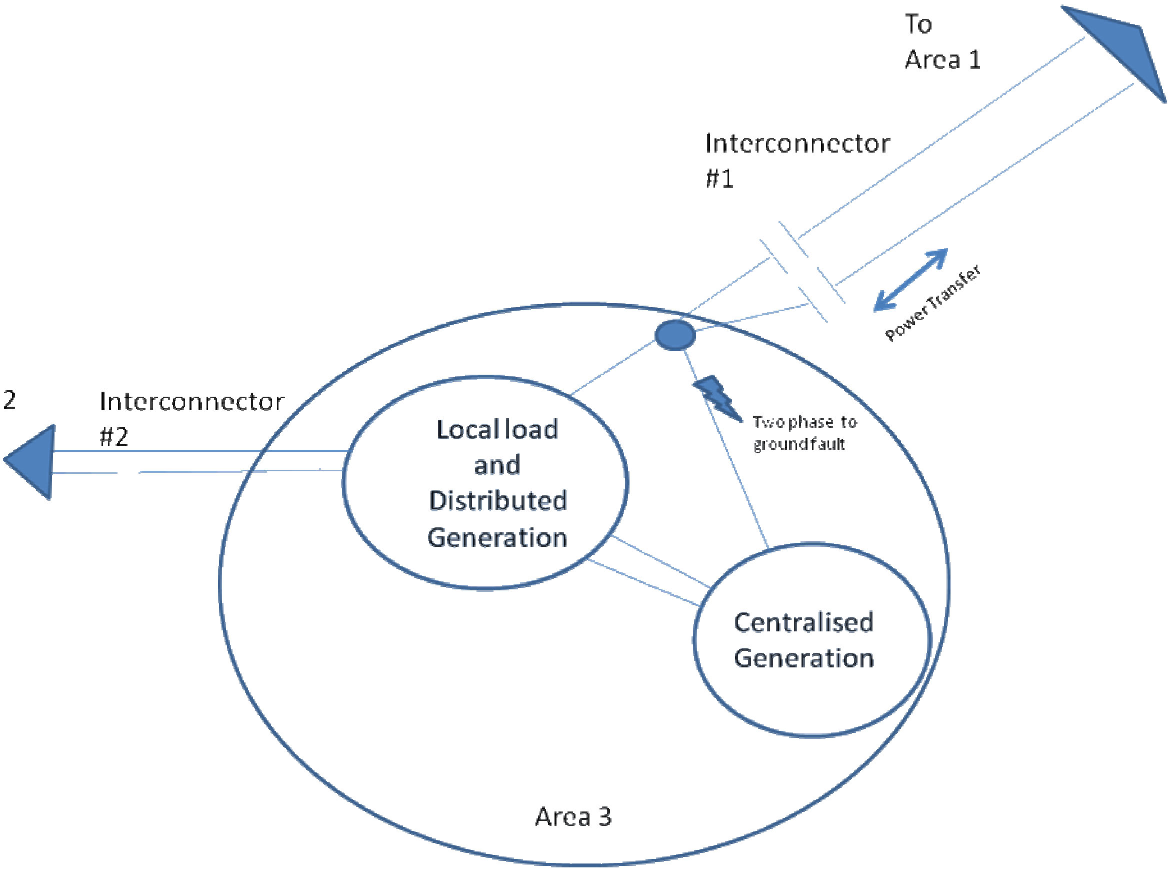

Figure 6.2 Case Study #1 – System Configurations

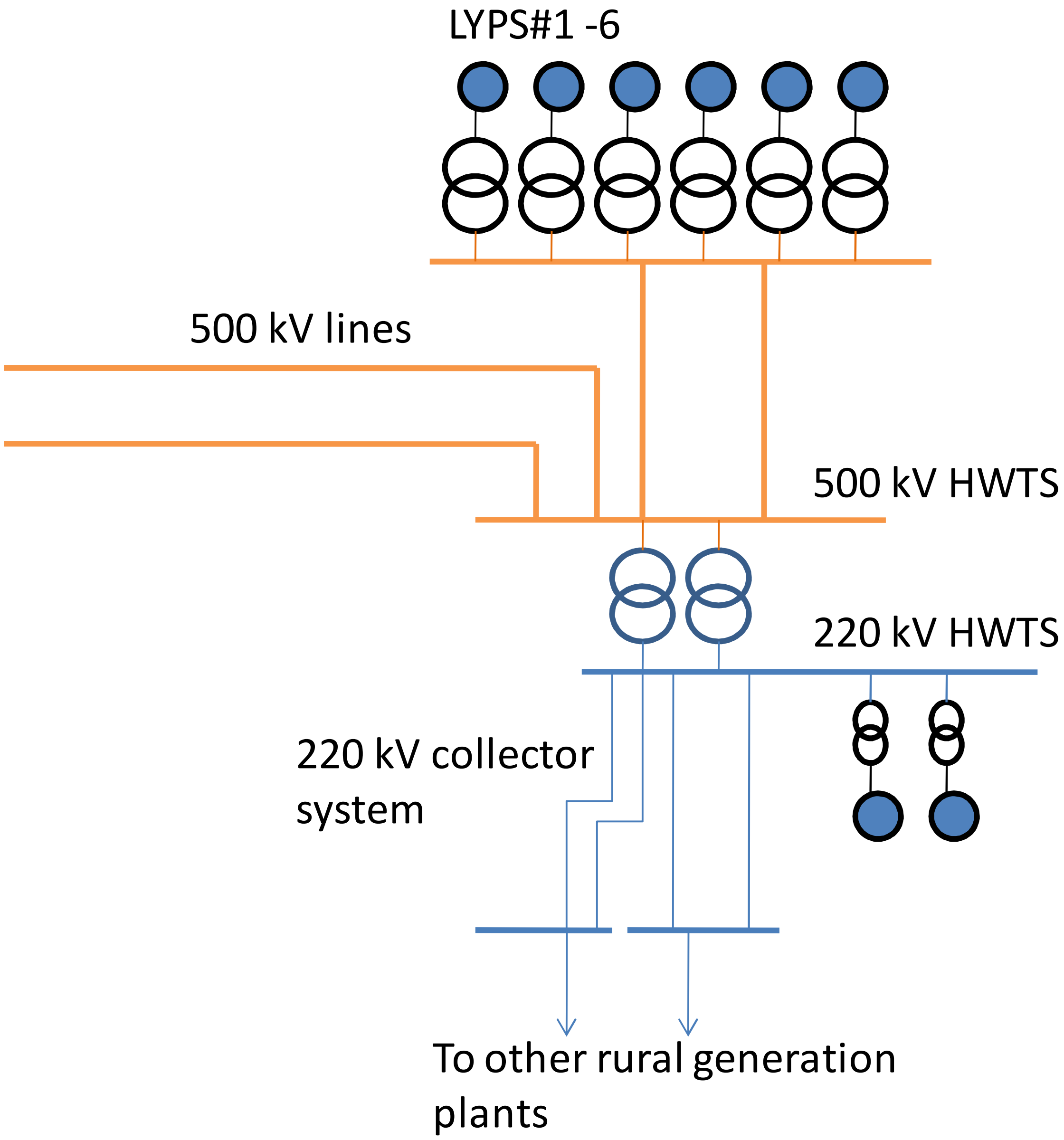

Figure 6.3 Case Study #1 – Central Generation System Configuration

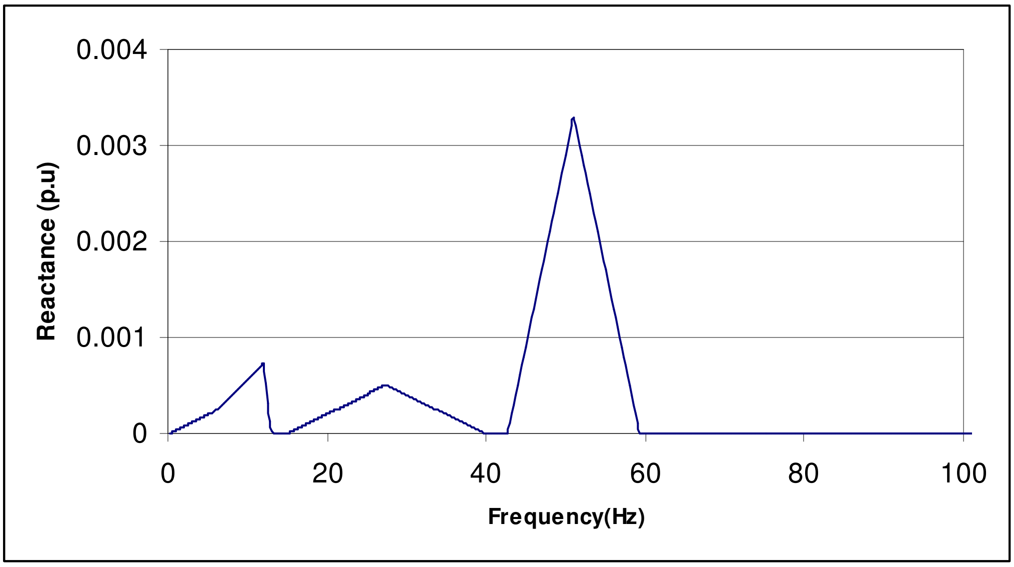

Figure 6.4a Frequency Spectrum of the Network Reactance at 500 kV HWTS

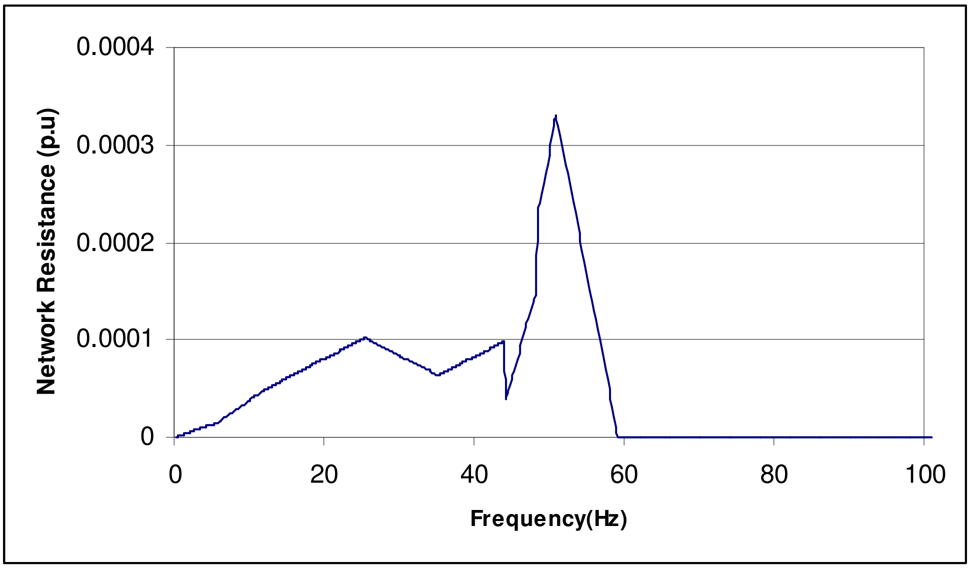

Figure 6.4b Frequency Spectrum of Network Resistance at 500 kV HWTS

6.2.7 Case Study #2 – Decentralised Generation

This actual case study is to demonstrate the SSR risk assessment for decentralised generation plants. Figure 6.5 illustrate the connection of two Combined Cycle Gas Plant (CCG) that are proposed to be connected to 500 kV double line that extends near Interconnector #2. G1 is doubly switched to the 500 kV line while G2 is connected to one of the 500 kV lines. There is numerous future augmentations to be implemented adjacent to the connection points. G1 has an ultimate capacity of 500 MW, while G2 ultimate capacity is 250 MW. Although it seems that series capacitors are far from the connection point, SSR frequencies can be evident under certain possible configurations.

Implementation of New Proposed Technique

Up to 1000 cases can be generated to include most of systems' condition and configurations' probabilities .The probabilities of the system states are weighed using Frequency Duration Method.

The proposed technique and the criteria tests as described in section were applied. Table 6.1 illustrates the probability weighting and SSR criteria test indices.

There is a notable SSR risk under reasonably probable network condition. The impact of this risk would be generation tripping. The consequence will be the loss of revenue for the generator proponent for up to a day. The transmission utility enforced the generator proponent to wear the cost of deep network enforced countermeasure to mitigate the risk. The expenditure would be justified if the cost is lower than the weighted cost of the consequence. Assuming a pool price of $45/MWh and annual capacity factor of 45%, the revenue loss is estimated at $44M per annum. The probability weighted cost is $443k (at 1% probability weighting). This cost is lower than the annualised cost of capital $550k (assuming 7.5% discount factor to annualise the capital of $7.3M for a countermeasure). The capital cost of the countermeasure should be at least equal or less than the weighted cost.

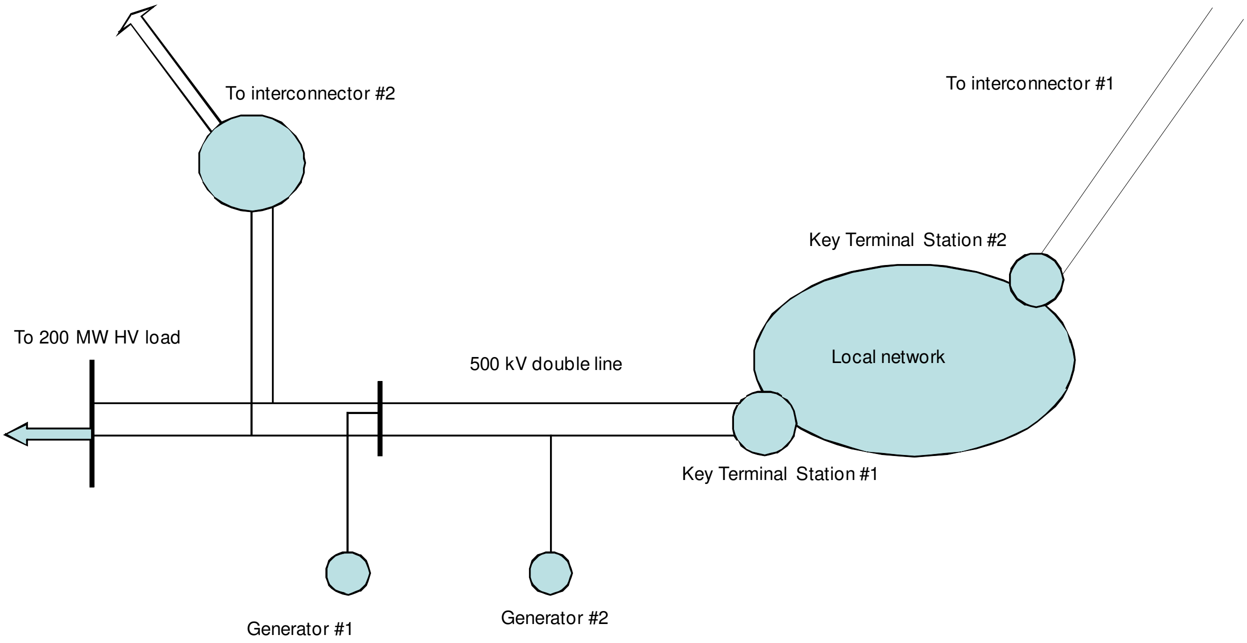

Figure 6.5 Case Study #2 – System's Configuration

Table 6.1 Probability Weighting of SSR System Cases for Case Study #2

System Case	Network Scenarios	Generation Switching Mode	Series Compensation level	Status of C	Probability weighting of System State
1	Scenario 1	R0	fixed	0	not performed
2	Scenario 2	R0	fixed	0	not performed
3	Scenario 3	R0	fixed	0	not performed
4	Scenario 4	R0	fixed	0	not performed
5	Scenario 5	R0	fixed	0	not performed
6	Scenario 6	R0	fixed	0	not performed
7	Scenario 1	R1	fixed	0	not performed
8	Scenario 2	R1	fixed	0	not performed
9	Scenario 3	R1	fixed	0	not performed
10	Scenario 4	R1	fixed	1	15%
11	Scenario 5	R1	fixed	0	not performed
12	Scenario 6	R1	fixed	1	56%

6.3 Optimisation of System’s Parameters

In this section, a technique is briefly outlined to establish a relation between the SSR instability and the system’s specific parameters (e.g series compensation level, AVR gain, critical fault clearing time, etc).

Further, this assessment is proposed for system with identified SSR issue, where system parameters or remedial actions need to be optimised to achieve acceptable SSR risk.

This concept is not new to transmission utilities. AEMO optimise two independent operating parameters to manage the transfer capability at the interconnectors without compromising system’s stability. This optimisation is performed when considering new connection point in the Victorian Transmission Network. The two independent parameters fault clearance times at the connection point and the gain of the excitation control if a generator is to be connected, will be adjusted to maintain the system barely stable at maximum transfer levels at the interconnectors. The optimisation however will involve only transient stability which does not include the SSR issue. So it is worth considering optimisation of series compensation level to achieve barely stable system with respect to SSR instability, through a number of iterations of system analysis for various system states.

7. Chapter Seven - Discussion & Conclusions

Series compensation and HVDC links are network solution to providing supply to remote areas or interconnect new remote generation hub to established network. Nowadays the need for such technologies can also include utility's plan to increase power transfer capability between regions during contingencies due to lack of local reserve within a region. Subsynchronous resonance will become an important network condition to investigate when such technologies are considered.

In chapter one, a review of the modelling, analysis techniques to address SSR condition and SSR countermeasures is carried out. Frequency scanning has proved to be the most practical technique to identify SSR risk due to its rapid application and simplicity of the used system model. Other techniques such as, eigenvalue analysis and time domain simulation, are also used for more thorough analysis. Despite the computation difficulties of the last two methods, they are preferred for the purpose of quantifying the SSR mode and the damping capability of the system, and evaluating effectiveness of the SSR mitigation countermeasure.

The author discussed the disproportion between the cost of SSR mitigation solution and the cost implication of SSR conditions. This disproportion led the utilities to neglect these risks increasing system vulnerability to failure.

In chapter two, a new view of key characteristics of modern power systems is presented. The risk of introducing HVDC and series compensation to power systems can be limited or eliminated by these characteristics:

1) Ability to apply fixed dc current control in a HVDC link will prevent the subsynchronous oscillation.

2) Operating a series capacitor at compensation levels lower than 30% can reduce the risk of SSR. However, a rduction of the compensation levels below 30% could results in decreasing the transfer levels between interconnected areas which may be economically unacceptable. Having a series compensated line in parallel with uncompensated line can extend their compensation levels to 70% without compromising the SSR stability

3) Shunt reactors can change the system's characteristics at low frequency range (below 100 Hz), while shunt capacitor banks will only impact the impedance spectrum at higher frequency range. Therefore, shunt reactors should be given careful considered when performing SSR assessment.

Modelling guidelines have been presented which can assist in selecting the appropriate representation of power components based on the frequency range of the required study. For large scale systems, system simplification is essential when running simulations using software with limited capabilities. A number of guidelines are presented to select system scale appropriate for the frequency range of the study problem. For SSR analysis, it is recommended to have a detailed model of the system.

In chapter three, a continuous model of the TCSC reactance is presented and used for investigating the characteristics for a range of firing angles. At a certain range of firing angle, the TCSC excites series resonance frequencies (below 50 Hz). In order to avoid the resonance conditions at subsynchrounous frequencies, it is recommended to operate the TCSC at firing angle lower than that initial range.

A new application for Time Frequency Distribution (TFD) algorithm for SSR analysis is presented. Through TFD algorithm, the frequency contents can be extracted from the time domain signal without losing reference to the timing of the frequency content ramp-up and decay.

A computation algorithm for eigenvalue calculation is developed based on TFD concept, by capturing the time variation of the frequency component. This technique is dependent on the information obtained from the time domain signal. The benefit of this technique is the ability to identify the oscillatory modes from the time domain response of the system to fault condition. This approach will save the effort taken in modelling complicated system in state space form. A case study was used to illustrate the implementation of the algorithm

In chapter four, a review of existing planning criteria from various utilities was presented with reference to SSR assessment and performance requirements. Most of the utilities consider deterministic requirements to assess the capability of a system for stability. One utility, namely WECC, enforces probabilistic requirements depending on disturbance probability of occurrence and severity of the event. New requirements for the purpose of a quantitative SSR risk assessment are presented in this chapter. The new proposed requirements include design requirements for HVDC link and series compensation to reduce the risk of SSR. The requirements include performance requirements to assess the risk of SSR. Indicative probabilistic requirements for SSR system response was proposed based on probability and severity of contingency event.

The financial challenges facing the utilities put a certain pressure on system planning and operation. Power system nowadays are operated under a certain level of risk, as planning a system to operate at zero risk would be economically not feasible. However, system risk should be managed at an acceptable level without compromising overall system reliability and power quality.

SSR problem was always investigated based on deterministic consideration, on extreme worst case scenario without taking into account the probability of SSR conditions and the cost of the consequence. This has led to overestimating the risk and its cost implications.

In chapter five, a review of risk assessment and treatment concepts is carried out. The deterministic and probabilistic context of SSR risk is outlined in this chapter, to establish basis for discussing the SSR risk assessment in chapter six.

In chapter six, the following conclusions were reached:

1) The worst cases may not be appropriate for SSR risk investigation and economically justification of the mitigation countermeasure

2) Two context are realised in SSR risk, firstly is the probability of system state used for SSR risk assessment and secondly, the ability to optimise system operating conditions to mitigate the risk

3) A new technique is proposed to utilise the analysis tools and input data to assess SSR risk

4) Probability weighted SSR risk can effectively estimate the cost implication of the consequence. A well informed decision can be made when comparing the weighted cost with the cost of mitigation measure.

5) SSR risk can be controlled by optimising system's operating condition to achieve acceptable risk of SSR. This is achieved by establishing a quantitative relationship between the system's constraints and the system's operating conditions.

6) Optimising the system's operating conditions may lead to operating the system near its constraints which results in a higher risk associated to other problems other than SSR.

8. References

[1] P.M. Anderson, B.L.A., J E V, 'Sub-synchronous Resonance in Power Systems', IEEE Press, 1989 Editorial Board, New York

[2] Farmer, R.G., Agrawal, B.L., ' Power System Dynamic Interaction with Turbine-Generators', The Electric Power Engineering Handbook, 1990.

[3] IEEE SSR Working Group, 'Proposed Terms ad Definitions for Subsychroous Resoance',IEEE publication PWR,1981

[4] Subsynchronous Resonance Working Group of the System Dynamic Performance Subcommitee, ' Reader Guide to Subsynchronous Resonance', IEEE Transaction on Power System, Vol. 7, No. 1, February 1992.

[5] Prabha Kundur, Neal J. Balu, Mark G. Lauby, 'Power system stability and control', The EPRI Power System Engineering Series 1994

[6] IEEE Guide for Planning DC Links Terminating at AC Locations Having Low Short-Circuit Capacities, IEEE Std 1204-1997

[7] Kumar, R. ; Harada, A. ; Merkle, M. and Miri, A.M. ; 'Investigation of the influence of series compensation in AC transmission systems on bus connected parallel generating units with respect to subsynchronous resonance', power Tech Conference Proceedings, 2003 IEEE Bologna, June 2003

[8]K S. Smith, L R,'Tortional Resonance Risk Management in Islanded Industrial Power Systems Supplying Large VFDs', IEEE Transactions on Industry applications,VOL 44, NO.6 Nov/Dec 2008

[9] R H, S P, ‘Power Quality and Generator Subsynchronous Oscillation’, 1995 IEEE publication.

[10] NGET/SPT Upgrades Ltd, ‘Sub synchronous Resonance Study for the GB Transmission System’, Sep 2010.

[11]. Alfayoumy, C M ‘ A comperhansive approach for Sub synchronous Resonance screening analysis using frequency scanning technique’, IEEE bologna Power Tech Conference, Bologna, Italy, Jun 2003

[12] Agrawal B, Farmer RG, “Use of Frequency Scanning Techniques for Subsynchronous Resonace Analysis”, IEEE PAS Vol.PAS-98, No.2, March 1979.

[13] Surendra R. Puchalapalli, ,Richard G. Farmer, George G. Karady, John Hernandez, and Yeolkyu Suh,’ Z-Bus Based Frequency Scanning Program for Sub-Synchronous Resonance Screening’, IEEE power delivery, Nov 2007

[14] P. Vuorenpää, T. Rauhala*,* and P. Järventausta, ‘Applying TCSC Frequency Response Data Derived Using Electromagnetic Transient Analysis in SSR Frequency Scanning Studies’, 2009 IEEE Bucharest Power Tech Conference, June 28th - July 2nd, Bucharest, Romania

[15] Nadia Yousif, and Majid Al-Dabbagh, ‘Time-Frequency Distribution Application for Sub-synchronous Resonance Analysis in Power Systems’, Power Engineering Conference, 2005. IPEC 2005. The 7th International

[16] Siemens Energy, ‘Power System Simulator for Engineering PSS/E’

[17] DIgSILENT Pacific Pty Ltd, Power Factory

[18] SSWEIGEN, User’s manual for the computation of eigenvalues and eigenvedm in problems related to power system subsynchronous resonance, Power Math Associates, Inc. Del Mar, CA, 1987

[19] D.J. Vowles, M.J. Gibbard, Mudpack User Manual; Version 10.R, May 2004, Department of Electrical and Electronic Engineering, The University of Adelaide.

[20] H. W. Dommel, "Digital computer solution of electromagnetic transients in single - and multiphase networks," IEEE Trans. Power App. Syst., vol. PAS-88, pp. 388-399, April 1969

[21] G. Gross and M. C. Hall ,'SYNCHRONOUS MACHINE AND TORSIONAL DYNAMICS SIMULATION IN THE COMPUTATION OF ELECTROMAGNETIC TRANSIENTS',IEEE Transactions on Power Apparatus and Systems, Vol. PAS-97, no. 4 July/Aug 1978

[22] Yu Yang , Xiaolin Li, Zilong Mu, Xingyuan Li and Yuhong Wang, 'Rapid Risk Assessment of SSR Caused by Series Capacitors Compensations in Large Power Grid', Power and Energy Engineering Conference (APPEEC), 2010 Asia-Pacific, March 2010

[23] IEEE Subsynchronous Resonance Working Group of the System Dynamic Performance Subcommittee Power System Engineering Committee, 'COUNTERMEASURES TO SUBSYNCHRONOUS RESONANCE PROBLEMS, IEEE Transactions on Power Apparatus and Systems, Vol. PAS-99, No. 5 Sept/Oct 1980

[24] IEEE Committee Report, "Comparison of SSR Calculations and Test Results" IEEE Transactions on Power Svstems, Vol. 4, No. 1, pp. 336-344, February 1989

[25] Midwest Reliability Organization (MRO), Subsynchronous Resonance (SSR) Assessment, Dec 2009

[26] Australian Energy Market Operator (AEMO), 'Assessment of Material Inter-Network Impact', under public consultation, 2006

[27] PowerWater, NT Australia, ‘Planning Criteria – Power Network –Technical Code’, 2006

[28] Western Power, ‘Electricity Transmission Access – Technical requirements’, 2003

[29] Mohammed J. Beshir, SM,’Probabilistic Based Transmission Planning and Operation Criteria Development for the Western Systems Coordinating Council’, 1999 IEEE/PES Summer Meeting Panel Session Reliability Criteria for Transmission System Operation and Planning under Restructuring

[30] Juan A. Martinez, ‘Parameter Determination for Power Systems Transients’, Power Engineering Society General Meeting, 2007, IEEE ,24-28 June 2007

[31] CIGRE WG 33.02, “Guidelines for Representation of Network Elements when Calculating Transients,” CIGRE Brochure 39, 1990.

[32] F. Auger, P. Flandrin, P. Goncalves, ‘Time Frequency Toolbox’, CNRS (France), Rice University (USA), 1995-1996.

[33] L. Cohen, ‘Time-Frequency Distribution-A review’, Proceedings of IEEE,77(7):941-980, 1989.

[34] IEC 31010,:’ Risk Management - Risk Assessment Techniques’

[35] M.Bhavaraju, “Application of Contingency Evaluation Techniques to Practical Systems,” in Reliability Assessment of Composite Generation and Transmission Systems, IEEE 90EH0311-1-PWR, 1990

9. Glossary

AC	Alternating Current
AEMO	Australian Energy Market Operator
ATP	Alternative Transient Program
BPA	Bonneville Power Administration
DC	Direct Current
D-Q	Direct and Quadrate (a form of three phase system)
EMTP	Electromagnetic Transient Program
FACT	Flexible AC Transmission
FFT	Fast Fourier Transform
GB	Great Britain
HP	High pressure
HVDC	High Voltage DC
IEEE	Institution of Electrical and Electronic Engineers
IP	Intermediate Pressure
IRPC	Inter Regional Planning Committee
LP	Low Pressure
MMF	Magnetic Motive Force
NT	Northern Territory
SSO	Sub Synchronous Oscillation
SSR	Subsynchronous Resonance
SVC	Static VAr Compenstator
TCSR	Thyristor Controlled Series Reactor
TFD	Time Frequency Distribution

UIF	Unit Interaction Factor (risk of network interaction)
VSD	Variable Speed Drive
WECC	Western Electricity Coordinating Council

Appendix A – Effective Inductance & Linear System Equations

A1. Effective inductance

To derive the r.m.s of the fundamental component of the TCR current, it is assumed that:

$v_C = \sqrt{2}\cdot V_C \sin(\omega \cdot t)$ ………………………….. (a.1)

Where V_C is the r.m.s value of the capacitor voltage.

$v_C = L \cdot \frac{di_L}{dt}$ ……………………………….... (a.2)

The instantaneous TCR current is:

$i_L = \frac{\sqrt{2}\cdot V_C}{\omega \cdot L}\int_{\alpha}^{t} \sin(\omega \cdot t)$ ……………………..….(a.3)

$= \frac{\sqrt{2}\cdot V_C}{\omega \cdot L}(-\cos(\omega \cdot t) - \cos(\alpha))$ ………… (a.4)

The amplitude of the fundamental component for even functions is:

$a_n = \frac{4}{\pi}\cdot\int_{0}^{\pi} f(t)\cdot\cos(\omega \cdot t)d\omega \cdot t$ ………………(a.5)

Since the TCR current is an even function as shown in Fig. 2, the amplitude of the fundamental component of TCR current is:

$a_n = \frac{4}{\pi}\cdot\frac{\sqrt{2}\cdot V_C}{\omega \cdot L}\int_{0}^{\pi}(-\cos(\omega \cdot t) - \cos(\alpha))\cdot\cos(\omega \cdot t)d\omega \cdot t$ ..(a.6)

$= \frac{\sqrt{2}\cdot V_C}{\omega \cdot L \cdot \pi}(2\pi - 2\alpha + \sin(2\alpha))$ ……(a.8)

Therefore, the r.m.s value of the fundamental component is:

$I_{L_1} = \frac{V_C}{\omega \cdot L \cdot \pi}(2\pi - 2\alpha + \sin(2\alpha))$ ………………(a.9)

$I_{L_1} = \frac{V_C}{\pi \omega L}\cdot(2\pi - 2\alpha + \sin(2\alpha))$ …………………....(a.10)

$$L_{eff} = \frac{V_C}{\omega I_{L_1}} = \frac{\pi \cdot L_1}{(2\pi - 2\alpha + \sin(2\alpha))} \qquad \text{…………......(a.11)}$$

A2. Linear System

$$\dot{X} = A.X + BU$$ ……………………………………..(a.16)

$$Y = CX$$ …………………………………………..(a.17)

$$\begin{bmatrix} \Delta \dot{i}_{line} \\ \Delta \dot{v}_C \end{bmatrix} = \begin{bmatrix} -\frac{R}{L_{line}} & -\frac{1}{L_{line}} \\ \frac{1}{C} & 0 \end{bmatrix} \cdot \begin{bmatrix} \Delta i_{line} \\ \Delta v_C \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{C} \end{bmatrix} \Delta i_{Leff}$$ …..(a.18)

$$Y = \begin{bmatrix} 0 & 1 \end{bmatrix} \begin{bmatrix} \Delta i_{line} \\ \Delta v_C \end{bmatrix}$$ ……..……………………….(a.19)

Appendix B – Probabilistic State Sampling

The Monte Carlo method was used to perform the sampling for a probabilistic reliability assessment. This sampling process which is summarised below is partially proposed to perform the state development for SSR risk assessment:

(a) Generating unit states are modelled using **multiple state random variables**. If generating units do not create different impacts on selected transmission planning alternatives, the generating units can be assumed 100% reliable.

(b) Transmission circuit states are modeled using **two states (up and down) random variables**. For some special transmission components such as HVDC lines, a multiple state random variable can be applied. Weather-related transmission line forced outage frequencies and repair times can be determined using the method of recognizing regional weather effects. Transmission line common cause outages are simulated by separate random numbers.

(c) The bus load uncertainty and correlation are modelled using a correlative normal **distribution random vector**. A tabulating technique of normal distribution sampling and a correlation sampling technique are used to select bus load states.

The most common platform for performing quantitative risk analysis is the spreadsheet model. Many people still unnecessarily use deterministic risk analysis in spreadsheet models when they could easily add Monte Carlo simulation using

@RISK in Excel. @RISK adds new functions to Excel for defining probability distributions and analysing output results. @RISK is also available for Microsoft Project, assessing risks in project schedules and budgets.