ANALYSIS AND MITIGATING OF SUBSYNCHRONOUS RESONANCE IN POWER SYSTEM INTEGRATED WITH PV POWER STATION

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Sravan Kumar Mittapally

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The following faculty members have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirement for the degree of Master of Science, with a major in Electrical Engineering.

Chengzong Pang, Committee Chair

Visvakumar Aravinthan, Committee Member

Krishna Krishnan, Committee Member

DEDICATION

To my family and friends

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I would like to thank my advisor, Dr. Chengzong Pang, for his persistent encouragement and support from the beginning of my Master’s. His guidance during research and writing thesis made it possible to happen.

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ABSTRACT

Conventionally transmission line power transfer capability can be increased by inserting the series compensation into the transmission lines. Though series compensation is an economical solution compared to building a new transmission line, it brings the risk of Sub-Synchronous Resonance in turbine-generator system-based power plants. In literature mitigation of SSR was actively studied using wind turbine generators and FACTS devices, where certain type of WTGs is vulnerable to SSR and FACTS devices are expensive and are not capable to exchange active power with the grid. The structure of PV farms can bring the can bring the capabilities of WTGs and FACTS devices together while addressing their problems at the same time. Among different renewables wind and solar are the fastest growing, according to DOE SunShot initiative studies by 2050 solar serves an estimated 27% of the U.S. electricity needs. The rapid growth in utility connected PV farms has opened new possibilities, and due to its flexibility and dispatchability PV farms can handle the grid support functions more effectively, whereas its ability to mitigate the SSR is rarely investigated.

This thesis addresses the potential of PV Power Station to mitigate SSR problem particularly torque amplification in series compensated systems by augmenting the GSC control loop with damping controller using a control signal which is closely related to the network resonant mode, utility scale PV farms are a promising solution to combat the increasing demand and grid support functions simultaneously. The simulation studies are performed in MATLAB/Simulink software using IEEE Second Benchmark Model (SBM) for SSR studies.

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (continued)

LIST OF ABBREVIATIONS

DFIG	Doubly-Fed Induction Generator
DOE	U.S. Department of Energy
EIA	U.S. Energy Information Administration
FACTS	Flexible Alternating Current Transmission System
GSC	Grid Side Converter
ICS	Input Control Signal
NERC	North American Electric Reliability Corporation
PV	Photovoltaics
SEDC	Supplementary Excitation Damping Controller
SSR	Sub Synchronous Resonance
STATCOM	Static Synchronous Compensator
SVC	Static Var Compensator
VSI	Voltage Source Inverter
WECC	Western Electricity Coordinating Council
WTG	Wind Turbine Generator

CHAPTER 1

INTRODUCTION

1.1 Background

Due to the rapid growing demand, the main consideration of system operators is to meet the demand in a reliable and efficient manner. Transmission demand requirements can be met by constructing new power plants at reasonable distance from load center or increasing the transmission capacity by constructing new transmission lines or enhancing the existing lines. Considering the economic and geographical aspects utilizing the existing line by enhancing is a better solution to meet the requirements. The power transfer capability of existing transmission line can be increased using series compensation. On the other hand, series compensation helps in increasing system stability, reduces line voltage drops and transmission angle and has influence on parallel transmission lines load flows. Even though series compensation has many advantages series compensation brings the risk of SSR problem in the generating units with the rotating masses, more details about SSR will be discussed in the next chapter. At present most of the energy generated using conventional generators such as coal, nuclear, hydro power plants. All these power plants use turbo machinery to drive the generators and are potential candidates at risk of SSR. If the SSR problem is not mitigated it can cause irreparable damage to the conventional generator's shaft system.

1.2 Motivation

SSR problem in a series compensated system can be successfully mitigated by augmenting improvements such as Power System Stabilizers at generating units, enhancing system with FACTS devices or by utilizing utility scale renewable generation. Even though FACTS devices can mitigate SSR problem efficiently, yet they cannot exchange the active power with the grid and are expensive. Whereas the advancement in interfacing converter technology enabled fast exchange of both active and reactive power of renewables with the grid.

EIA studies show that the net-generation from renewables increases at a rate of 2.8%/year from 2015 -2040 and an average of 4.9%/year rise can be seen from non-hydro renewables, of which wind and solar has two-third capacity by 2040. The net power generated by renewables will be equal to power generated by the coal in 2040 which can be seen in Figure 1, which shows significant generation from the renewables in the future. DOE and EIA report shows that power from solar plants increases at a considerable level in the future. With the increased penetration of PV, they can be utilized for the grid support functions. Solar has clear benefits according to the DOE SunShot Vision which includes economic benefits, reduced carbon emissions, increased employment.

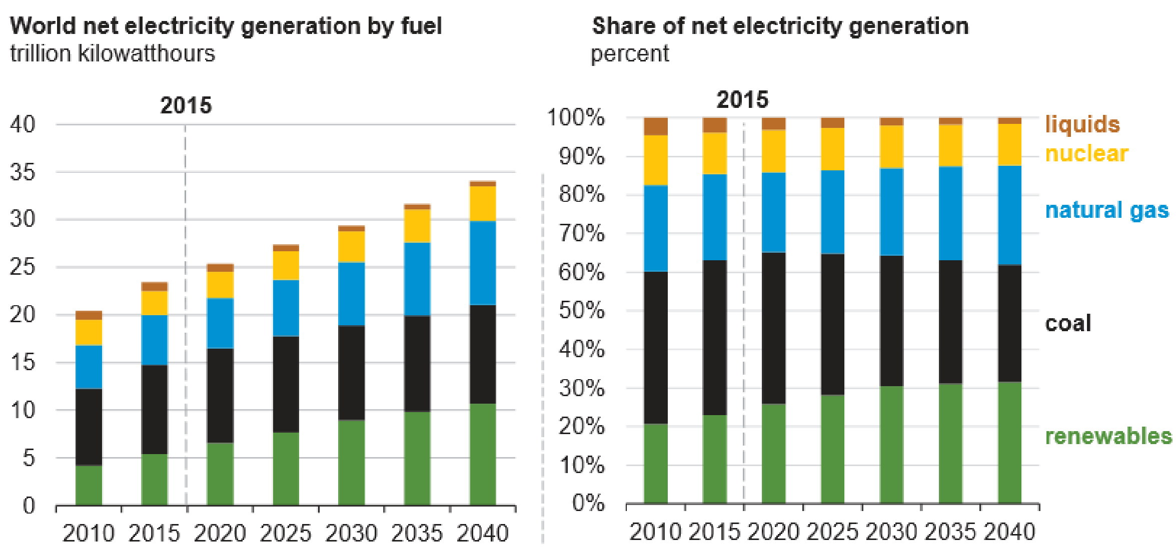


Figure 1. Net Electricity Generation

Recent study by DOE estimates cost of solar decreases between 2010 and 2020, same study estimated that by 2050 solar serves 27% of the U.S. Electricity needs, carbon emissions in 2050 is 28% lower than present emissions and estimated $50 billion in annual savings and 390,000 new solar jobs by 2050. Several large scale solar projects of First Solar such as Topaz Solar Farm (550

MW) in California, Desert Sunlight (550 MW) in California and Agua Caliente Solar Project (290MW) AC PV solar plant are being realized in the recent years. And Agua Caliente solar project, which connected to 500kV transmission can provide support functions like voltage, frequency and power factor regulation and able to control both active and reactive power.

Several authors investigated the mitigation of SSR using WTGs in series compensated systems. Here comes the question can we use utility-scale solar plants for the mitigation of SSR? The effect of utility scale PV farms on grid stability studies was performed by many authors but, its potential to mitigate the SSR was rarely investigated. Solar plant connection to the grid is like the FACTS device STATCOM with an energy source or DFIG grid side connection. PV plant, DFIG and STATCOM has same grid side connection using VSI, Filter and step-up transformer. In literature recent studies using utility scale solar farm were presented and in those studies rotor speed deviation is utilized as control signal. The main aim of thesis is to check whether capacitor voltage can be used as a control signal or not.

1.3 Objectives and Outline

The main objective focused in this study is whether a grid-connected large-scale PV farm can mitigate the torque amplification in a synchronous generator connected to a series compensated line using the capacitor voltage as the input control signal by utilizing a simple proportional controller in the GSC of the PV farm and to evaluate how controller is performing at different compensation levels of the series compensation.

Chapter 2 presents what is SSR? and what are the different types of SSR can arise during normal and abnormal conditions in the system and various techniques applied to mitigate the SSR problem in series compensated line by using the FACTS controllers, type-3 and type-4 WTGs by considering various control signal and by combination of the above devices. Also presents the recent studies conducted utilizing PV farms for solving SSR problem applying rotor speed deviation as the input control signal.

Chapter 3 describes the methodology of connecting the PV farm to grid and the IEEE Second Benchmark Model used in this system for studying the torque amplification and explains the damping controller used for the mitigation of SSR in turbine generator system. MATLAB/SIMULINK is used for simulation purposes.

Chapter 4 illustrates the torque amplifications at different compensation levels for the second benchmark model and evaluates the effectiveness of the damping control using FFT analysis.

Finally, Chapter 5 presents the conclusions and future work.

CHAPTER 2

LITERATURE REVIEW

This chapter focuses on explaining the Sub Synchronous Resonance Phenomenon and types of SSR problems that could affect the system. Later the counter measures for SSR problem were discussed in detail.

2.1 Sub Synchronous Resonance

"Subsynchronous Resonance is an electric power system condition where the electric network exchanges energy with a turbine generator at one or more of the natural frequencies of the combined system below the synchronous frequency of the system."

2.1.1 Classification of SSR

A. Self-excitation

i. Induction Generator Effect

The natural frequencies which are less than the system nominal frequency is termed as subsynchronous frequencies which is given by,

$$f_o - f_m \tag{2.1}$$

The electrical resonance frequency f_{er} of a series compensated line is given by,

$$f_{er} = f_o\sqrt{\frac{x_C}{x" + x_T + x_E}} \tag{2.2}$$

Where, x_C is reactance of series compensation

x_T is leakage reactance of transformer

x_E is inductive reactance

$x"$ is subtransient reactance of transformer

f_o is system nominal frequency

Induction generator effect can be seen in a machine when it is viewed as an induction machine from the armature terminals at the subsynchronous frequency. The slip of the machine is negative when the speed of the rotor (N_r) is greater than speed of rotating mmf (N_m) produced by the armature currents at the subsynchronous frequency.

$$S = \frac{N_m - N_r}{N_m} \tag{2.3}$$

Where N_r is always greater than N_m at subsynchronous frequencies

The sum of resistance of the armature and network is less than the magnitude of negative resistance as viewed from armature, i.e. the resistance of generator is less than the armature and networks resistance.

ii. Torsional Interactions

At torsional mode frequencies f_m generator rotor oscillations induce armature voltage components at frequencies f_{em} which are super synchronous frequencies $(f_o + f_m)$ or subsynchronous frequencies $(f_o - f_m)$ given by,

$$f_{em} = f_o \pm f_m \tag{2.4}$$

Torsional interaction is the interaction between the electrical systems and mechanical systems at the subsynchronous frequency f_{em} which is close to electrical resonant frequency f_{er}.

The generator shaft experiences much more effect due to torsional interaction compared to induction generator effect.

B. Transient Torques

Transient torques are the generator rotor oscillatory torques excited due to system disturbances caused by switching in the network. In general, transient electrical torque has many components of which some are unidirectional in nature, some are exponentially decaying with time and the important oscillatory torques ranging from subsynchronous to multiples of the system natural frequency. The amplitude of transient torques produced by the subsynchronous components following a system disturbance was very high, but these torques will decay eventually. The high amplitude torques produces significant amount of stress and strain on the shaft system which progresses to a permanent structural damage and at each occurrence the cumulative damage reduces the shaft life. Once the damage reaches its threshold value crack will initiate at high stress and propagates into irreversible damage and breaks eventually.

[1] presents the analysis of SSR in power systems and detailed the interactions with different power system equipment and it is explained that linearized models cannot be used for analysis of transient SSR which is used for study of steady state SSR, the reason behind this is that transient problems are the effect of large disturbances like faults and capacitor reinsertions. The system model is non-linear in nature and requires the complete system simulations which uses special simulation programs.

2.2 Countermeasures

With the ever-growing demand, the main consideration of system operators is to meet the demand in a reliable and efficient manner. Transmission demand requirements can be met by constructing new power plants at reasonable distance from load center or increasing the transmission capacity by constructing new transmission lines or enhancing the existing lines. Considering the economic and geographical aspects utilizing the existing line by enhancing is a better solution to meet the requirements. One of the basic and most economical solution for increasing transmission capacity is by introducing series compensation, which increases the system stability and helps in damping the torsional oscillations in the system [2] The series compensation can be introduced using schemes [3] like fixed capacitors, thyristor-controlled capacitors. Although series compensation is an economic solution with advantages, it brings the risk of Sub-Synchronous Resonance to the system. In the following section various counter measures in use were explained.

2.2.1 Conventional

The SSR problem can be solved or mitigated by conventional counter measures [1] like system planning considerations, filtering schemes and damping schemes. System planning considerations such as adding series and/or shunt compensation at the initial stage, turbine-generator modifications are not feasible for long term because of future growth, system modifications, series capacitor protection and reinsertion, can be done by bypassing or coordinating the capacitor banks in the system but, it requires proper spark gap setting for successful reinsertion. Filtering schemes utilizes Static Blocking Filters (SBF) and bypass damping filters, where SBF provides solution to both steady state torque and transient torque problems and has less affect due to system changes but they require much space and high insulation levels. On the other hand, Bypass Damping Filters helps in induction generator but are very expensive. Damping Schemes such as supplemental excitation damping control (SEDC) is utilized at Navajo as main counter measure for SSR problem as a supplement to blocking filters, NGH damping scheme is a passive scheme which requires no feedback signal and effective for both steady state and transient problems but, SEDC is required to overcome undamping of off tune torsional modes. Finally, Dynamic stabilizers can compensate subsynchronous currents due to resonance by generating required current however this scheme is useful only when rotor oscillations present in the system. There are various countermeasures for mitigation and elimination of SSR problem [4] with their own pros and cons, this can be done using sensor data from mechanical and electrical signals for SSR monitoring [5]. Whereas in this study the series compensation voltage is utilized as control signal, requires no additional schemes for damping the SSR problem.

2.2.2 Facts Devices

FACTS devices involve the application of power electronic controllers in ac transmission system. There are several controllers available in market such as SVC, TCSC, STATCOM, SSSC and UPFC, these controllers can be utilized to enhance system oscillatory response and in the mitigation of SSR problem in a series compensated transmission system. These devices can be connected as series element, shunt element and combination of both series and shunt. FACTS device like TCSC can mitigate the SSR without any feedback control signal, where as other devices can damp the IG effect and TI effect by supplementing with a supplementary damping controller [4], [5], [6] by proper coordination and design. FACTS devices can be used in enhancing the performance of series connected windfarms. Devices like SVC is used for the dynamic support of the reactive power [7]. The constraints and control variables associated with FACTS controllers is in Table 1.

Table 1. Constraints and control variables associated with FACTS Controllers [1] [8]

	Controller	Constraint Equation	Control Variable
1	SVC	$e_s = 0, i_p = jB_{SVC}V_p$	B_{SVC}
2	TCSC	$i_p = 0, e_s = jX_{TCSC}I_s$	X_{TCSC}
4	STATCOM Without energy source	$e_s = 0, Re\left[V_p i_p^*\right] = 0$	i_{pr}
5	STATCOM With energy source	$e_s = 0$	i_{pa}, i_{pr}
7	SSSC With energy source	$i_p = 0$	e_{sr}, e_{sa}

The main problem associated with the FACTS controllers was they are very expensive and requires an additional energy source to control active power, whereas renewables can support the system by active and reactive power control using the power electronic converters [8] in the GSC. Utilization of renewables can overcome the active power short coming of FACTS devices.

2.2.3 Renewables

The ability of fast exchange of both active and reactive powers with the grid makes wind and solar as potential candidates for mitigating SSR problem. Wind and Solar are the dominant renewable sources with great potential, both systems utilize VSC based system for interfacing with the grid. Reshaping the output characteristics such as output impedance [9] or output admittance [10] of VSC based systems alone can damp the SSR problem.

Most of the wind farms use Type-3 or Type-4 wind turbine generators in the present trend, where both Type-3 and Type-4 utilize back to back converters for interfacing with the grid. Significant study was conducted to mitigate the SSR in nearby wind turbines by modifying the control structure of back to back converters in DFIG based windfarms [11], [12] by utilizing rotor speed deviation as the control signal. Other input control signals such as series capacitor voltage, transmission line power and current were also studied to find the optimal input control signal, in both the papers [13] and [14], studies concluded that series capacitor voltage has the optimal performance in mitigating the SSR. Even though wind turbines helps in mitigating SSR problem they are prone to risk of SSR because wind turbines utilize rotating systems like the conventional generators, when these WTGs connected to a series compensated line they can lead to subsynchronous oscillations (SSO) which is explained based on commonly used Nyquist stability criterion by Fan et.al [15] and based on impedance model by Miao [16].

WECC working group develops the generic models of variable generation for grid studies, which also provides the generic modeling guidelines for Wind plant. It suggests that using Type-3 and Type-4 grid side converter model yields satisfactory in PV-farm based grid studies. According to the report by NERC on variable generation, both PV and Type-4 WTG has similar electrical interfacing structure, connected to grid using VSC [17].

Unlike the wind turbines, PV farms are immune to the risk of SSR due to no moving parts, over the years many papers studied the effect of large scale photovoltaics penetration effect on power system oscillatory stability, Shah et.al [18] used POD based minimax linear quadratic Gaussian method [19] on New England-New York test system for investigation. But mitigation of SSR was not given much attention due to less presence of utility scale PV farms, recent high penetration of large scale PV farms into the grid opened new opportunities in exploring utility scale PV farms for mitigation of SSR. Recently effect of PV farms in SSR mitigation was investigated [20], [21] to alleviate the SSR problem utilizing rotor speed deviation as the ICS, where WAMS based approach is used in one and novel [17] technique PV-STATCOM used to alleviate SSR in other respectively. Most of the studies utilized speed deviation as the input control signal for damping SSO which only provides sufficient details about rotor oscillations of single turbine generator. So, to achieve better performance utilizing control signal which only contains common mode component of oscillation and control signal closely related to the series compensation itself seems to be more effective. In this study capacitor voltage is utilized as control signal for SSR damping controller to mitigate the SSR problem in grid connected with PV power station.

CHAPTER 3

MITIGATING SSR IN GRID CONNECTED WITH PV POWER STATION

Utilizing Wind turbine generators in the mitigation of SSR problem was studied in many papers mentioned in the literature. However, utilizing PV farms is rarely investigated and recently it started attracting due to large scale utility integration of PV based generation in the recent years. This chapter is focused in detailing integration of PV farms with the grid for the mitigation of SSR problem in series compensated synchronous generator.

3.1 Study System

In this chapter the focus is on the system considered to mitigate the SSR and particularly torque amplification, IEEE second benchmark model is used for the study. The mechanical system synchronous generator consists of four spring-mass system: high pressure turbine (HP), low pressure turbine (LP), generator (GEN) and exciter (EXC). The system consists a single generator of 600 MVA connected to an infinite system all the details of the system are given in Appendix-A. the Figure 2 shows IEEE-SBM used in the study.

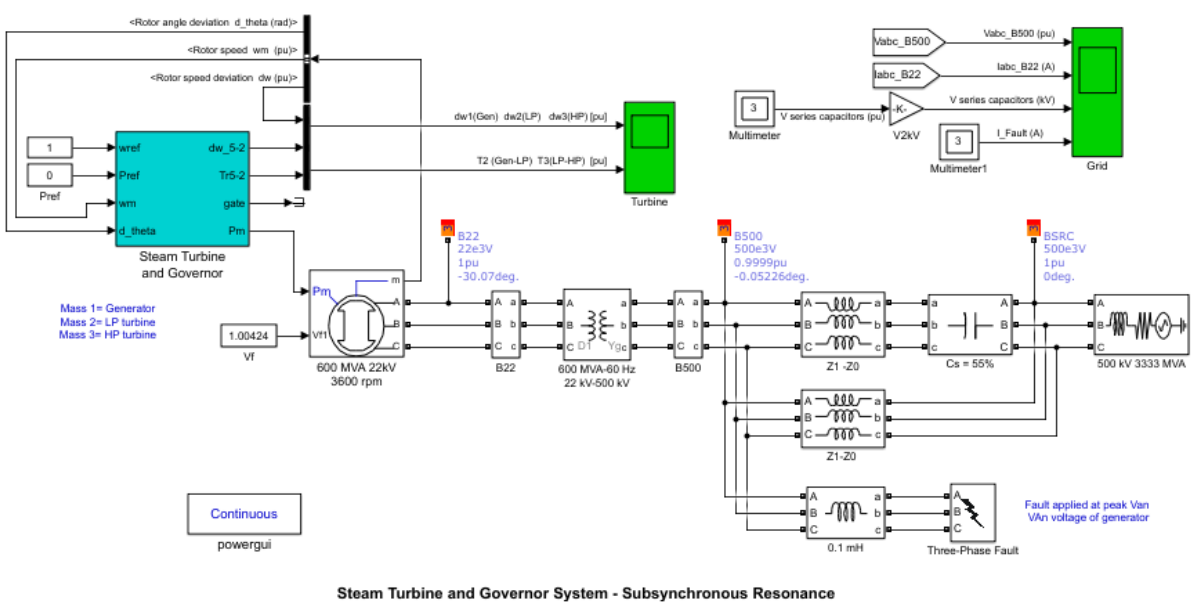


Figure 2. IEEE- Second Benchmark Model

In this study IEEE-SBM is modified by connecting the PV farm. In most of the practical situations it is very hard to build PV very close to the existing generating units so in this study PV farm is placed at the mid-point on the transmission line with the series capacitive compensation, where complete series compensation is placed on one side of the line as shown in Figure 3. All the simulations were performed in the MATLAB/Simulink, using the IEEE SBM Simulink model shown in the Figure 2. The PV is connected at point of interconnection as shown in Figure 3.

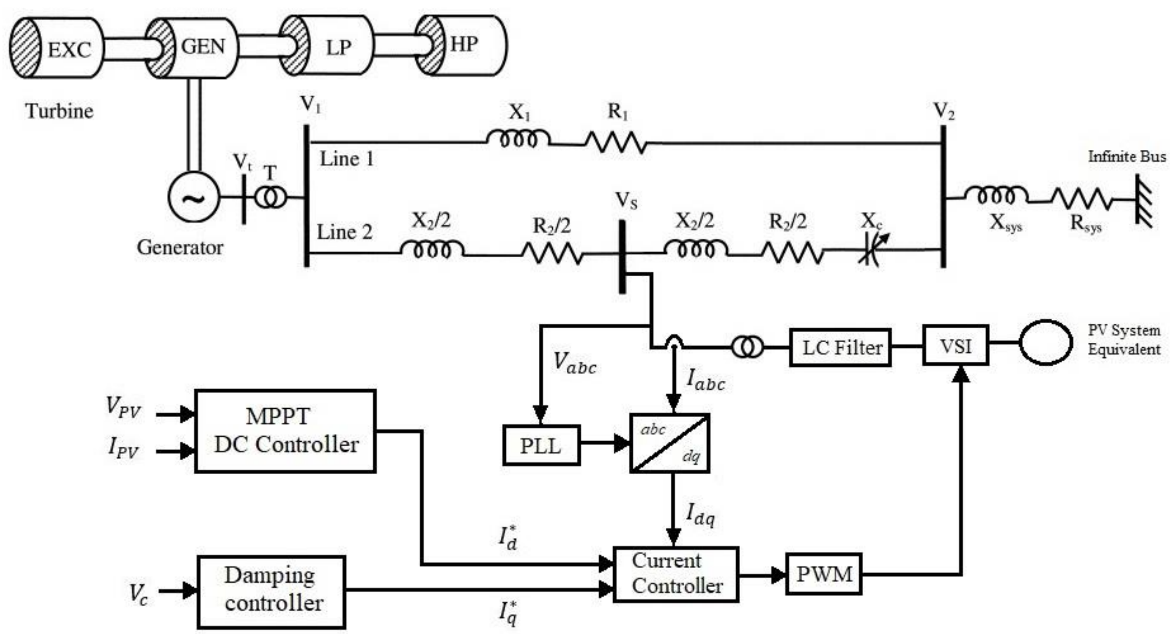


Figure 3. Single Line Diagram with PV Connected at Mid-point of Line-2

According to WECC one of the key assumption that should be incorporated for Central PV system model was ignoring dynamics related to DC side of inverter, which includes dynamics of PV array, DC link and Voltage regulator. The aggregated PV system equivalent and VSI used in this study rated at 50MW.

For bulk system level transient stability simulations, the representation shown in Figure 4 is sufficient.

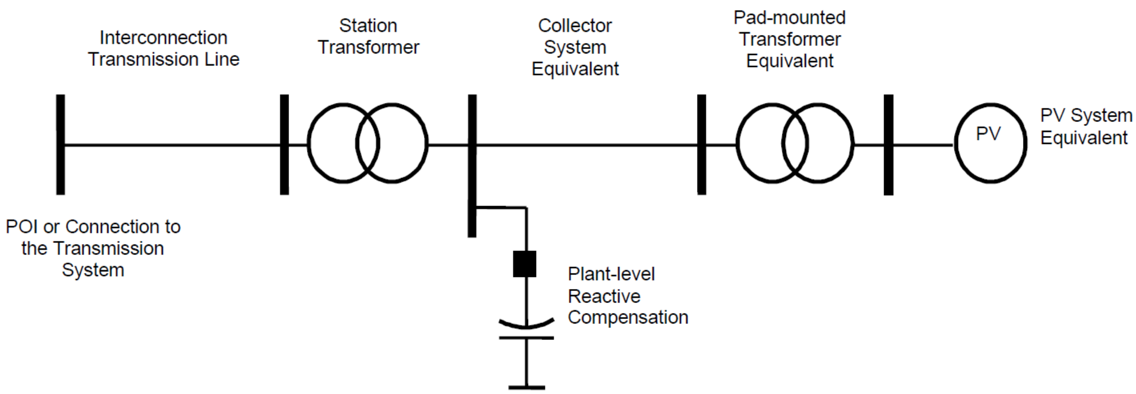


Figure 4. Single Machine Equivalent Load Flow Representation According to WECC [8]

3.2 PV Technology

In this study PV farm uses single diode model and the classification of PV systems is based on power capacity, they are classified as following [22]:

- P < 50 kW small scale
- 50 kW < P < 1 MW Medium scale
- P > 1 MW utility scale

3.2.1 Single Diode Model

I-V curve of a cell or module or array can be defined by the equivalent circuit model as shown in Figure 5,

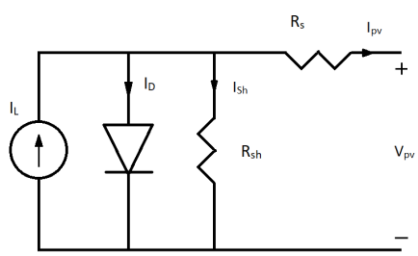


Figure 5. Single Diode Model with Shunt Resistor

Applying Kirchhoff's current law, the current equation can be written as

$$I_{pv} = I_L - I_D - I_{sh} \tag{3.1}$$

$$I_D = I_0 \left[exp\left(\frac{V+I_{pv}R_s}{\eta V_T}\right) - 1\right] \tag{3.2}$$

$$I_{sh} = \frac{V+I_{pv}R_s}{R_{sh}} \tag{3.3}$$

$$V_T = \frac{kT_c}{q} \tag{3.4}$$

$$I_{array} = N_p * I_{module},\ I_{module} = I_{cell} \tag{3.5}$$

$$V_{array} = V_{module} = N_s * V_{cell} \tag{3.6}$$

The amount of current of PV cell is given by,

$$I_{pv} = I_L - I_0 \left[exp\left(\frac{V+I_{pv}R_s}{\eta V_T}\right) - 1\right] - \frac{V+I_{pv}R_s}{R_{sh}} \tag{3.7}$$

Where,

- I_L: light current (Amps)
- I_0: diode reverse saturation current (Amps)
- R_s: Series resistance (Ω)
- R_{sh}: Series resistance (Ω)
- η : Ideality factor
- V_T : thermal voltage
- k: Boltzmann's constant
- q : elementary charge

$$I_M = I_L - I_0 \left[exp\left(\frac{V_M+I_M N_s R_s}{\eta N_s V_T}\right) - 1\right] - \frac{V_M+I_M N_s R_s}{N_s R_{sh}} \tag{3.8}$$

PV array size can be aggregated to any size by using the N_s, N_p coefficients and PV cell model, it is adjustable and flexible to simulate power outputs from watts to megawatts range. The aggregation of single cell model is valid only when the irradiation and cell temperature are uniformly distributed. The N_s and N_p represents number of cell connected in series and parallel respectively.

The output characteristics of PV are represented by the current-voltage (I-V) and power-voltage (P-V) curves. The characteristics shown in Figure 8 and Figure 9 for irradiance at STC which is 1000 W/m^2 and temperatures 25^oC in red and 45^oC in grey.

3.2.2 I-V and P-V Characteristics

The knee of I-V characteristics shown in Figure 6 represents the values of current and voltage at Maximum Power Point.

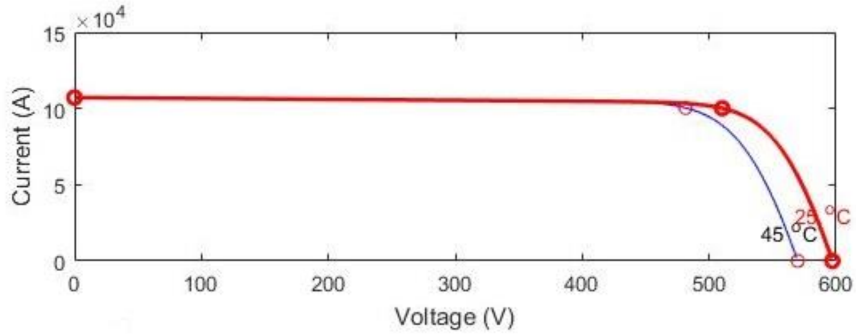


Figure 6. I-V Characteristics

The Maximum Power Point is clearly shown in the P-V characteristics at the irradiance at STC which is 1000 W/m^2 and temperatures 25^oC in red and 45^oC in grey.

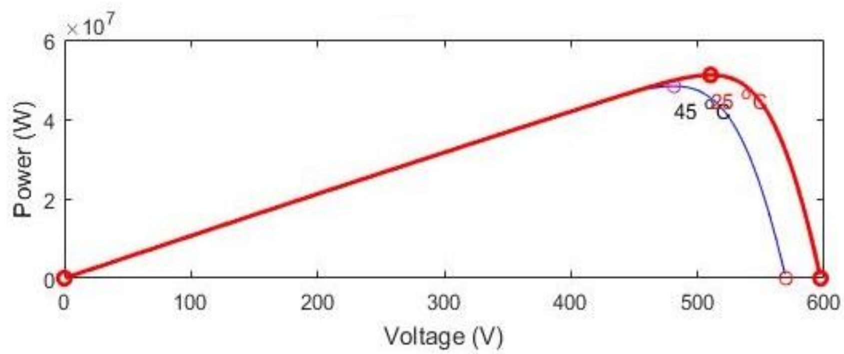


Figure 7. P-V Characteristics

3.2.3 Interfacing with The Grid

PV systems requires power electronic converters for interfacing with the grid, in general they use current source inverters and voltage source inverters for interfacing purposes. There are different topologies available in market for PV-grid interconnection such as two stage conversion, single stage conversion systems.

The PV arrays will be connected across PV-link in two stage conversion system, the two-stage conversion system was shown in Figure 8. In the two-stage conversion system the MPPT function was performed by the DC-DC conversion stage, which allows to maintain a desired voltage levels at the DC link.

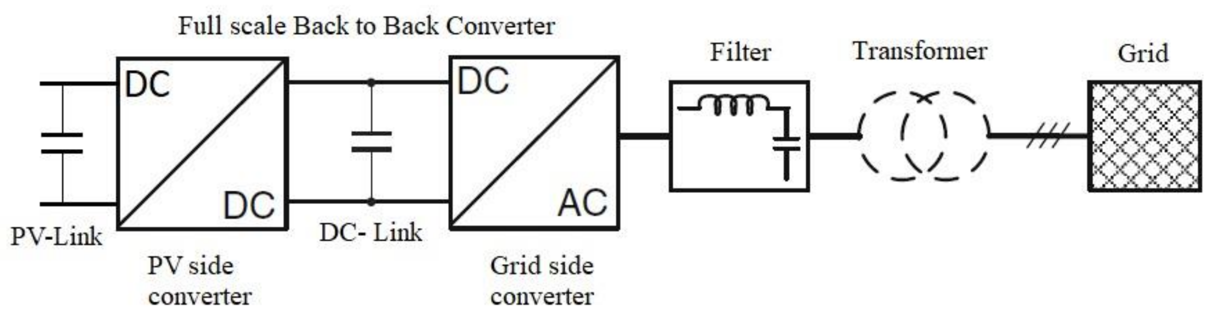


Figure 8. Two Stage Conversion System

Whereas the PV is connected across DC link in single stage conversion system as shown in Figure 9. The single stage conversion system is simple and has high conversion efficiency compared to the two-stage conversion system. In the single stage conversion system, GSC undertakes the MPPT and grid interconnection functions itself. In this study single stage conversion system shown in Figure 9, is adopted because of its advantages and as we are ignoring the DC side dynamics of inverter in Central PV system model.

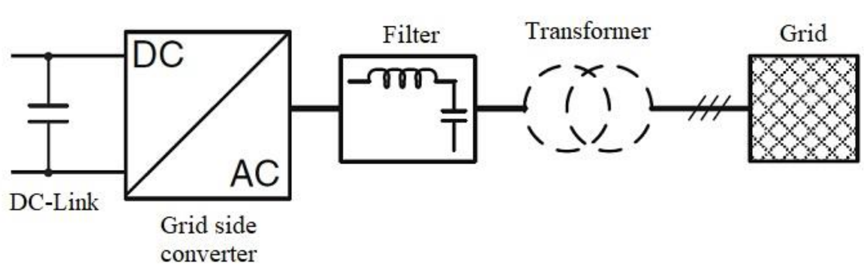


Figure 9. Single Stage Conversion System

The control of three phase PV-inverters can be realized by using one of the three available reference frames, which are synchronous rotating or dq reference frame, stationary or αβ reference frame and natural or abc reference frame. In this study dq- reference frame is utilized, and injected current is synchronized with grid voltage using the state-of-the-art Phase Locked Loop (PLL) technique.

In VSI applications LC filters are used to mitigate the harmonics in output voltage signal, the parameters of LC filter can be calculated using the following equations (3.9) and (3.10) below,

$$L_g \frac{di_{Lg}}{dt} = v_{ab} - v_{Load} \tag{3.9}$$

$$C_g \frac{dv_{Load}}{dt} = i_{Lg} - \frac{v_{Load}}{R_{Load}} \tag{3.10}$$

A. Inverter Control

In the single stage conversion system DC/AC converter stage is considered as GSC. One of the major control function of GSC is DC voltage regulation. Grid-connected functions are also implemented to control the GSC, which includes anti-islanding during unnecessary conditions, regulation of power factor etc.

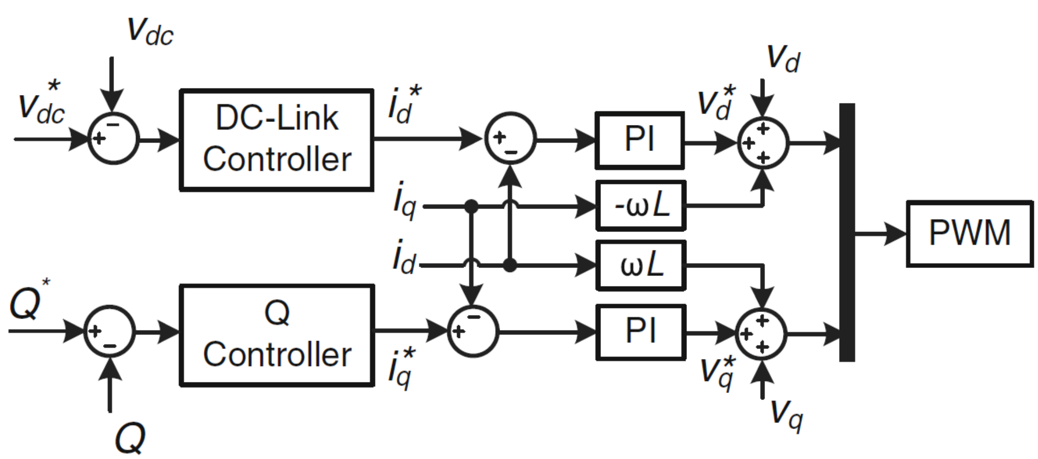


Figure 10. Inverter Control in Synchronous Frame

The reference DC-link voltage $Vdc^*$was generated by the MPPT algorithm, in this study MPPT utilize perturb and observe algorithm to generates the Vdc^* and the reactive power reference Q^* was set to 0. Pulse Width Modulation technique is used to generate the inverter pulses.

The control loop in synchronous frame is formed by two different control loops; 1. Outer control loop and 2. Inner control loop, both the control loops are explained in the following sections.

i. Outer Control Loop

The outer control loop of the GSC generates the synchronous frame d-axis current reference I_d^* and q- axis current reference I_q^*. The outer loop is also known as voltage or power control loop, which includes the DC-link controller which determines the active power injected into the grid and damping controller determines the reactive power. The outer control loop is as shown in Figure 11. In this study the Q controller in the outer loop is replaced with the damping to generate the q-axis current reference.

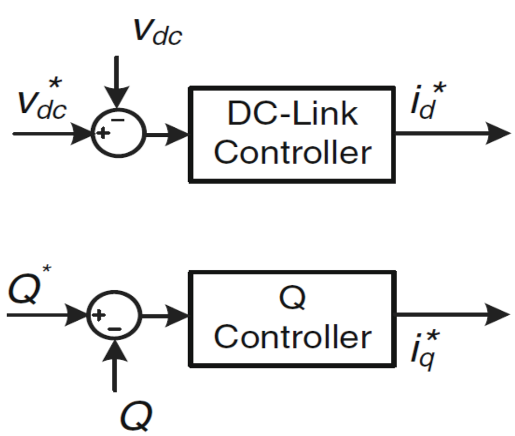


Figure 11. Outer Control Loop

ii. Inner Control Loop

The inner current control loop is responsible for power quality issues and inverter current protection, which plays a key role in the design of current controllers and filters. The d-axis current reference generated by the DC voltage controller and q-axis current reference generated by the damping controller using capacitor voltage as the input control signal are the inputs for current controller. The reference d-axis and q-axis currents are compared with the measured ac side d-axis and q-axis currents and then processed using the PI controller to generate the d-axis and q-axis voltage references. The generated reference signals are augmented with the feedforward signal and then normalized with the converter ac side signal to generate the modulation index. The modulation is used to generate the converter references and later compared with carrier wave to generate the PWM pulses. Both the PI controllers in the control loop are identical.

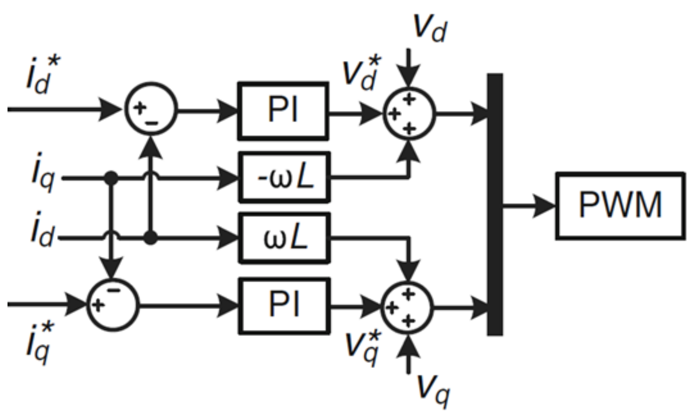


Figure 12. Inner Control Loop

B. DC Voltage Controller

In this study the dc voltage reference is generated by the MPPT controller using the perturb and observe algorithm, the obtained reference is compared with the measured dc-link voltage to generate the error signal. The dc voltage controller utilizes the nominal DC voltage to normalize the generated error signal then it uses PI controller to process the signal and generates the d-axis current reference required for the inner current control loop.

3.3 Damping Controller

The proposed technique utilizes a simple proportional gain controller with a washout filter, the washout filter is used as a high pass filter, which rejects dc and very low frequencies from the input control signal. The washout filter time constant has a significant effect on the SSR damping. In this study voltage across series capacitor is utilized as the control signal for damping controller to mitigate the SSR problem, the main reason to choose capacitor voltage as control signal because it doesn't depend on any individual Turbine-Generator (T-G) set and the other concern in the deregulated market all the generators may not be ready to provide the information about the rotor oscillations of the T-G set to the competitors, but the system operator can provide information about series capacitor voltage to the concerned parties, who are at the risk of SSR problem and to the parties who can mitigate the problem at a competitive price. The literature review has couple of papers which utilized voltage across series capacitor as the input control signal, but they studied the effect of this signal in case of DFIG to alleviate the SSR due to self- excitation, to the best of my knowledge this is the first attempt to use capacitor voltage as the control signal for large scale PV for SSR mitigation particularly torque amplification studies.

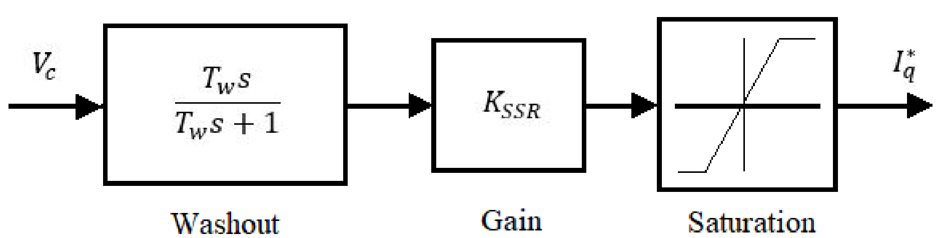


Figure 13. Damping Controller

The control signal can be applied at different locations in the outer control loop and the inner control loop, in this study the control signal is applied at q-axis current reference I_q^*. The quadrature current reference has a direct impact on the reactive power of the PV farm. The structure of PV farm is similar to STATCOM with energy source, where control variables are both d-axis current and q-axis current.

As the main aim of the study is to check whether the voltage across the series capacitor can be used as an input control signal or not? To verify the effectiveness of the capacitor voltage as input control signal for damping controller, it is tested by simulating cases such as different levels of compensation and different fault clearing times.

CHAPTER 4

RESULTS AND DISCUSSIONS

In this chapter the results were presented for three different case studies using different compensation levels, the three cases are base case, PV farm without control and PV farm with control. Finally analyzed whether the damping controller can mitigate the SSR problem particularly torque amplification or not? to study the torque amplification, a balanced three phase fault is applied at the bus close to the 600 MVA generator in IEEE-Second Benchmark Model in all the cases. The fault begins at t=1s and cleared after 75ms in this study, the responses depicts the oscillations of generator (GEN), low-pressure turbine (LP) and high-pressure turbine (HP) turbines, torque amplification of shafts between GEN-LP and LP-HP turbines.

4.1 Base Case

Before going in detail let us understand which compensation levels leads to undamped rotor speed deviation and pu torque in the base system applied with the same fault at the same

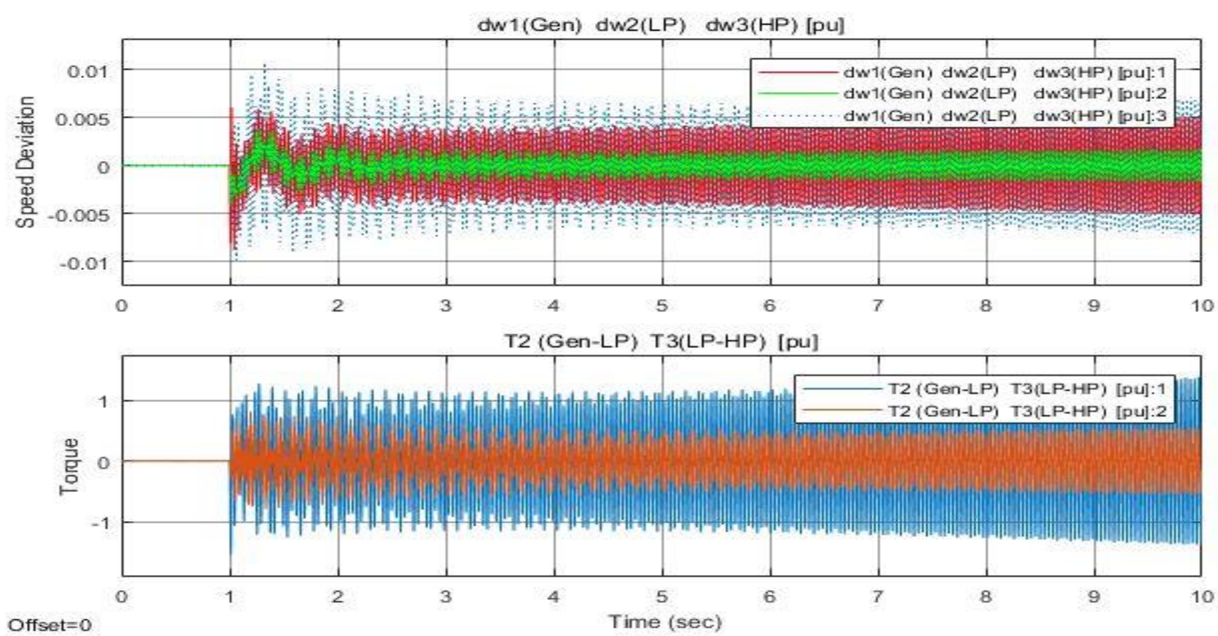


Figure 14. Base Case Speed Deviation and Torque at 45% Compensation

location for the following compensation levels 15%, 30%, 45%, 50%, 55%, 70% and 85%. In the base case all the simulations were carried out for 10s-time period.

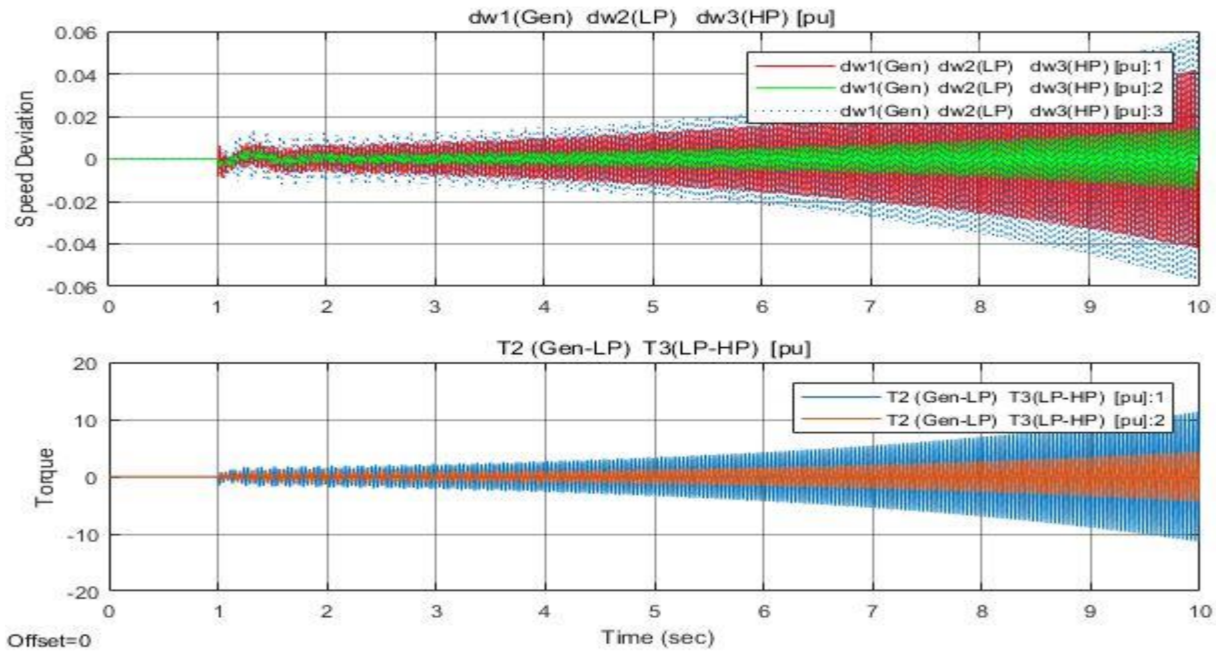


Figure 15. Base Case Speed Deviation and Torque at 50% Compensation

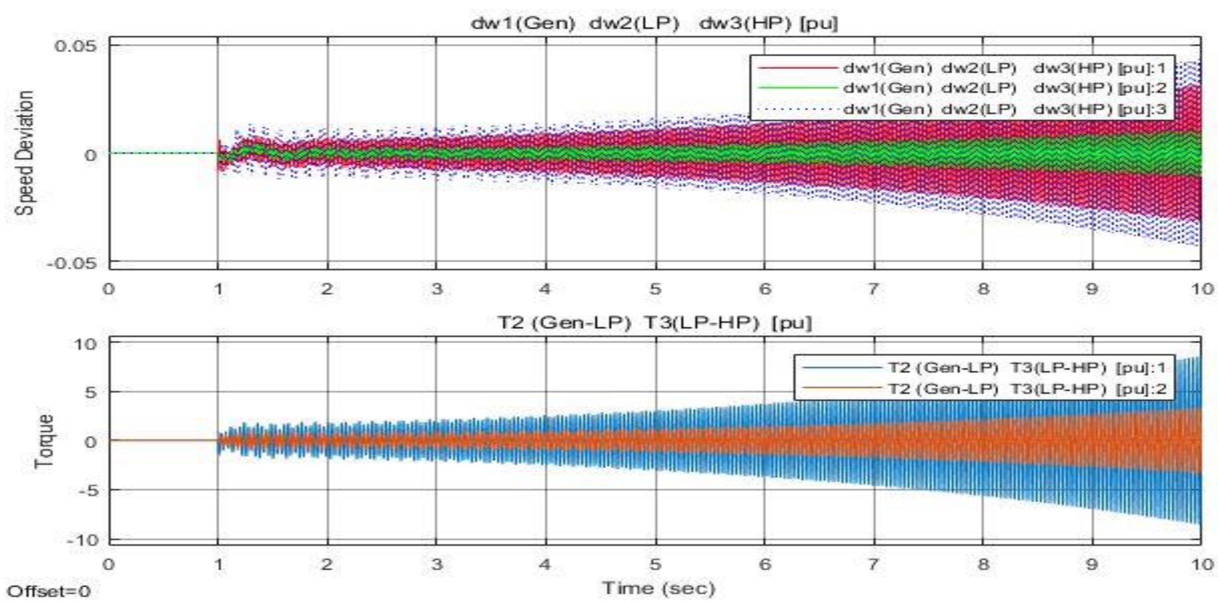


Figure 16. Base Case Speed Deviation and Torque at 55% Compensation

In the simulated responses it is observed that the speed deviations of generator, low-pressure turbine and high-pressure turbine and torque between GEN-LP and LP-HP is reducing in the systems with series compensation levels 15%. 30%, 70% and 85%, where as in case of the system with the following series compensation levels 45%, 50% and 55%, the pu torque is increasing rapidly, which clearly breaks the shaft in no time. For the above compensation levels, the system destabilizes due to SSR problem, the system requires supplemental damping controller to mitigate the torque amplification in the system.

In the following sections we mainly concentrate on the series compensation levels that have undamped torque amplification, because only at certain compensation levels the electrical system resonates with the mechanical system, which leads to unstable condition in the system. In the literature different techniques were applied such as PSS at generators, FACTS devices [4], [5], [6] and [7] and utilized DFIG based systems [15], [16], [11], [12], [13], [14]to mitigate the SSR problem. In this study the focus is applying utility scale PV farm based renewable energy source for damping SSR problem. Due to rapid growth of utility scale PV farms at a comparable rate to other sources at transmission level, they can offer services offered by FACTS devices in more cost-effective way.

4.2 PV Farm Without Control

In this case the IEEE-SBM is modified by connecting the PV farm at the midpoint of the transmission line with series compensation and in the later sections it is referred as the modified IEEE-SBM for convenience. In this case the same balanced three phase fault is applied as in previous case at t=1s and cleared after 75ms duration, at the following compensation levels 45%, 50% and 55% compensation levels.

It is observed that modifying the IEEE-SBM by connecting the utility scale PV improved the positive damping to some extent, but this is not sufficient to incapacitate the subsynchronous oscillations completely. It can also be seen that the PV farm alone has observable effect in case of 45% compensation level, but in the systems with 50% and 55% compensation levels, the amplitude of the rotor oscillations was continuously increasing with time, though the pu torque is

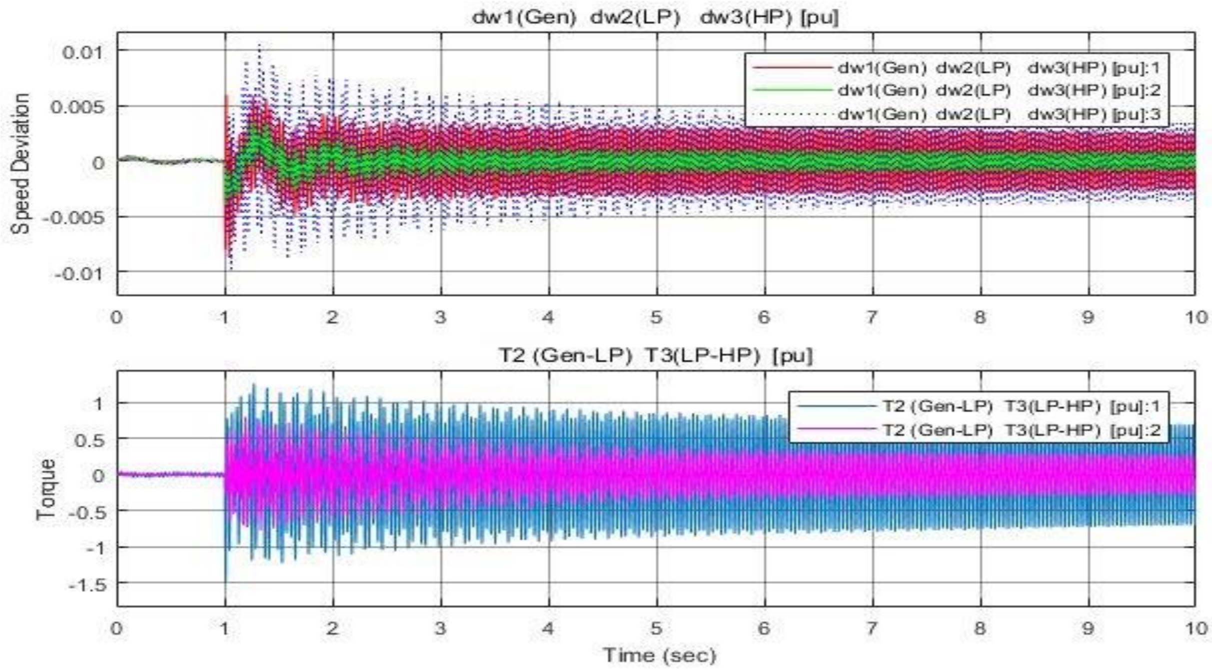


Figure 17. Modified Case Speed Deviation and Torque at 45% Compensation

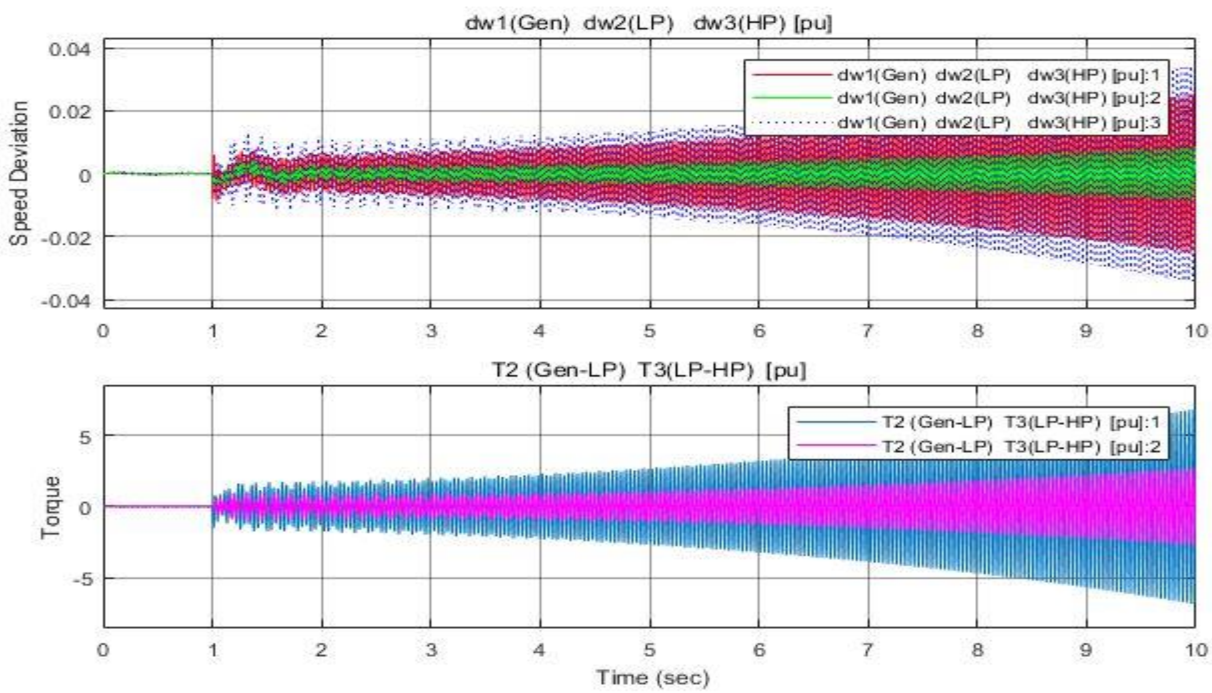


Figure 18. Modified Case Speed Deviation and Torque at 50% Compensation

reduced compared to the base case it is still not a desired condition. Therefore, the modified IEEE-

SBM was supplemented with a damping control to alleviate the SSR problem completely at all the compensation levels.

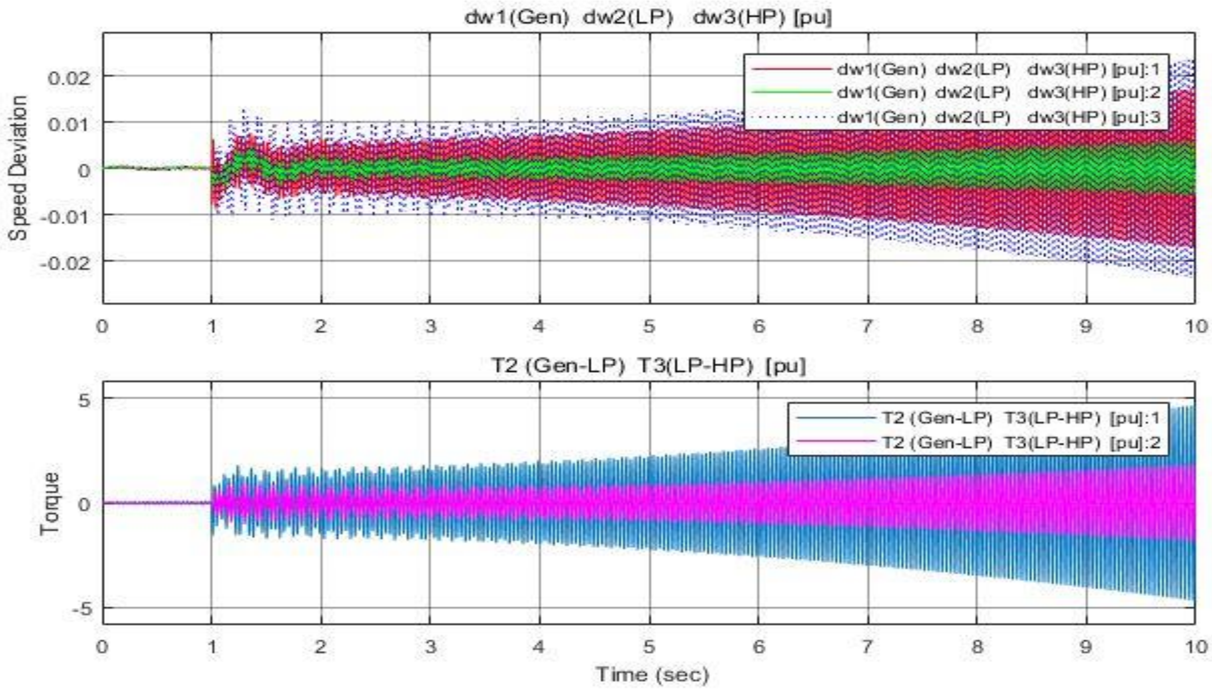


Figure 19. Modified Case Speed Deviation and Torque at 55% Compensation

Advancement in grid interfacing structure enabled integration of large scale PV farms to the grid. Flexibility and fast dispatchability of PV farms helps in grid supporting functions but, it can be clearly observed from the above responses that PV farms requires an external supplementing damping controller for mitigation of SSR problem effectively. In the following case PV is supplemented with damping controller to realize the mitigation of SSR problem emerged with the use of series compensation.

4.3 PV Farm With Control

It is clear from the above illustrated responses that the system will become unstable due to SSR in both cases mentioned previously. To improve the system response in this case, the modified IEEE-SBM is augmented with the damping controller in the GSC current control loop of the PV farm for mitigating the SSR problem. But for the damping controller, the control signal should closely have related to the main cause of the problem for effective mitigation. In this case series

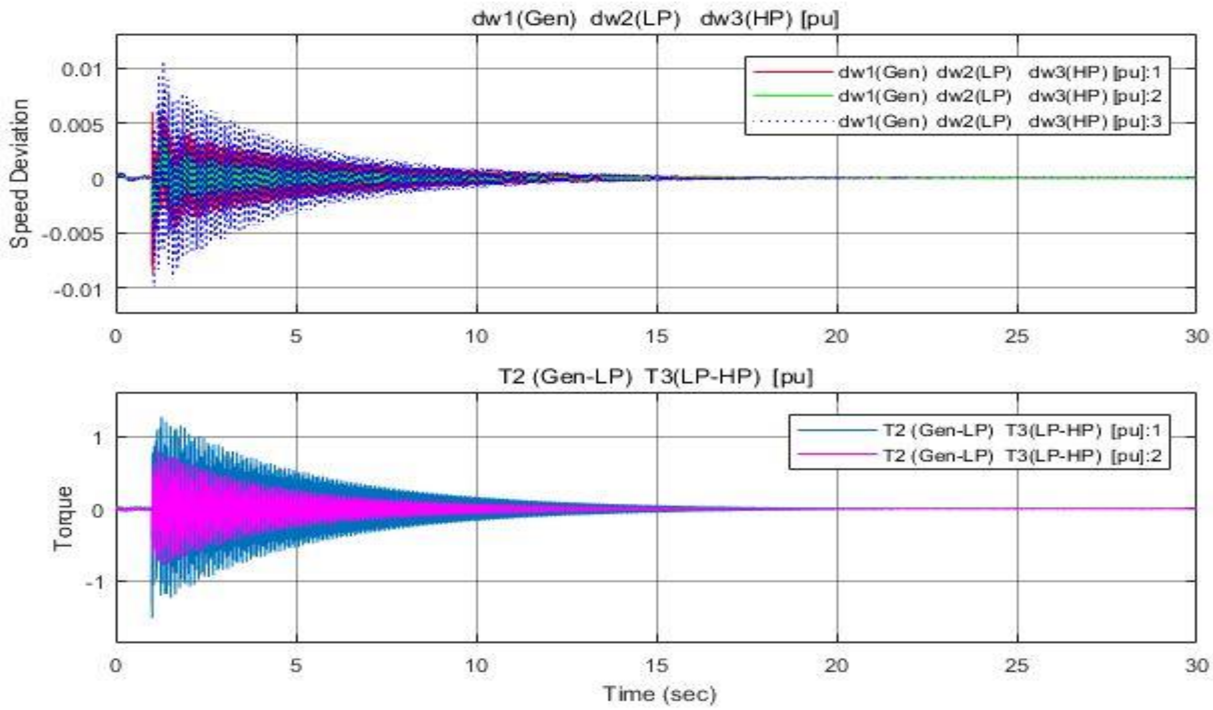


Figure 21. Modified Case with Control Speed Deviation and Torque at 45% Compensation

compensation voltage is utilized as the control signal for the mitigation purpose. Similar to the

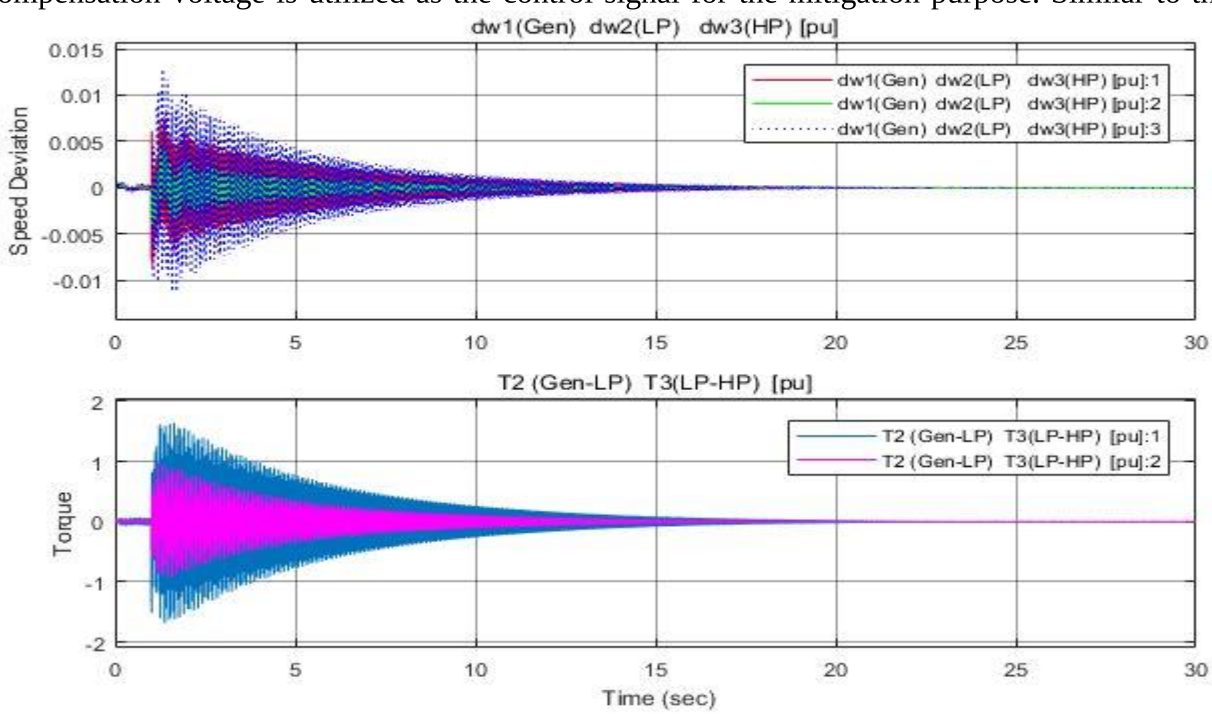


Figure 20. Modified Case Speed Deviation and Torque at 50% Compensation

previous cases at all the compensation levels, the fault is initiated at t=1s and cleared after 75ms duration.

After applying the supplemental damping control at the q-axis current reference of GSC, it

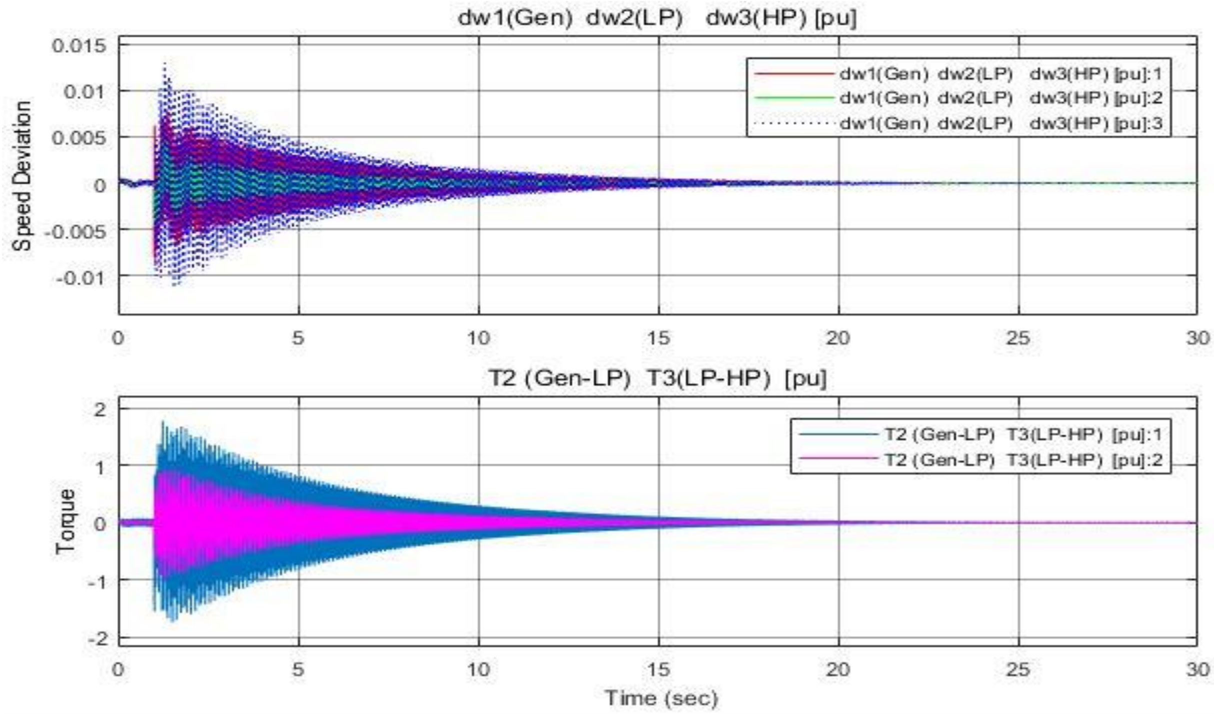


Figure 22. Modified Case Speed Deviation and Torque at 55% Compensation

can be clearly observed that the generator rotor oscillations and torque amplifications are completely incapacitated in less than half a minute at all the different compensation levels. It shows that utility scale PV farms with proper control of reactive power injection into the grid can mitigate the SSR problem similar to FACTS devices and at the same time PV farms are able to inject active power into the grid.

4.4 Analysis

4.4.1 FFT Analysis

The FFT analysis is carried out at first subsynchronous mode of IEEE SBM i.e. 55% compensation level. The FFT analysis is used to observe the pattern of magnitude of the dominant component of frequency over the time. It is also performed to check, whether the THD levels of injecting currents meeting the limits of grid requirements are or not? In the case system augmented with PV farm alone it can be observed that the magnitude of dominant component is increasing continuously, which is as shown in the figure. Other frequency magnitudes are gradually diminishing over the time in case of PV farm, whereas the magnitude of dominant 25 Hz component is increasing.

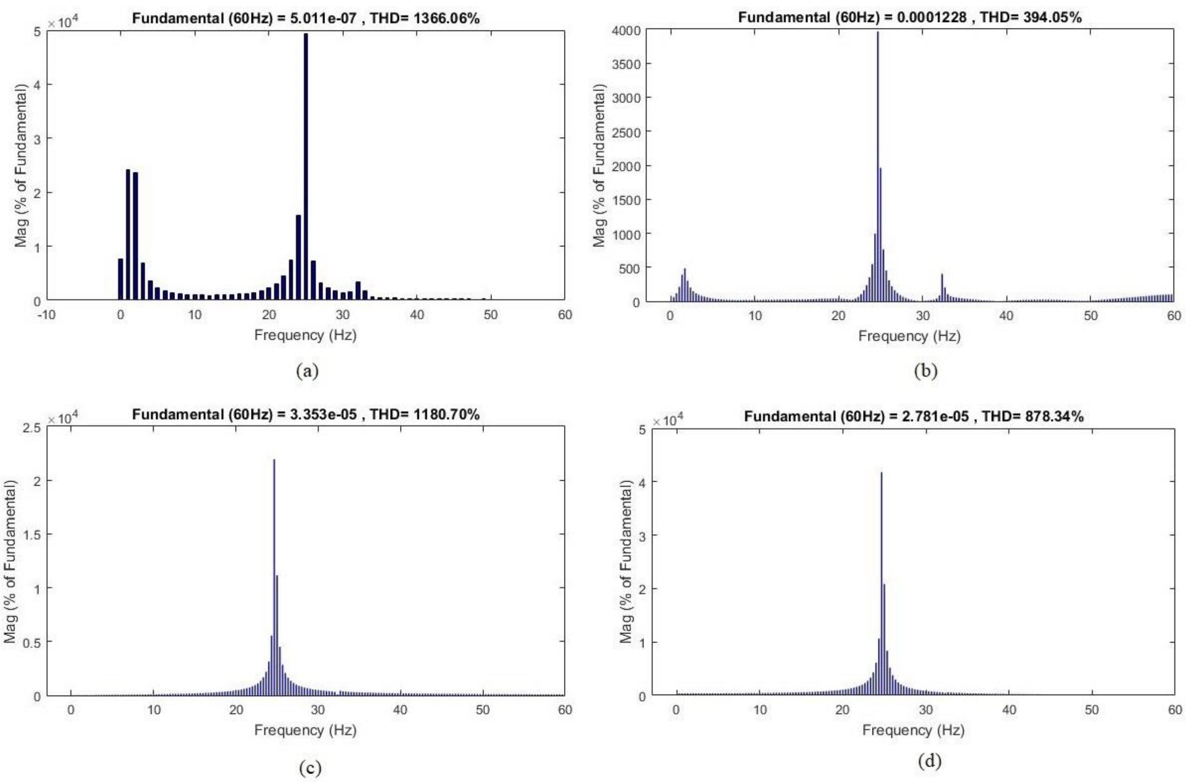


Figure 23. FFT Analysis at 55% Compensation Level Without Damping Controller

The responses in the system with PV farm augmented with the supplementary damping controller utilizing series compensation voltage as control signal, the magnitude of the dominant 25 Hz component and magnitude of other frequencies is diminishing slowly with the time as shown in the Figure 24.

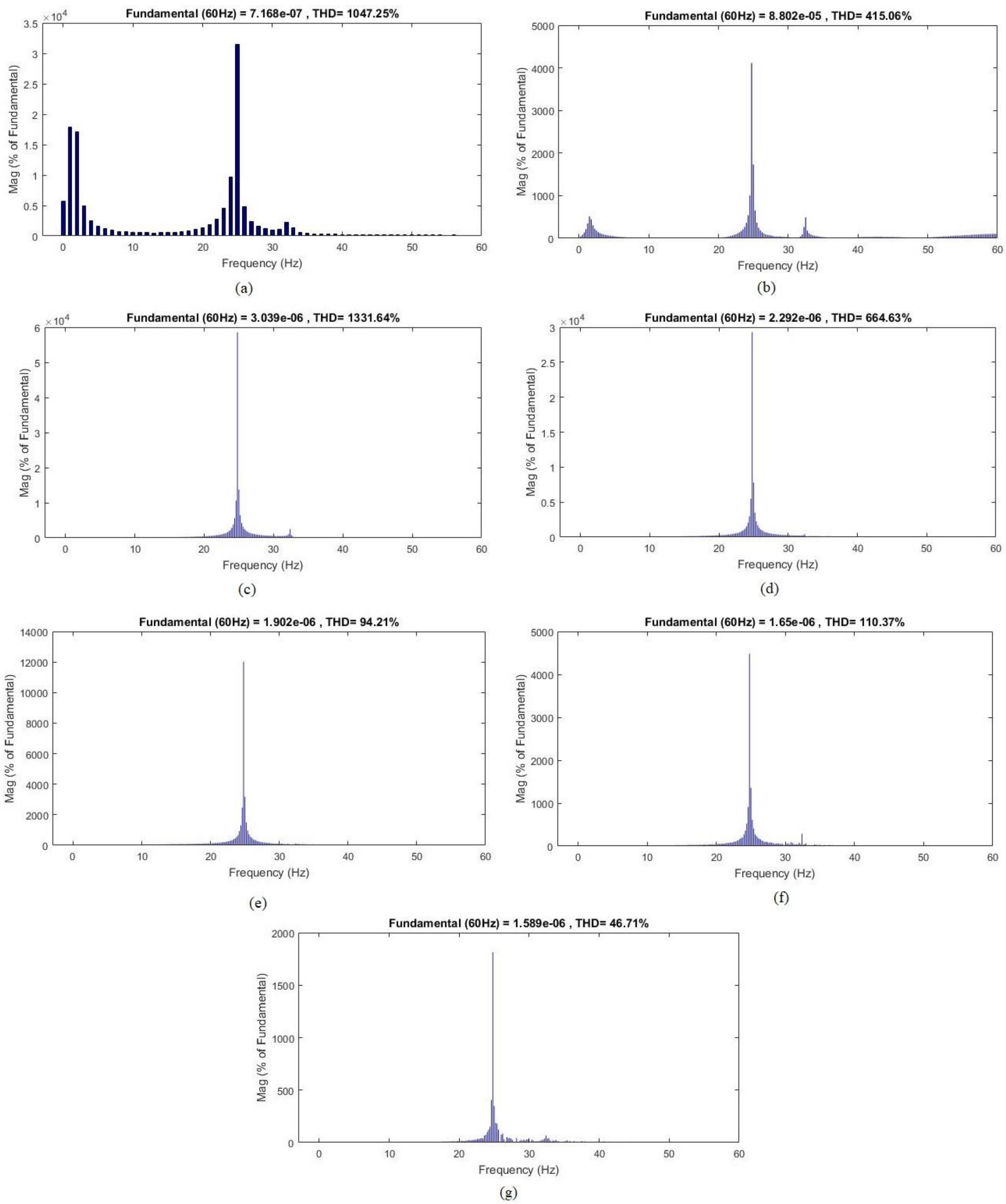
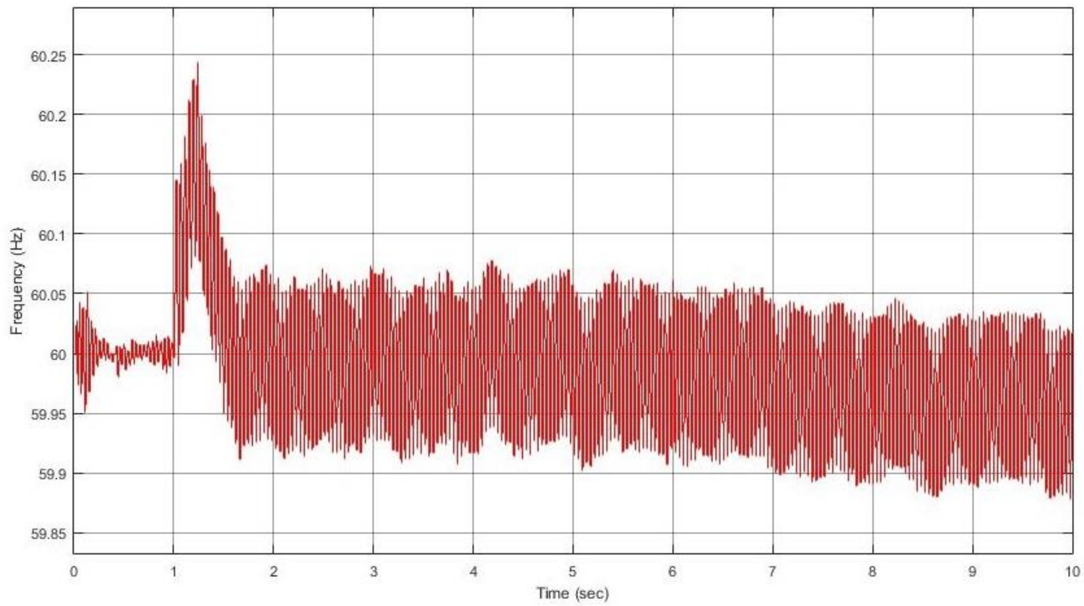


Figure 24. FFT Analysis at 55% Compensation Level with Damping Controller

4.4.2 Frequency at PCC

The frequency at point of common coupling needs to be maintained within the limits as per the requirements of IEEE 1547 protection thresholds, but with the integration of PV farm into the system, it can be observed from the response that the frequency started dropping after clearing the



(a)

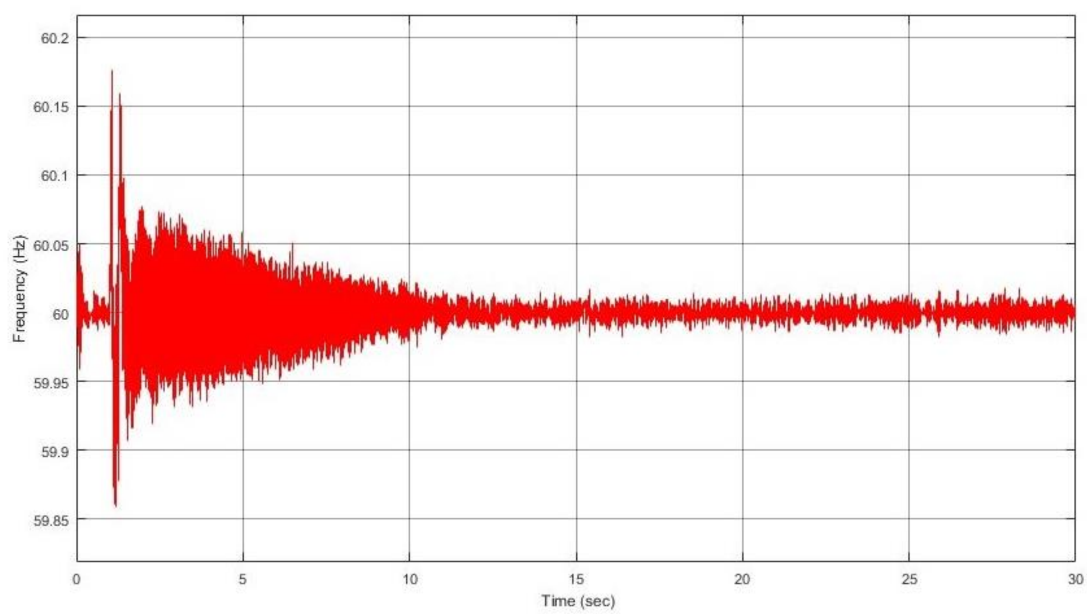


Figure 25. Frequency at PCC (a) Without Damping Controller, (b) With Damping Controller

fault as shown in Figure 25(a). Whereas with the use of capacitor voltage as input control signal for the damping controller the frequency at PCC is returning to nominal frequency as shown in Figure 25(b).

4.4.3 Series Compensation Voltage

Utilizing voltage across the series compensation as the input control signal for the damping controller for mitigating the SSR problem is the main objective. After the fault applied at bus near to the synchronous generator in the case with PV farm, initially the voltage across series compensation going back to the initial condition, but it is progressing gradually with the time as shown in the Figure. 26(a), which not a desirable condition. Whereas in the case with PV farm augmented with the damping controller, the voltage across series compensation is not only restore to the initial condition as shown in the Figure 26(b) but also remaining at the pre-fault value.

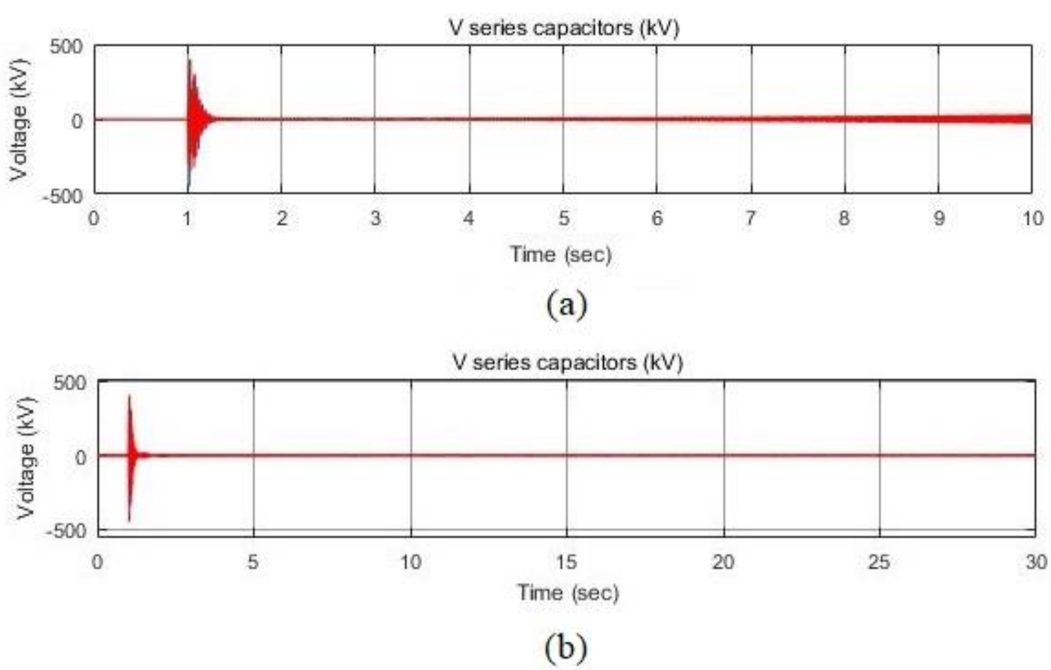


Figure 26. Series Compensation Voltage (a) Without and (b) With Damping Controller

4.4.4 Effect of Fault Clearing Time

The fault clearing time has impact on the maximum torque of the GEN-LP shaft, the maximum one half of peak to peak values of torque amplification for different fault clearing times was tabulated [23] in and plotted maximum torque to fault clearing time. Applying the series compensation voltage as control signal to the damping control, it is observed that the SSR problem is mitigated. Which implies that voltage across series compensation as control signal able to mitigate the SSR problem for different fault time duration.

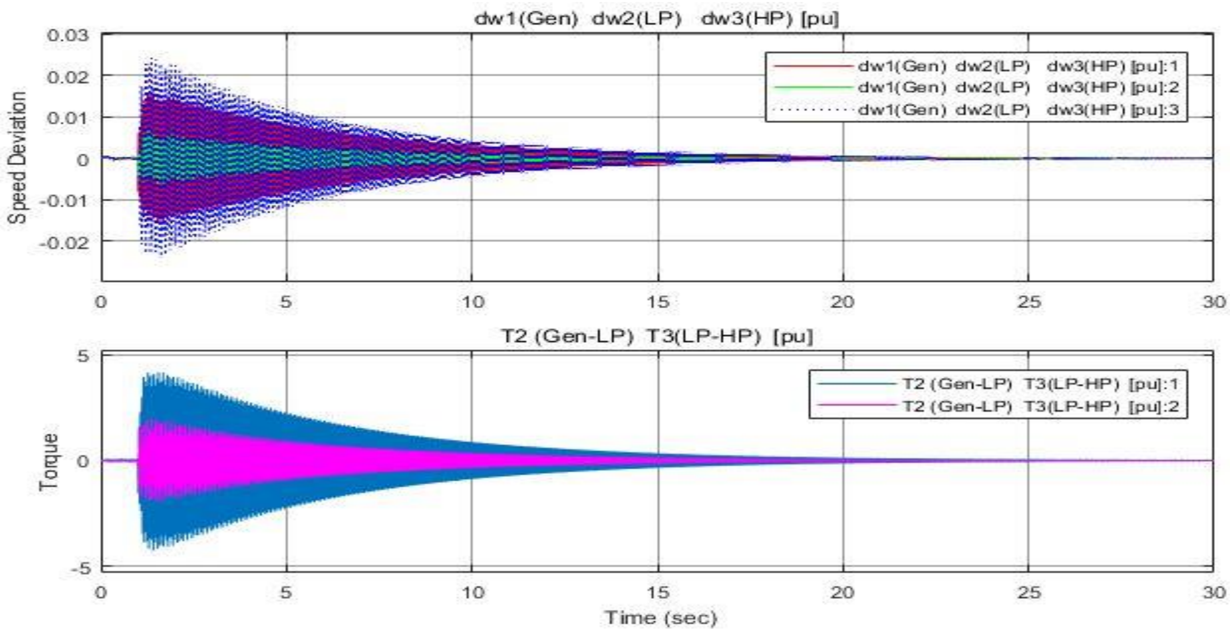


Figure 27. Speed Deviation and Torque at 55% Compensation Fault Time 17msec

The illustrated responses show that utilizing voltage across series compensation can mitigate the SSR problem for different compensation levels and fault time durations successfully. Utilizing capacitor voltage for SSR mitigation has a positive impact on the system frequency compared to PV farm without any supplementary control.

CHAPTER 5

CONCLUSIONS AND FUTURE WORKS

5.1 Conclusions

The technological advancement in the PV integration clearly makes the utility scale PV farm as one of the tough competitor to other generation sources. The fast dispatchability and flexibility of PV power stations can help in grid support functions and meeting the demand requirements. In this study SSR problem is countered using the utility scale PV power station, by supplementing the PV farm's GSC with a damping controller. This method allows the use of existing Fixed Series Capacitors, without raising the SSR problem in the system.

The study is conducted on IEEE-Second Benchmark Model, by integrating the PV farm at midpoint of series compensated transmission line in MATLAB/Simulink environment. The series compensation voltage is used as control signal for damping controller to damp the torque amplifications, the proposed technique can damp the amplifications at different compensation levels, also mitigates the SSR problem at different fault clearing times in less than half minute in all the cases considered in the study. All the cases were validated using time-domain simulation in MATLAB/Simulink software.

The FFT analysis showing that using capacitor voltage as control signal can reduce the magnitude of dominant 25 Hz frequency component over the time. Voltage across series compensation as control signal doesn't depend on individual T-G sets for injecting reactive power to counter the oscillations in the system. The study shows that capacitor voltage as control signal for utility scale PV farms can help in successfully mitigating the SSR problem in series compensated systems. Utilizing the utility scale PV farms instead of the expensive FACTS device is an economic solution for mitigating the SSR problem.

5.2 Future Works

In this study the gain of damping controller was adjusted equal to the percentage of compensation and washout time constant is adjusted based on trial and error method, as the sole purpose of the study is to evaluate whether capacitor voltage as damping signal can mitigate the SSR problem. To realize better performance the gain and washout time constant of damping controller should be able to adjust autonomously based on the system condition.

REFERENCES

REFERENCES

[1] K. Padiyar, Analysis of Subsynchronous Resonance in Power Systems, Boston: Kluwer Academic Publishers, 1999.

[2] A. A. Fouad and K. T. Khu, "Damping of Torsional Oscillations in Power Systems with Series-Compensated Lines," *IEEE Transactions on Power Apparatus and Systems,* Vols. PAS-97, no. 3, pp. 744-753, 1978.

[3] R. Grünbaum, P. Halvarsson and P. Jones, "Series compensation for increased power transmission capacity," in *5th IET International Conference on Power Electronics, Machines and Drives (PEMD 2010),* Brighton, UK, 2010.

[4] S. Golshannavaz, F. Aminifar and D. Nazarpour, "Application of UPFC to Enhancing Oscillatory Response of Series-Compensated Wind Farm Integrations," *IEEE Transactions on Smart Grid,* vol. 5, no. 4, pp. 1961 - 1968, 2014.

[5] T. Rajaram, J. M. Reddy and Y. Xu, "Kalman Filter Based Detection and Mitigation of Subsynchronous Resonance with SSSC," *IEEE Transactions on Power Systems,* vol. 32, no. 2, pp. 1400 - 1409, 2017.

[6] D. Rai, S. O. Faried, G. Ramakrishna and A.-A. Edris, "An SSSC-Based Hybrid Series Compensation Scheme Capable of Damping Subsynchronous Resonance," *IEEE Transactions on Power Delivery,* vol. 27, no. 2, pp. 531 - 540, 2012.

[7] R. K. Varma, S. Auddy and Y. Semsedini, "Mitigation of Subsynchronous Resonance in a Series-Compensated Wind Farm Using FACTS Controllers," *IEEE Transactions on Power Delivery,* vol. 23, no. 3, pp. 1645 - 1654, 2008.

[8] W. R. E. M. T. Force, "WECC Guide for Representation of Photovoltaic Systems In Large-Scale Load Flow Simulations," 2010.

[9] L. Harnefors, "Analysis of Subsynchronous Torsional Interaction With Power Electronic Converters," *IEEE Transactions on Power Systems,* vol. 22, no. 1, pp. 305-313, 2007.

[10] K. M. Alawasa, Y. A.-R. I. Mohamed and W. Xu, "Modeling, Analysis, and Suppression of the Impact of Full-Scale Wind-Power Converters on Subsynchronous Damping," *IEEE Systems Journal,* vol. 7, no. 4, pp. 700 - 712, 2013.

[11] K. M. Alawasa and Y. A.-R. I. Mohamed, "A Simple Approach to Damp SSR in Series-Compensated Systems via Reshaping the Output Admittance of a Nearby VSC-Based System," *IEEE Transactions on Industrial Electronics,* vol. 62, no. 5, pp. 2673 - 2682, 2015.

[12] S. O. Faried, D. R. I. Unal and J. Mahseredjian, "Utilizing DFIG-Based Wind Farms for Damping Subsynchronous Resonance in Nearby Turbine-Generators," *IEEE Transactions on Power Systems,* vol. 28, no. 1, pp. 452-459, 2013.

[13] P. H. Huang, M. S. E. Moursi, W. Xiao and J. L. Kirtley, "Subsynchronous Resonance Mitigation for Series-Compensated DFIG-Based Wind Farm by Using Two-Degree-of-Freedom Control Strategy," *IEEE Transactions on Power Systems*, vol. 30, no. 3, pp. 1442-1454, 2015.

[14] L. Fan and Z. Miao, "Mitigating SSR Using DFIG-Based Wind Generation," *IEEE Transactions on Sustainable Energy,* vol. 3, no. 3, pp. 349 - 358, 2012.

[15] H. A. Mohammadpour and E. Santi, "SSR Damping Controller Design and Optimal Placement in Rotor-Side and Grid-Side Converters of Series-Compensated DFIG-Based Wind Farm," *IEEE Transactions on Sustainable Energy*, vol. 6, no. 2, pp. 388 - 399, 2015.

[16] L. Fan and Z. Miao, "Nyquist stability criterion based ssr explanation for type 3 wind generators," in *IEEE Power & Energy Society General Meeting*, Vancouver, 2013 .

[17] Z. Miao, "Impedance-Model-Based SSR Analysis for Type 3 Wind Generator and Series-Compensated Network," *IEEE Transactions on Energy Conversion,* vol. 27, no. 4, pp. 984-991, 2012.

[18] R. Teodorescu, M. Liserre and P. Rodriguez, Grid Converters for Photovoltaic and Wind Power Systems, John Wiley & Sons, 2011.

[19] R. Shah, N. Mithulananthan and K. Y. Lee, "Large-Scale PV Plant With a Robust Controller Considering Power Oscillation Damping," *IEEE Transactions on Energy Conversion,* vol. 28, no. 1, pp. 106 - 116, 2013.

[20] R. Shah, N. Mithulananthan and R. Bansal, "Oscillatory stability analysis with high penetrations of large-scale photovoltaic generation," *Energy Conversion and Management*, vol. 65, pp. 420-429, 2013.

[21] K. M and K. R, "Sub-synchronous resonance damping using high penetration PV plant," *Mechanical Systems and Signal Processing,* vol. 84, pp. 431-444, 2017.

[22] R. K. Varma and R. Salehi, "SSR Mitigation With a New Control of PV Solar Farm as STATCOM (PV-STATCOM)," *IEEE Transactions on Sustainable Energy* , vol. 8, no. 4, pp. 1473 - 1483 , 2017.

[23] W. Xiao, Photovoltaic Power System: Modeling, Design, and Control, Hoboken, NJ: John Wiley & Sons, 2017, 2017.

[24] "Second Benchmark Model for Computer Simulation of Subsynchronous Resonance," *IEEE Transactions on Power Apparatus and Systems,* Vols. PAS-104, no. 5, pp. 1057 - 1066, 1985.