UNIVERSITY OF TURKISH AERONAUTICAL ASSOCIATION
INSTITUTE OF SCIENCE AND TECHNOLOGY

APPLICATION AND SIMULATION OF STATIC SYNCHRONOUS SERIES COMPENSATOR (SSSC) IN ELECTRIC POWER TRANSMISSION GRIDS

MASTER THESIS

Khaldoon Mohammed Aeal AEAL

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE IN
ELECTRICAL AND ELECTRONICS ENGINEERING

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Supervisor: Prof. Dr. Doğan ÇALIKOĞLU

Khaldoon Mohammed Aeal AEAL, having student number 1406030004 and enrolled in the Master Program at the Institute of Science and Technology at the University of Turkish Aeronautical Association, after meeting all of the required conditions contained in the related regulations, has successfully accomplished, in front of the jury, the presentation of the thesis prepared with the title of: Application And Simulation Of Static Synchronous Series Compensator (SSSC) In Electric Power Transmission Grids.

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Thesis Defense Date: 09 October 2017

UNIVERSITY OF TURKISH AERONAUTICAL ASSOCIATION
INSTITUTE OF SCIENCE AND TECHNOLOGY

I hereby declare that all the information in this study I presented as my Master's Thesis, called: "Application And Simulation Of Static Synchronous Series Compensator (SSSC) In Electric Power Transmission Grids" has been presented in accordance with the academic rules and ethical conduct. I also declare and certify with my honor that I have fully cited and referenced all the sources I made use of in this present study.

09.10.2017
Khaldoon Mohammed Aeal AEAL

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October 2017 Khaldoon Mohammed Aeal AEAL

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ROSTER OF SCHEDULES

LIST OF ABBREVIATIONS AND SYMBOLS

AC : Alternative Current
CPU : Central Processing Unit
DC : Direct Current
DFC : Dynamic Flow Controller
DPFC : Dynamic Power Flow Controller
DVR : Dynamic Voltage Regulator
EMI : Electromagnetic Interference
EPRI : Electric Power Research Institute
FACTS : Flexible AC Transmission Systems
GTO : Gate turn-off
GUI : Graphical User Interface
GUPFC : Generalized Unified Power Flow Controller
HIL : Hardware In the Loop
HV : High Voltage
IEEE : The Institute of Electrical and Electronics Engineers
IGCT : Integrated Gate Commutated Thyristor
IPFC : Interline Power Flow Controller
KVAR : Kilo Volt Amperes Reactive
LL : Lead-lag
LMI : Linear Matrix Inequality
MIMO : Multiple-input, Multiple-output
MSC : Mechanically switched shunt capacitor
MVA : Mega Volt Amperes
MW : Mega Watts
PI : Proportional Integral
PID : Proportional Integral Derivative
POD : Power Oscillation Damping
PST : Phase Shifting Transformer
PWM : Pulse Width Modulation
RFI : Radio Frequency Interference
RGA : Relative Gain Array
SCCL : Short-Circuit Current Limiter
SSR : Sub synchronous Resonance
SSSC : Static Synchronous Series Compensator
STATCOM : Static Synchronous Compensator
SVC : Static Var Compensator
TCPS : Thyristor-Controlled Phase Shifter
TCPST : Thyristor-Controlled Phase-Shifting Transformer
TCR : Thyristor Controlled Reactor

TCSC	: Thyristor- Controlled Series Capacitor
THD	: Total Harmonic Distortion
TSC	: Thyristor Switched Capacitor
UPFC	: Unified Power Flow Controller
VSC	: Voltage Source Converter
MSR	: Mechanically Switched Reactor
DLM	: Dynamic Load Model
SSG	: Static Synchronous Generator
TSR	: Thyristor Switched Reactor
IGBT	: Insulated Gate Bipolar Transistor
TPSC	: Thyristor-Protected Series Capacitor
HVDC	: High Voltage Direct Current
GCC	: Gulf Cooperative Council
PLL	: Phase- Locked Loop
P	: Active Power (Real Power)
Q	: Reactive Power
3-Ø	: Three Phase
cct	: circuit

ABSTRACT

APPLICATION AND SIMULATION OF STATIC SYNCHRONOUS SERIES COMPENSATOR (SSSC) IN ELECTRIC POWER TRANSMISSION GRIDS

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October 2017, 111 pages

The Static Synchronous Series Compensator (SSSC) is an effective tool in improving power system parameters to increase power transfer capacity, stabilize the system, help energy suppliers solve problems caused by congestion and maximize the economic value of transmission systems. An SSSC incorporates a solid-state voltage source inverter that injects a close-to-ideal sinusoidal voltage of a variable magnitude in series with the transmission line. It has a similar structure to the Static Synchronous Compensator (STATCOM) with the exception of the coupling transformer that is connected in series with the transmission line. To compensate for the losses in the inverter, a part of the inserted voltage that is in-phase with the transmission line current is used.

The objective of this thesis is to study the behavior and applications of the SSSC in electric power transmission networks. SSSC topology and principle of operation are explained. Then, SSSC applications in power transmission grids are illustrated. The results of the research are simulated using Simscape Power Systems, a product of the MATLAB family. The simulation is comprised of SSSC operations with and without a Power Oscillation Damping Controller (POD).

Keywords: SSSC, Static Synchronous Series Compensator, POD, Power Oscillation Damping, FACTS, Flexible Alternating Current Transmission Systems, MATLAB.

ÖZET

ELEKTRİK İLETİM ŞEBEKELERİNDE STATİK SENKRON SERİ KOMPANZATÖR (SSSK) UYGULAMA VE SİMÜLASYONU

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Yüksek Lisans, Elektrik ve Elektronik Mühendisliği Bölümü
Danışmanı: Prof. Dr. Doğan ÇALIKOĞLU
Ekim 2017, 111 sayfa

Statik Senkron Seri Kompanzatör (SSSK) güç aktarım kapasitesini artırmak, sistemi dengelemek, enerji tedarikçilerinin tıkanıklığın neden olduğu sorunları çözmesine yardımcı olmak ve iletim sisteminin ekonomik değerini en üst düzeye çıkarmak için güç sistemi parametrelerini değiştirmede etkili bir araçtır. SSSK, iletim hattına seri olarak değişken büyüklüğe sahip ve ideale yakın sinüzoidal voltaj enjekte eden bir katı hal voltaj kaynağı invertörü içermektedir. İletim hattına seri bağlanmış kuplaj transformatörü dışında STATCOM ile benzer yapıdadır. İnverterdeki kayıpları telafi etmek için, enjekte edilen voltajın, hat akımı ile aynı fazda olan bir kısmı kullanılır.

Bu tezin amacı, SSSK'nın elektrik iletim şebekelerindeki performans ve uygulamalarını incelemektir. SSSK topolojisi ve çalışma prensibi açıklanmaktadır. Daha sonra, güç iletim şebekesinde SSSK uygulamaları gösterilmektedir. Araştırmanın sonuçları, MATLAB ailesinin bir ürünü olan Simscape Power Systems kullanılarak simüle edilmiştir. Simülasyon, Güç Salınımlı Sönümleme Kontrol Cihazı devredeyken ve devre dışındayken SSSK operasyonunun incelenmesini kapsamaktadır.

Anahtar Kelimeler: SSSK, Statik Senkron Seri Kompanzatör, GOS, Güç Osilasyon Sönümlendirme, FACTS, MATLAB.

CHAPTER ONE

INTRODUCTION

1.1 Presentation of The Work

In this thesis, the operation of the Static Synchronous Series Compensator (SSSC) and its applications in electric power transmission networks are investigated. These include the explanation of their related topologies and principles. The applications of the SSSC in power transmission grids are specifically given through illustration. The results of the research are simulated using Simscape Power Systems, a product of the MATLAB family. The simulation is comprised of SSSC operations with and without a Power Oscillation Damping (POD) Controller.

The growing complexity of interconnected power systems that are comprised of thousands of generators, buses, and sophisticated load demand characteristics makes inevitable the continuous improvement of the throughput and quality of electric power while sustaining reliability and maintaining security. The availability of power generation, which is generally not located near a growing load center, is subject to regulatory policies and environmental problems. In order to meet the growing demand for electricity, utilities prefer to rely on existing agreements for the export and import of electricity instead of building new lines due to environmental and regulatory policies. On the other hand, power fluxes in a number of the transmission lines are well below their thermal limits, while other lines are quite overloaded, which has a global effect of deterioration of the voltage profiles and the stability and safety of the system. In addition, existing conventional transmission systems are, in most cases, not designed to meet the requirements for the control of complex and highly interconnected power systems. This global situation requires the examination of traditional transmission methods and practices and the creation of new concepts that would make it possible to use the existing production and transport lines to their full capacity without reducing the stability and safety of the transmission system.

The rapid development of power electronics technology provides exciting opportunities to develop new power system equipment for better utilization of existing systems.

The SSSC, one of the key Flexible Alternating Current Transmission System (FACTS) devices, comprises a Voltage-Sourced Converter (VSC) and a transformer linked in sequence in a line. The SSSC inserts a voltage of variable magnitude in quadrature with the transmission line current, thereby emulating an inductive or capacitive reactance. This emulated variable reactance in sequence with the line can then affect the transmitted electrical power.

The SSSC is an effective tool in improving power system parameters to increase power transfer capacity, stabilize the system, control power flow, improve damping of power oscillation on power grids following a three-phase fault, help energy suppliers solve problems caused by congestion and maximize the economic value of the transmission system. Power oscillation has been documented as one of the key problems in power system operations. Voltage and power oscillations can be damped well using SSSC under 3-ph fault conditions.

SSSC not only damps power oscillations during system disturbances; it can also efficiently regulate real and reactive power in a line. For inductive or capacitive compensation cases, the reference voltage that the SSSC takes as the injected or recommended scalar voltage can, in reality, be positive or negative only. The reference voltage will always conform to the anticipated control parameter, such as when it is the active power to be controlled in the transmission line, the input of the controller will be the real power that is measured at the output, whereas the reference voltage will follow the difference between the setpoint and the line power. In an effort to attain lower generator oscillation so as to avoid synchronism problems, the rate of change in the angular velocity of the generator (i.e. derivative $d\omega$) can also be fed into the controller.

This thesis describes the improvement of power transfer capability in IEEE 4 bus bars, two-machine system using an SSSC. It is known that a series controller always contributes a better performance for active power transfer capability through the transmission line. Here, the SSSC has been used as a switching converter type series compensation. The POD has been incorporated as a controller to damp out the oscillation. Simulation results show that after installing the SSSC at bus 1, the power flow improves. The work was simulated in MATLAB Simulink 2015 and the output has been compared with and without the SSSC. The SSSC was included with and without POD Controller.

Series compensation always plays a significant role in improving power transmission ability through the transmission line. A series manager can be applied changeably the impedance kind and the switching converter type. An SSSC comes under the family of switching converter types. The elementary aim of an SSSC device is to regulate power inflow in the steady state case, while it can also produce better transient stability of a power system. The main interest is to use the SSSC to adjust power inflow (P and/or Q) in transmission lines. The SSSC is connected at 4 buses in 2 machine power systems.

The power grid that is simulated is comprised of duo power generation stations, M1 and M2, and one main load major situated at busbar B3. M1 has a valuation of power of 2100 MVA, whereas M2 has a valuation of power of 1400 MVA. The load major, rated almost at 2200 megawatts (MW), is designated as a Dynamic Load Model (DLM) type in which the real (P) and reactive power (Q) absorbed is a function of the system voltage. The transmission lines L1 and L2 connect this load to the generation substation M1. L1 is a 280-kilometer transmission line, whereas L2 is made up of 2 × 150–kilometer parts so as to simulate the three-phase fault by the help of the fault breaker right at the center of the line. Transmission line L3, which is 50- kilometer long, connects the load to generation substation M2. We will first validate the SSSC’s control capabilities of real power, followed by studying another critical feature, the power damping in cases of severe power conditions.

Finally, the damping controller design for the SSSC and simulations are performed using the software simulation environment Simscape Power Systems, a product of the Simulink family from Mathworks.

1.2 Static Synchronous Series Compensator

The SSSC is a FACTS family member device whose output voltage is controllable independently of the line current. It is linked in sequence with a power system and contains a solid-state voltage source converter (VSC) which creates a manageable alternating current voltage at the essential frequency. When the inserted voltage is saved in quadrature with the transmission line current, it can act as inductive or capacitive reactance in order to compensate for the power inflow along the electric line. The SSSC is primarily designed to regulate power inflow in a steady state. However, it can also be utilized to enhance transient stability.

In order to boost the dynamic performance of the power system, a SSSC might also comprise a transiently evaluated power source or power absorbing device. This produces temporary real power compensation by altering the total real voltage drop through the transmission line.

The SSSC incorporates a solid-state voltage source inverter that injects a close-to-ideal sinusoidal voltage of a variable magnitude in series with the transmission line. It has a similar structure to a STATCOM apart from the coupling transformer that is linked in sequence with the line. To compensate for the losses in the inverter, a part of the inserted voltage that is in phase with the transmission line current is used. However, almost all of the inserted voltage that is in quadrature with the transmission line current acts as sequence inductance or capacitance, thereby altering the transmission line series reactance. This emulated reactance, which can be altered by varying the magnitude of the injected voltage, favorably affects the electrical power inflow in the transmission line. The structure of the SSSC is presented in Figure (1.1) [1].

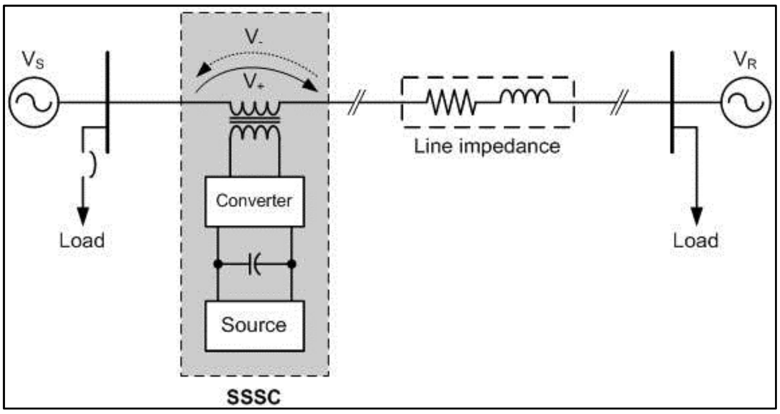


Figure 1.1: Static synchronous series compensator (SSSC).

Overall, the SSSC can be considered to be identical to an ideal synchronous voltage source as it also generates three-phase AC voltages with controllable amplitudes and phases at the desired fundamental frequency. It also appears as a synchronous compensator as it can produce or absorb reactive power from a power system and can, independently from the reactive power, create or absorb real power if an energy storage device, rather than a DC capacitor, is used in the SSSC.

The SSSC is a solid static VSC founded series FACTS organizer. It is a sequence compensator whose output voltage is in quadrature with and manageable independently of the transmission line current with the aim of varying the total line reactive drop, thereby adjusting the transferred electric power. It is mainly utilized for regulating power inflow. A form diagram of an SSSC is displayed in Figure (1.2) [2].

Since the SSSC is in sequence with the line, it can be constant at the receiving or sending end station. A diagram of the tantamount circuit is displayed in Figures (1.2) and (1.3). For ease of analysis, the resistances of both the line and the SSSC joining transformer are ignored. Therefore, the SSSC losses are also ignored.

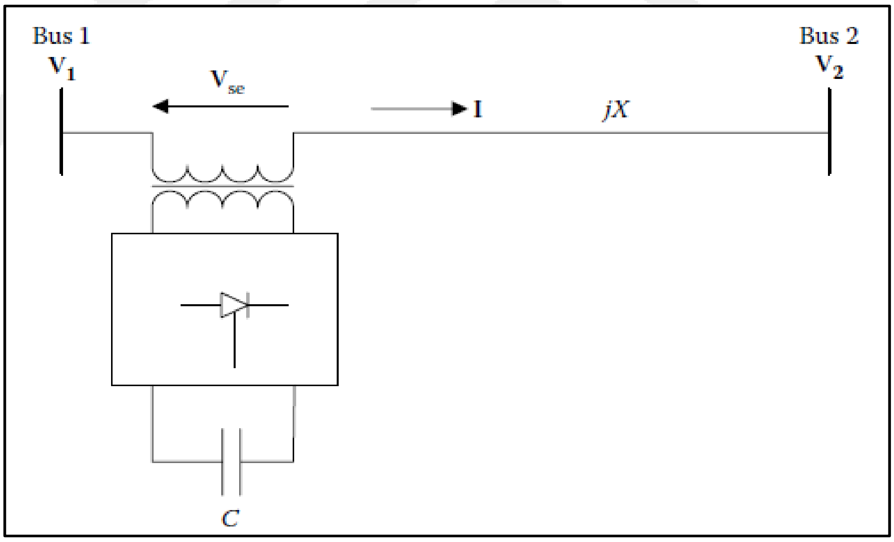


Figure 1.2: SSSC located at the sending end of the line.

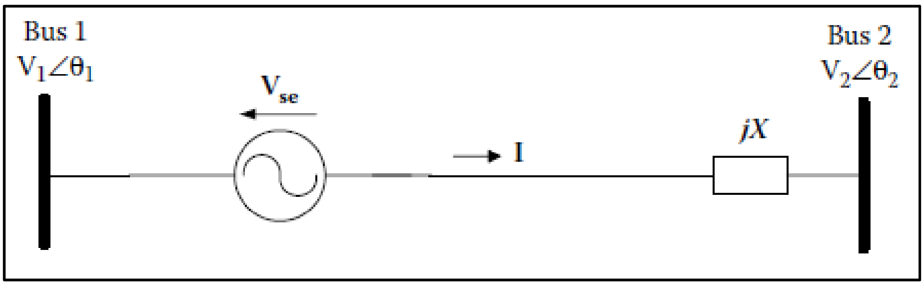


Figure 1.3: An equivalent cct of the diagram displayed in (Figure 1.2).

X indicates the common reactance of the transmission line along with the leakage reactance of the conjugation transformer. The (main frequency, positive concatenation) o/p voltage of the SSSC is seen as V_{se}. The current passing through the line and the SSSC is symbolized by **I**. From the shape, the relationship between the sending and receiving ends, and the SSSC o/p voltages along with the transmission line current can be explained as $V_1 = V_2+V_{se}+jX\mathbf{I}$. The phasor drawings conforming to this are seen in Figures 1.4 (a) and (b). It is important to note certain the important parts of the figure. For basic analysis, it allows the receiving and sending end busbar voltages to be identical. It is also assumed that some non-zero real power is inflowing amidst the transmission line from the sending end to the receiving end, creating a variance in phase angles between the sending and receiving end busbar voltages $\theta_1 - \theta_2 > 0$; that is, the busbar voltages in the phasor diagram, V_1 and V_2, are not collinear and subtend a non-zero angle with each other. Due to the assumption that the SSSC is lossless, it does not absorb any real power. Nor can it source any real power as there is no real power source.

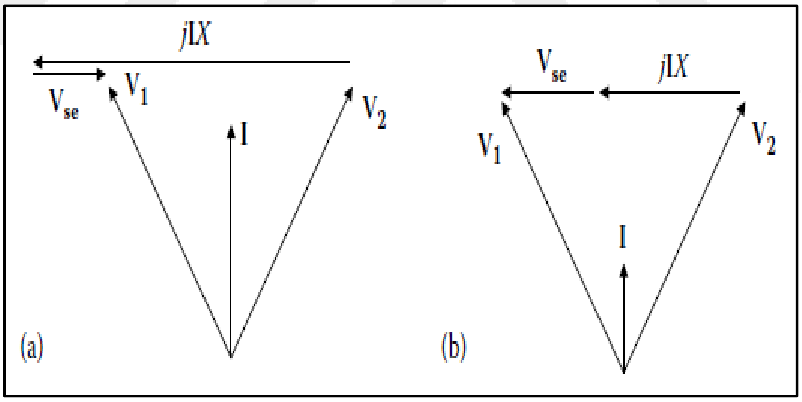


Figure 1.4: Phasor schema of voltages describes by (a) the capacitive model, (b) the inductive model.

Henceforth, the SSSC o/p voltage phasor diagram V_{se} and the transmission line current I should be perpendicular to everything else. This yields two possibilities: I lagging or leading V_{se} by 90 degrees. These two states correspond to Figures 1.4 (a) and (b), respectively. In the former case (Figure 1.4 (a)), the disposition of the V_{se} type transmission line voltage drop phasor jIX is larger, resulting in a growth of the transmission line current value. However, in the latter case (Figure 1.4 (b)), the line drop is smaller, resulting in a smaller line current magnitude. In Figure 1.4 (a), the current through the SSSC (**I**) leads the voltage across it (V_{se}), making it act similarly to a changeable capacitor (as the magnitude of V_{se} is controllable) and allowing it to deliver reactive power to the line. However, in Figure 1.4 (b), the current through the SSSC (**I**) lags the voltage across it (V_{se}) and the SSSC performs similarly to a variable inductor and absorbs the reactive power from the line. The manner of the reactive power conforming to the phasor diagrams in Figures 1.4 (a) and (b) is explained in Figures 1.5 (a) and (b), respectively, in thick white (unshaded) arrows (Q) [2].

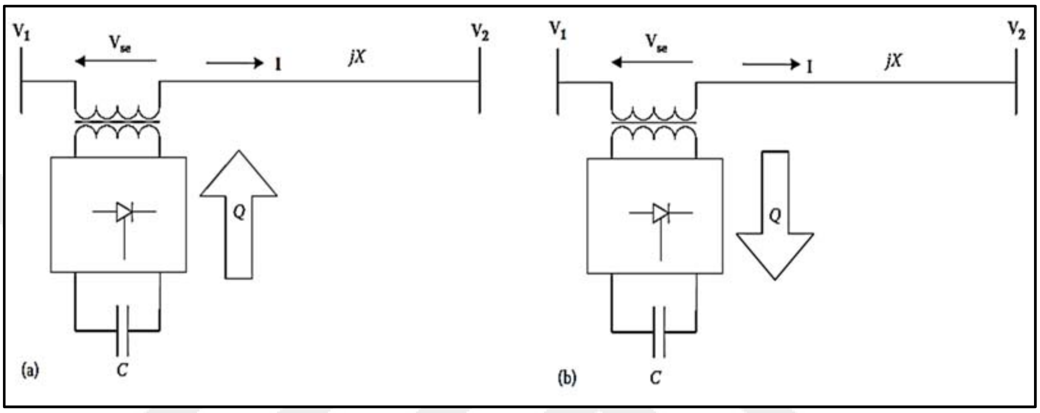


Figure 1.5: (a) the manner of reactive power inflow of the SSSC in the capacitive style; (b) the manner of reactive power inflow of the SSSC in the inductive style.

1.3 Power Quality Problems

Figure (1.6) presents power quality problems [3]. Power distribution systems should ideally supply their users an uninterrupted flow of energy at a well-formed sinusoidal voltage, complying with the level and frequency of the contracted amplitude.

However, modern distribution systems have many non-linear loads, and these significantly disturb the quality of power supplies. As a result, the purity of the waveform of the supply is at stake. In addition to non-linear loads, some system events, both common (e.g., capacitor switching, engine start-up) and unusual (e.g., faults), may also affect power quality.

The Institute of Electrical and Electronics Engineers (IEEE) 1100 standard defines energy quality as “the concept of powering and grounding sensitive electronic equipment in a manner appropriate to the equipment” [4]. The quality of the feed imposes a predetermined quality and a reliability of supply. This predefined quality may contain a combination of the following features: low phase imbalance, the absence of power interruption, low flicker and low harmonic distortion on the load voltage, magnitude and duration of unaccepted voltage values within specified limits, acceptance of fluctuations, and power factor of loads without significant effect on the terminal voltage.

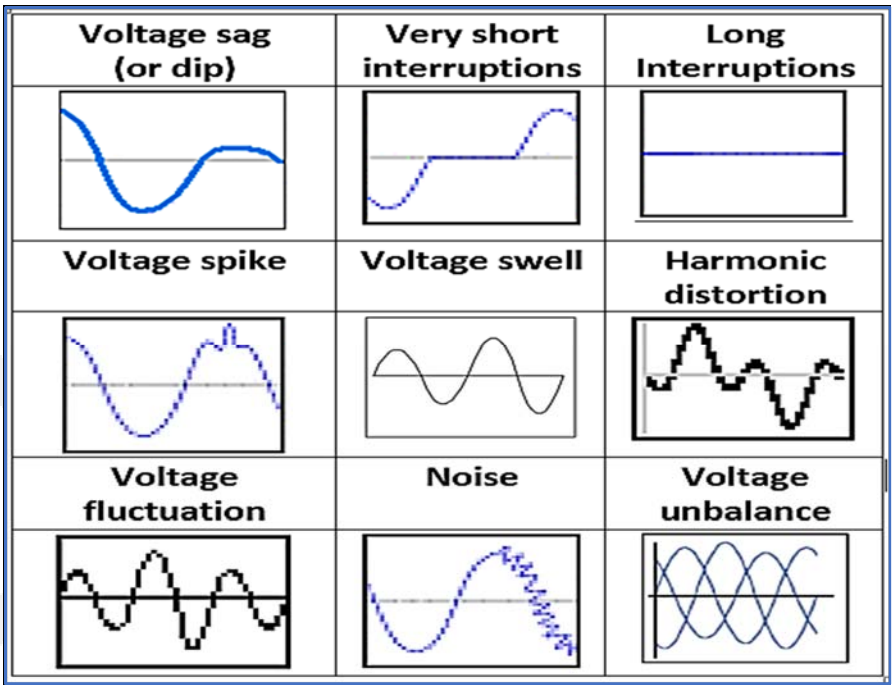


Figure 1.6: Power quality problems (PQ).

Latest thoughts advanced technology to make the life easier utilizing it depends onto the presentation of power electronics equipment in turn about power quality. With growing magnitudes of non-linear loads being surplus to electrical systems, it has become important to establish criteria that limit issues arising from system voltage degradation [5].

A recent study of Power Quality (PQ) indicates that 50 percent of total Power Quality issues are attributable to grounding, ground constraints, neutral point to ground voltages, ground circles, ground current or other ground related problems. Electrically worked or linked equipment is affected by PQ. Being cognizant of the exact issues requires sophisticated electronic test equipment.

The aforementioned symptoms are indicators of PQ issues [5]:

1. Part of an equipment malfunction at a similar time of day.
2. Equipment Circuit breakers (C.B.) trip without being full loaded.

3. A thunderstorm causing equipment failure.
4. Automatic systems stop for no apparent reason.
5. Electronic systems fail or fail to function on a repeated basis.
6. Electronic systems operate in one place but not in another place.

The usually utilized terms defining the parameters of electrical power are those that define or calculate power quality, such as voltage dips, voltage variations, interruption waves, brownouts, blackouts, voltage inequity, distortion, harmonics, harmonic resonance, interharmonics, notching, noise, impulse, spikes (voltage), ground noise, common mode noise, critical load, crest factor, electromagnetic compatibility, dropout, fault, flicker, ground, raw power, clean ground, ground loops, voltage fluctuations, transient, dirty power, momentary interruption, overvoltage, under voltage, nonlinear load, voltage dip, voltage regulation, blink, oscillatory transient, etc. The problem of electrical PQ is gaining importance due to many factors:

a) Society is becoming increasingly dependent on the electrical power supply. A small power outage has a huge economic impact on industrial customers. A longer interruption harms practically every operation in a new society.

b) Modern equipment is more sensitive to PQ variations.

c) Modern power electronic equipment, such as variable speed drives and switched mode power supplies, has brought new turbulences into the supply system.

There are many aspects of energy quality problems that can lead to the malfunction of an electrical device, as well as its premature failure or malfunction. The following are the most common failure issues and their possible influence on electronic equipment:

1.3.1 Voltage Fluctuations

Voltage fluctuations are the irregular variations and changes of magnitudes and amplitudes modified by a signal between frequencies of 0 Hz and 30 Hz. These are caused by arc kilns, the frequent starting and stopping of electric motors (e.g., lifts), and other fluctuating loads. The consequences include under-voltages and the flickering of screens and lights.

1.3.2 Voltage Spike

A voltage spike is a very quick change of voltage value lasting from numerous microseconds to a few milliseconds. These variances may even reach thousands of volts, even from low voltages. These can be caused by lightning, switching of lines or power factor adjustment capacitors and the disconnection of heavy loads. The consequences can include the destruction of components (particularly electronic components) and insulation materials, data processing errors or data loss and electromagnetic interference.

1.3.3 Voltage Sags and Dips

Voltage sags and dips are reductions of the natural voltage level between 10 and 90 present of the nominal R.M.S. voltage at the power frequency lasting from half a cycle to one minute. Short term under-voltages are referred to as “voltage sags” or “voltage dips.” A voltage dip is a decrease in the amplitude of the provided voltage followed by a voltage recovery after a short period of time. Voltage drops can be attributable to faults in the system and the start of large loads. Network overloads, loss of production, improper adjustment of transformer sockets and malfunctions of voltage regulators cause a voltage, which indirectly leads to heavy loading issues since equipment will take a raised current to maintain power output. The fault of information technology equipment; tripping of contactors and relays. Disconnection and loss of efficiency in electric rotating machines.

1.3.4 Very Short Interruptions

Very short interruptions may be explained as an overall interruption of electrical resources lasting from a few milliseconds to one or two seconds. Such interruptions can be fundamentally due to the functioning and automatic reclosure of defense devices to decommission a faulty sector in the grid. The major causes of this type of fault include insulation failure, lightning, and insulator flashover. The consequences of this issue include tripping of protection devices, loss of information and malfunction of data processing equipment in addition to stoppage of sensitive equipment.

1.3.5 Voltage Unbalance

Voltage unbalance can be described as a voltage deviation in a 3-Ø system in which the three voltage levels or the phase angle variances between them are not equal. It can be caused by large 1-Ø loads (induction furnaces, traction loads), incorrect distribution of all 1-Ø loads by the 3-Ø of the system (which might also be due to a fault). The consequences of unbalanced voltage may include unbalanced systems, implying the existence of a negative sequence that is harmful to all 3-Ø loads. The most affected loads are 3-Ø induction machines.

1.3.6 Noise

Noise is the superimposition of high-frequency pointers on the waveform of the power system frequency. The prime cause of noise is electromagnetic interventions provoked by Hertzian signals such as microwave radiation, television diffusion, and radiation due to arc furnaces, joining machines, and electronic components. The effects of noise include instability of sensitive electronic components. Noise is generally not destructive and but it can cause equipment interlocks and error or loss of data. Electric line noise is recognized as Radio Frequency Interference (RFI) and electromagnetic interference (EMI) and the reasons for equipment interlock and error or loss of data.

1.3.7 Long Interruptions

Long interruptions are the total interruption of electrical supply for durations greater than 1 to 2 seconds. They are caused by equipment failure in the power system network, storms and objects (such as trees, cars, etc.) striking lines or poles, fire, human error, bad coordination or failure of protection devices. The consequences include the stoppage of all equipment.

1.3.8 Voltage Swell

As defined by IEEE 1159, voltage swell is a 10 to 80-percent temporary increase in voltage levels at the power frequency lasting from half a cycle to 1 minute [6]. Moreover, it is further defined as a momentary increase of the voltage, at the power frequency, lasting for more than 1 cycle and typically less than a few seconds. The main causes are the start or stop of heavy loads, poorly sized power supplies, and poorly regulated transformers. The consequences include loss of data, flickering of lights and screens, and the stopping of or harm to sensitive tools.

1.3.9 Harmonic Distortion

The major causes of harmonic distortion are electric engines operating outside the magnetization arc (magnetic saturation), arc kilns, soldering machines, rectifiers and DC motors, all non-linear loads such as electronic power equipment, counting adjustable speed controllers, power supplies, data processing equipment, high-efficiency lighting, etc. The consequences have raised the likelihood of resonance, neutral heavy load in 3-Ø systems, overheating of all cables and equipment, loss of efficiency in electrical machines, and electromagnetic interference with communication systems. Harmonic distortions are voltage or current signals supposedly in non-sinusoidal form. The signal relates to the addition of various sinusoidal waves with various values and phases and frequencies that are multiples of the power-system frequency.

1.4 Other FACTS Devices That Can Serve Similar Purposes

FACTS is an advanced device with a power electronic controller base unit. The advancement of FACTS elements started with the increasing energy of power electronic components. Power flow is a function of the impedance of the electrical transmission line, as well as the amplitude of the transmitting and delivery end voltages and the phase angle between the voltages. By controlling one or more power flow arguments, it is possible to control the active power flow as well as the reactive counterpart in the transmission line.

In the past, power systems were simple and designed to be self-sufficient. Active power exchange of nearby power systems was rare, as AC transmission systems could not be controlled quickly enough to handle dynamic changes in the systems. To overcome such problems with dynamic behavior, the tolerances were generally kept large so as to recover from resultant contingencies.

In the present day, however, there are a variety of approaches and methods utilized to optimize system loads and increase security. Using shunt capacitors to preserve voltage levels at desired points has been a common practice for decades.

Capacitors installed in series fashion reduce transmission line reactance; hence, the power transfer capability of transmission lines is greatly enhanced. Power flow in the transmission lines is controlled by the application of phase shifting transformers by introducing an excess phase shift between the sending and receiving end voltages.

FACTS equipment supplies the best adaptability to changing operational settings and amending the use of remaining installations. The simple presentations of FACTS devices are [7] [8] [9] [10] [11]:

1. Power flow control and upgrade of lines.
2. The increase of system security by raising the transient stability limit and transmission ability.
3. Control of the voltage.
4. Compensation of the reactive power.
5. Improvement of the stability.
6. Improvement of the power quality.
7. Conditioning of the power.
8. Mitigation of flicker.

In the past, the control mechanisms of all relevant devices were mechanical, and therefore, relatively slow. These mechanical systems proved to be very useful in the steady-state operation of power systems. However, their response times were too slow to damp transient oscillations. If mechanically controlled systems were made to respond faster, power system security would be significantly improved, allowing the full utilization of system capacity while maintaining adequate levels of stability.

In the 1980s, the Electric Power Research Institute (EPRI) introduced a new approach called FACTS. Thanks to this concept and evolution in the field of power electronic components, FACTS meets the need for a more efficient utilization of existing systems and resources while improving the mitigation of security issues. Figure (1.7) and Table (1.1) presents an overview of major FACTS components and the role of FACTS controllers in electrical power system operation, respectively.

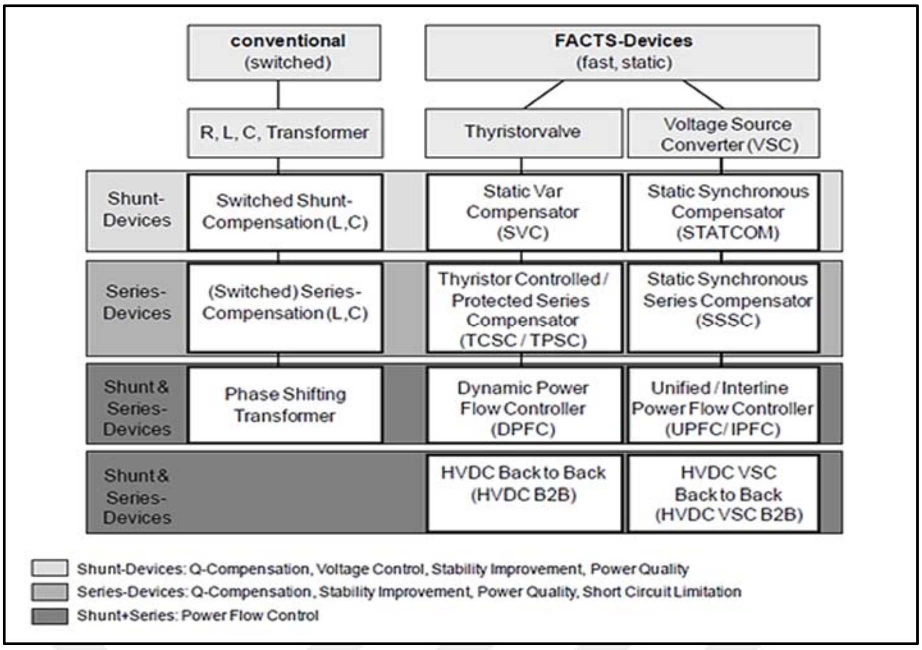


Figure 1.7: Overview of major flexible AC transmission systems (FACTS) devices [8].

Schedule 1.1: The role of FACTS managers in power system actions [9] [12].

Subject	**Operating problem**	**Corrective action**	**FACTS controller**
Voltage limits	Low voltage at heavy load	Supply reactive power	STATCOM, SVC
	High voltage at low load	Absorb reactive power	STATCOM, SVC, TCR
	High voltage following an outage	Absorb reactive power, prevent overload	STATCOM, SVC, TCR
	Low voltage following an outage	Supply reactive power, prevent overload	STATCOM, SVC
Thermal limits	Transmission circuit overload	Reduce overload	TCSC, SSSC , UPFC, IPC, PS
	Tripping of parallel circuits	Limit circuit loading	TCSC, SSSC , UPFC, IPC, PS
Loop flows	Parallel line load sharing	Adjust series reactance	IPC, SSSC, UPFC, TCSC, PS
	Post-fault power flow sharing	Rearrange network or use thermal limit actions	IPC, TCSC, SSSC, UPFC, PS
	Power flow direction reversal	Adjust phase angle	IPC, SSSC , UPFC, PS
Short circuit Power	High short circuit current	Limitation of short circuit current	TCSC, UPFC
Stability	Limited transmission power	Decrease line reactance	TCSC, SSSC

With the development of FACTS controllers, one or more parameters can be controlled simultaneously. Table 1.2 explains which parameters each device can control.

Schedule 1.2: FACTS controllers for enhancing power system control [13].

Equipment	**Impedance control**	**Voltage control**	**Angle control**
Static Synchronous Compensator(STATCOM)		✓	
Static Var Compensator (SVC)		✓	
Thyristor Controlled Series Compensator (TCSC)	✓		
Static Synchronous Series Compensator (SSSC)	✓	✓	✓
Unified Power Flow Controller (UPFC)	✓	✓	✓
Interline Power flow Controller (IPFC)	✓	✓	✓

1.4.1 Series-Connected Controllers

The major aim of the series compensator in an electric power system is a practical lessening of line reactance in order to boost electric power system stability and growth of the load ability of transmission lines. The distributed transmission line reactance compensation is further enhanced with the help of a series condenser. Since the reactive power created by the condenser is constantly relation to the square of the line current, the sequence condenser provides a self-regulating effect. While the electrical system loading grows, the reactive power created by the series condenser increases accordingly. Assuming that the capacitor current remains within operating limits, the reply of the series condenser is instantaneous, continuous and automatic.

However, this scheme is prone to SSR (Sub-synchronous Resonance). To overcome the risks of SSR, series FACTS devices are utilized. Series-connected controllers have been inspired and hence inherited from constantly or mechanically changed predecessors, even from Thyristor Controlled Series Compensation (TCSC) or VSC created counterparts. The major implications are [8]:

1- Lowering of the magnitude and phase of the series voltage decline above a power transmission line.

2- Lowering of the voltage variations within recognized limits by varying power transmissions.
3- An improvement of the system damping response (damping of fluctuations).
4- The limitation of short-circuit currents in grids or substations.
5- The avoidance of loop flow responses (power inflow regulations).

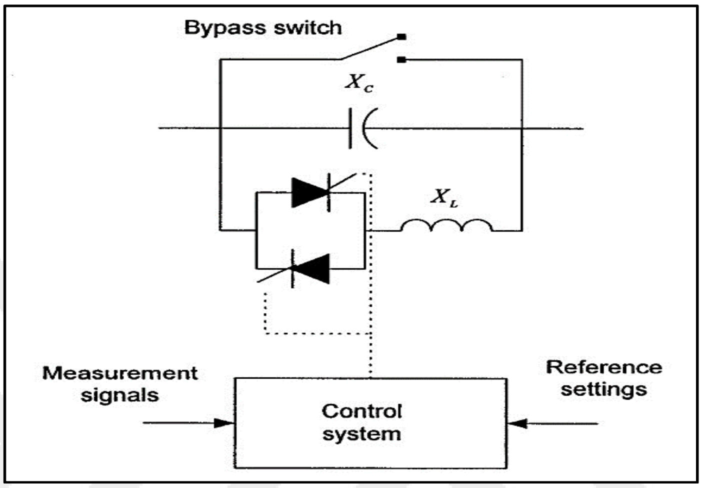


Figure 1.8: Basic structure of the thyristor controlled series compensation (TCSC) [14].

The most popular schemes of series-connected controllers are SSSC, Thyristor Controlled Series Capacitors (TCSC), and Short-Circuit Current Limiters (SCCL), as shown in Figures (1.8) and (1.9), respectively.

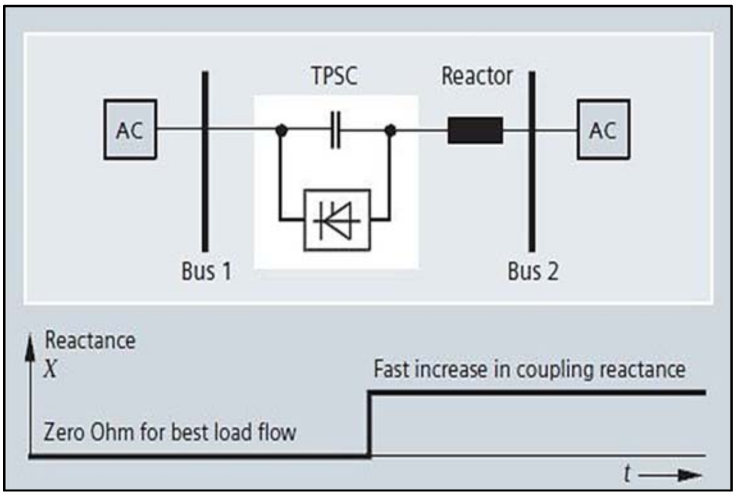


Figure 1.9: Basic structure of the short-circuit current limiter (SCCL) [8].

1.4.2 Shunt-Connected Controllers

The most utilized FACTS device is the SVC or its form with a Voltage Source Converter known as the STATCOM. These parallel devices function as reactive power compensators. The major implications in transmission, distribution, and industrial grids are:

1. The lessening of undesirable reactive power inflows and thus a reduction of grid losses.
2. The preservation of contractual power interchanges with stable reactive power.
3. Compensation of customers and enhancement of power quality, especially with huge demand fluctuations similar to industrial machines, metal melting plants, railway or underground train systems.
4. Compensation of thyristor converters; e.g., in conventional HVDC lines.
5. The enhancement of static or transient stability [8].

IEEE definitions state that reactive power compensators that are shunt connected can be analyzed in two groups as Static Var Compensators (SVC) and Static Synchronous Generators (SVG). According to the IEEE, a Static Var Compensator is a static VAR generator/absorber connected in a shunt fashion with output adjustment capabilities in order to exchange inductive or capacitive power with the aim of controlling the reactive power flow.

It was in the late 1960s when static var compensators were first developed in order to compensate for large fluctuating loads such as electric arc furnaces. Systems based on SVCs contain either Thyristor Controlled Reactors (TCR) or Thyristor Switched Capacitors (TSC) in order to employ capacitive or inductive reactive power and achieve harmonic filtering. These systems are good for solving problems arising from reactive power. However, they might have harmonic current problems. Different transformer connections or constant shunt filters are required in order to mitigate these problems.

Another popular item in this category is the STATCOM, as in Figure (1.10). A STATCOM uses switching converters to generate or absorb controlled reactive power. These converters need to employ low-pass filters for the input in order to reduce the switching frequency harmonics rather than using capacitor or reactor banks. Reactive power compensation is accomplished by creating magnitude- and phase-controlled three-phase sinusoidal waveforms at the supply terminals.

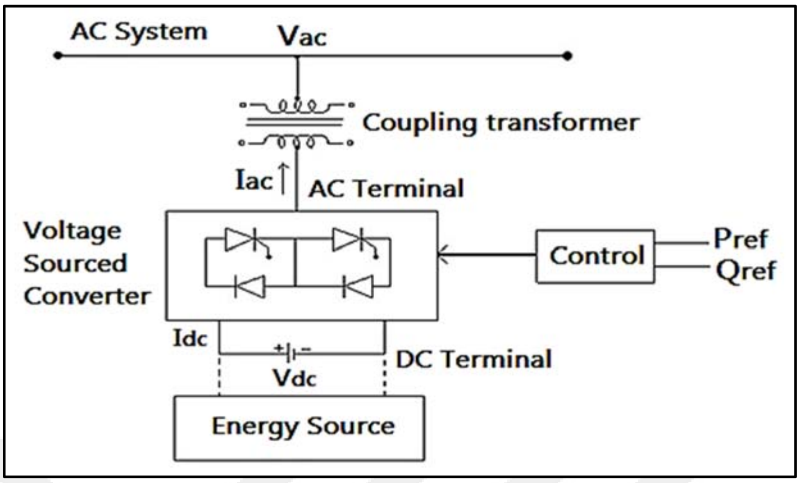


Figure 1.10: STATCOM block diagram.

The major purposes of using STATCOMs in transmission systems include controlling reactive power and supplying voltage support to buses. Transmission STATCOMs are high-power systems (20 MVAr-100 MVAr). Switching frequencies are kept low because of the high voltages and currents in the converters. Integrated Gate Commutated Thyristor (IGCT), Gate Turn-Off Thyristor (GTO) and High Voltage (HV) IGBTs are the candidate power semiconductors for Transmission STATCOMs.

1.4.3 Two-Port Combined Schemes

The Dynamic Power Flow Controller (DPFC), as shown in Figure (1.11), is a crossbred device between a Phase Shifting Transformer (PST) and exchanged sequence compensation. The DPFC contains the following components [8]:

1. A standard phase-shifting transformer (PST) with a tap-changer.
2. Series-connected Thyristor Switched Capacitors and Reactors (TSC/TSR).
3. A mechanically switched parallel capacitor (MSC). (This is elective count on the system reactive power supplies).

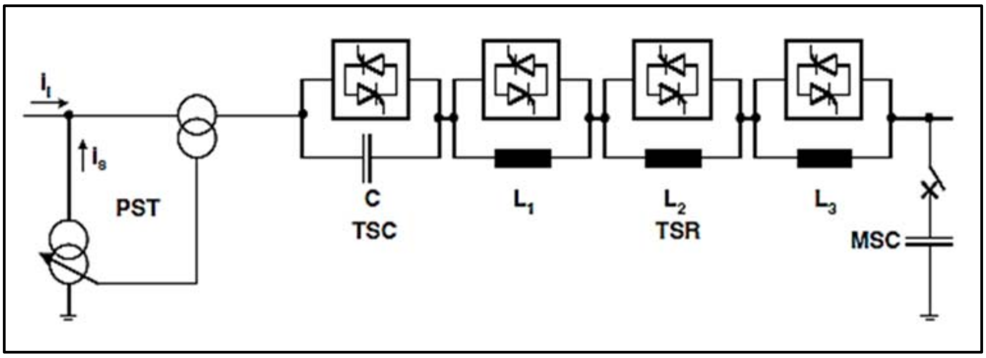


Figure 1.11: Principle configuration of dynamic power flow controller (DPFC).

The Unified Power Flow Controller (UPFC), as seen in Figure (1.12), is a blending of a static synchronous compensator and static sequence compensation. Besides shunt compensation, it also provides phase shifting.

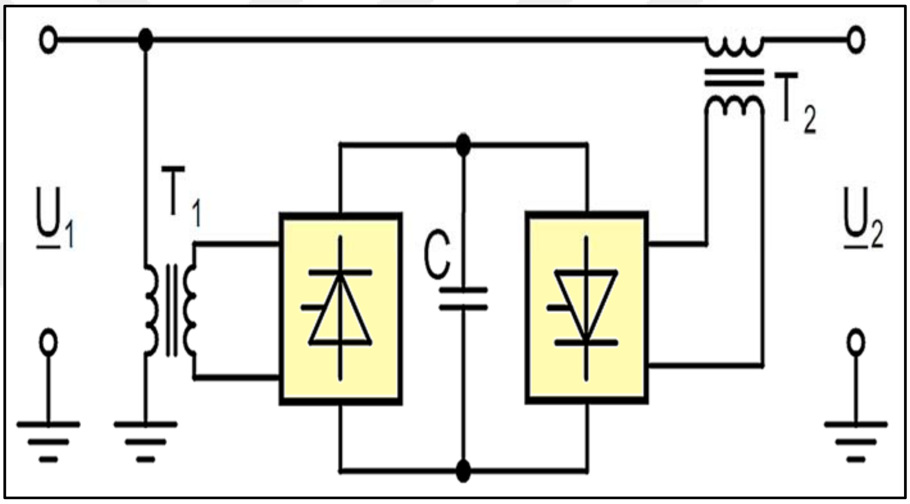


Figure 1.12: Block diagram of the unified power flow controller (UPFC).

The UPFC is comprised of parallel and sequential transformers that are linked with two VSCs sharing a DC capacitor. The phase shift of the series voltage is controlled by the real power interchange between the shunt and series transformers. Interchange of the real power is enabled by the DC circuit. This configuration, in which a thyristor bridge is utilized for protection, enables both voltage and power flow to be controllable. Although the UPFC is the best choice where both voltage and power flow control is required, its practical applications are limited due to its relatively high cost.

As in Figure (1.13), the Interline Power Flow Controller (IPFC) consists of two or more series converters. The goal is to regulate power inflows of multi-lines or a sub-network instead of adjusting the power inflow of a single line by, for example, a DPFC or UPFC. An Interline Power Flow Controller (IPFC) is utilized when any power flowing through two transmission lines that start from the same source are to be controlled.

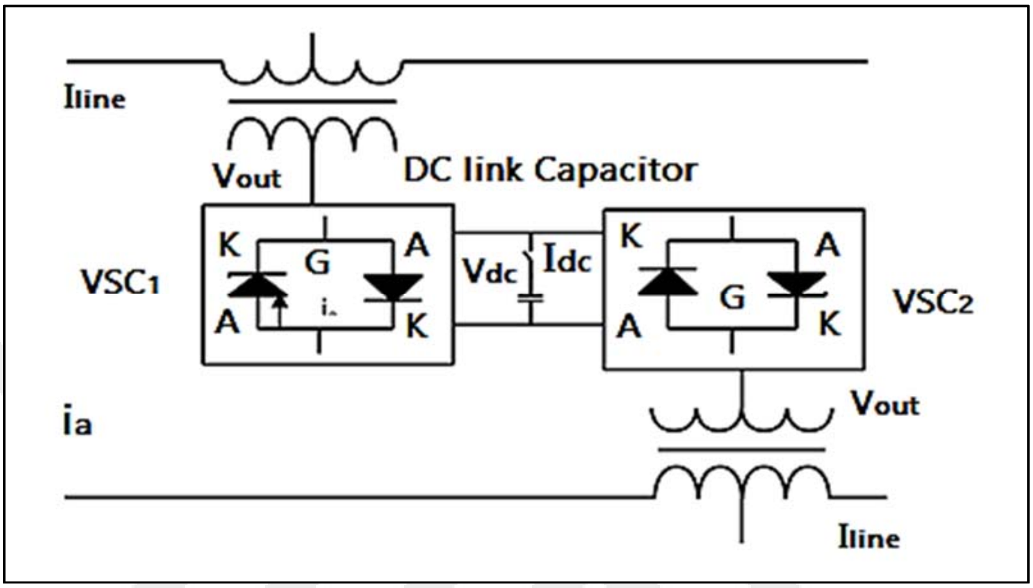


Figure 1.13: Block diagram of the interline power flow controller (IPFC).

The IPFC is comprised of two sequence VSCs whose DC capacitors are joined. This scheme enables real power circulation between the VSCs.

The Generalized Unified Power Flow Controller (GUPFC) or multi-line UPFC, as seen in Figure (1.14), combines a number of shunt and series converters, thus extending the power flow control and voltage capabilities behind what the known two-converter UPFC can already achieve. The most fundamental configuration of the GUPFC consists of one parallel and two series converters with two transmission lines at a substation. It can be extended to control more power system parameters such as the bus voltage, and independent real and reactive power flows through a number of transmission lines. GUPFC configuration may be further extended to adjust power inflows of more transmission lines or a sub-network if required. Power transfer capability of existing transmission lines has significantly been increased by incorporating GUPFC systems.

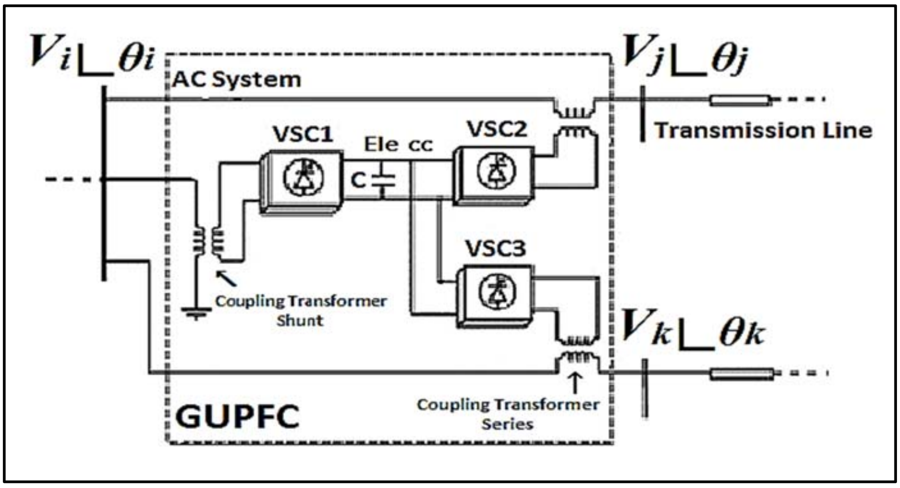


Figure 1.14: Block diagram of generalized unified power flow controller (GUPFC).

1.5 Literature Survey

The study of the literature indicates that much work has been accomplished in the field of FACTS controllers and SSSC; however, there is still a great necessity to improve the strategy in real and reactive power control and enhance the transient stability. The application of SSSC in long-distance power transmission networks has received a great deal of attention from researchers in the last decades. SSSC can improve several aspects of transmission system performance such as transient stability, sub-synchronous resonance damping and the damping of power oscillations thanks to its ability to provide continuous and rapid control of reactive power and voltage. Integrating energy storage systems to FACTS devices greatly improves the overall performance of a transmission system.

Fawzi A. Rahman AL Jowder (2004) explained the series capacitive compensation of transmission lines by a collection of SSSCs, and dielectric condensers lower the cost of series compensation. An SSSC has two functions: (1) to provide some series capacitive reactance compensation; (2) to damp out incipient unstable Sub-synchronous Resonance (SSR) modes. The SSSC has two modes of operation: (1) the constant reactance mode, in which the SSSC voltage is proportional to the line current, and (2) the constant quadrature voltage mode, in which the SSSC voltage is a constant quadrature voltage independent of the line current [14].

The SSSC has been utilized in various research articles and studies on power systems that aim to improve system performance. Cristina I. Terek has carried out a control of real power on AC transmission lines using a new static synchronous series compensator, (1999) [15].

The first step leading to 6-pulse, 12-pulse and 24-pulse inverters for the SSSC was a modest 3-level voltage source inverter. Amir H. Norouzi and Sharaf have proposed control structures that improve the dynamic performance of the SSSC (2005) [16].

Bhalani Kamal Kumar K. and Ass. Prof. Piyush Dodiya describe the improvement of power transfer capability in the IEEE 4 bus 2 machine system using SSSC. It is known that the series controller always contributes a better performance for power transfer capability through the transmission line. Here, SSSC has been used as a switching converter type series compensation. Power oscillation damping has been incorporated into a controller to dampen the oscillation. Simulation results show that after installing an SSSC between two buses, the power flow has been improved (2016) [17].

Irfan Unal (2011) explained the Damping of Power Oscillations by using an SSSC-founded half-breed series capacitive compensation form. This research presents the products of digital time-domain emulation research that have been accomplished to research the activities of a phase imbalance half-breed single-phase-SSSC form in damping oscillations of the power system in the multi-machine power system [18].

Anil Pradhan and Lehn (2006) [19] presented an analytical formulation of the frequency domain characteristics of the SSSC. The Vq control and the XSS control of SSSC were discussed. The influence of the parameters of the controller on the SSSC characteristics was studied.

C. Udhaya Shankar, Dr. Rani Thottungal, S. Mythili (2015) proved the regarding the problem of power flow control in a transmission network that with the assistance of an SSSC, the power oscillations could be damped. Because of the large demand on electrical transfer power system has initiated the system to load heavily leading to voltage unbalance situations. The SSSC is able to deliver a compensating voltage with an inductive and capacitive domain [7].

Kumkratug and Laohachai proposed a control strategy for an SSSC by presenting an energy function of a feeding structure with an SSSC component. This paper suggests the energy term function of a power system with an SSSC component. They make it viable for indirect manner to obtain the transient stability status or sensitive clearing time evaluation of an electrical power system. The suggested energy function of a power system network with an SSSC is a main derivative, and then it is applied to SSSC to regulate management of design.

Then it is applied to SSSC to control and manage design. The energy function is used for the analysis of the transient stability. The critical compensation time has been estimated from the proposed energy function and is compared with the time domain simulation method. The mathematical modeling and control strategy for the improvement of the transitional stability for the SSSC was presented by Prechanon Kumaratunga. Here, the SSSC is symbolized by a mutable voltage insertion with an associated transformer leakage reactance and the voltage source. The oscillating curves were presented and analyzed (2007) [20].

An SSSC built with a 48-pulse inverter on the power request of the network was discussed by Taha Selim Ustun and Saad Mekhilef (2010) [21]. The compensation improved by the SSSC and its effects on transmission line voltage, transmission line current, phase angle and P/Q power were analyzed. The Total Harmonic Distortion (THD) analyses were also completed to find the harmonic content.

Due to new developments in power electronics, FACTS devices have gained good popularity in recent years. FACTS devices have been generally used to solve several power systems and adjust problems such as voltage regulation, power inflow regulators, and transfer capacity improvement, damping the modes of the inter-area and improving the stability of the overall system.

Tariq Masood discussed the HVDC/FACTS management control device implementation framework in the Gulf Cooperative Council’s (GCC) international locations. It comprises of five layers of facts control management (STATCOM, SSSC, UPFC, HVDC and centralized/de-centralized management control). This 5-layer architecture is designed in order to configure and bring preferred results. Primarily based on these outcomes, GCC power system community control and operational troubles may be diagnosed and addressed in the management control architecture on the GCC power grid (2012) [22].

The different regulators based on power electronics regulate the supply flow and the emission voltage. Moreover, they attenuate any dynamic turbulence. The major purposes of FACTS are to raise the usable transmission capability of the transmission lines and regulate the inflow of power on the designated transmission routes. Hingorani and Gyugyi (2000) proposed the concept of FACTS [23].

There are two generations for FACTS controllers based on power electronics. The first generation uses conventional thyristor switching capacitors and reactors, and quadrature valve change transformers. The second generation uses thyristor switching (Gate Turn-Off) (GTO) as voltage source converters. The first generation resulted in Static Var Compensation (SVC), thyristor control series capacitor (TCSC) and thyristor controlled phase shift (TCPS). The second generation created the STATCOM, SSSC, Unified Power Flow Controller (UPFC) and Interline Power Flow Controller (IPFC). The two FACTS control teams have distinctly various working and performance features.

The configuration organized by the thyristors comprises capacitor and reactor batteries with fast semiconductor switches in branch devices or sequence circuits. By varying the periods of activation and deactivation of the thyristor switches, variable reactance values of the fixed capacitor and of the reactor banks can be obtained.

The FACTS controller configuration of the VSC has automatically switched AC to DC converters, utilizing GTO thyristors, which can inwardly create a capacitive and inductive reactive power for line compensation without the use of capacitors or reactor stores. A converter with an energy bank device can also interchange real power (P) with the system, in addition to the independent reactive power control. Yong-Hua Song and Allan T. Johns (1999) proposed that VSC could be used uniformly to adjust the voltage, impedance, and corner of a transmission line by provisioning reactive bypass compensation, serial compensation, and a phase shift, or to directly adjust the P and Q power flux in the transmission line [24].

Hanson et al. (2002) described the emergence of second-generation FACTS devices as serious alternatives to conventional devices [25].

Later, the Multiple-input, Multiple-output (MIMO) controller was designed by Ghaisari et al. (2005) to increase the damping of the power oscillation and regulation of the DC link voltage [26]. Since the SSSC in the power system results in a multivariable system with effective interactions between its state variables, multivariate control strategies and techniques should improve its performance.

In an advanced power system, the fault case in the system is estimated, which leads to power oscillation and an unsteady state in the system. Therefore, the damping of power oscillations is an important issue of concern when dealing with the stability of a power systems model. The major aim of this paper is to mitigate power system oscillations, which has been considered as one of the major causes for concern in power system operation. The study above was presented by Kiran Yadav, Kuldeep Kumar Swarnkar (2015) [27].

Habibur, Md. Fayzur Rahman, Harun studied and explained the variety of new and different types of SSSC model controllers and compared their performance for different types of faults through transient conditions to enhance the voltage level of a large-scale power system. Thus, the grid differential equations were changed by a set of algebraic equations at a fixed frequency, which dramatically deteriorates the simulation time. Moreover, this study contributes to the enhancement of the transient stability of multi- machine power systems by using virus-type SSSC controllers such as POD, PI, PID, PLL and generic controller methods. The power system response was simulated and evaluated through single and 3-phase faults supplied to the end terminals. This work is presented to enhance voltage stability and damping out of their performance to improve the stability of power systems. Simulation and analysis results show that an SSSC with controllers effectively enhances the stability of a multi-machine power system [28].

Rusejla Sadikovi´C presented aim of this dissertation is to examine the ability of FACTS devices, such as TCSC, UPFC and SVC controller devices for power flow control and the damping of electromechanical oscillations in a power system. Power flow control planning is based on the linearization of active and reactive power about an operating place. A control strategy for the damping of oscillations system, including many FACTS models and PSSs, is based on a variety of approaches, both (off-on) line, residue-based methods and pole shifting approaches (2006) [29].

Geethalakshmi et al. (2008) developed a fuzzy-based SSSC controller to enhance the transient stabilization of a single machine unlimited bar power system operation [30]. The SSSC is designed by means of a voltage source inverter with 48 pulses. Fuzzy logic controllers are designed to work the SSSC component in an automatic inflow regulated mode.

1.6 Literature Survey Conclusion

A detailed study of the literature was carried out in the fields of SSSC, FACTS devices, and corresponding control systems. It is clear from the literature survey that SSSC has broad applications in the fields of power flow control, transient stability improvement, voltage stability, power oscillation damping and the damping of sub-synchronous oscillations. Many works in general and intelligent control systems were discussed. The PI controller is effective for linear systems where mathematical models are available including intelligent controllers such as fuzzy logic, neural networks, neuro-fuzzy controllers, and so on. These offer good performance for non-linear and dynamic systems.

CHAPTER TWO

STATIC SYNCHRONOUS SERIES COMPENSATOR (SSSC)

2.1 Introduction

An SSSC component is a series-connected converter type FACTS scheme. It inserts a manageable voltage in sequence with a line at the major frequency by using a VSC with a coupler transformer. This injected voltage is a closely sinusoidal AC voltage with varying values and phase angles. The quadrature motif of the inserted voltage can be lagging or leading the line current by 90° such that the reactive power is removed or created. This prepared both capacitive and inductive compensation. Furthermore, the motif of the inserted voltage in phase with the transmission line current allows the SSSC to exchange real power and provide resistive compensation. Resistive compensation is very useful for power oscillation damping. These reactive and resistive compensations affect the power flow in the transmission line [15].

The suggested meaning for the SSSC by IEEE's FACTS Terms and Definitions Task Force of the FACTS Occupied Group of the DC and FACTS Subcommittee is as follows:

SSSC: A static, synchronous creator worked without an outer electric energy provenance as a sequence compensator whose o/p voltage is in quadrature with, and manageable independently of, the transmission line current for the goal of decreasing or increasing the total reactive voltage drop towards the line and that manner adjusting the transferred electric power. The SSSC component might contain transiently estimated energy storage or energy absorbing devices to boost the dynamic state of the power system operating by extra temporary active power compensation, to increase or decrease momentarily, the total real (resistive) voltage drop at the transmission line.

SSSC is a FACTS family member whose output voltage is manageable independently of the transmission line current. It is linked in sequence with a power system and it contains a voltage source converter that creates a manageable alternating current voltage at the central frequency. When the injected voltage is saved in quadrature with the transmission line current, it can act as either inductive or capacitive reactance in order to compensate for the power inflow along the transmission line. An SSSC is primarily supposed to regulate power inflow in steady state cases; however, it can also be utilized to enhance the transient stability.

In order to boost the dynamic disposal of the power system, the SSSC might also comprise a transiently fated energy source or energy absorbing appliance. This prevails temporary real power compensation by altering the total active voltage drop on the transmission line.

The SSSC incorporates a solid-state voltage source inverter that injects a close-to-ideal sinusoidal voltage of a variable magnitude in series with the transmission line. This has a similar structure to the STATCOM apart from the coupling transformer that is linked in sequence with the line. To compensate for the losses in the inverter, a part of the injected voltage that is in phase with the transmission line current is used. However, almost all of the injected voltage that is in quadrature together with the inflow of the transmission line current acts as series inductance or capacitance, thereby altering the transmission line series reactance. This emulated reactance, which can be altered by varying the magnitude of the injected voltage, favorably affects the electric power inflow on the line. The structure of the SSSC is presented in Figure (2.1).

Overall, an SSSC can be considered analogous to an ideal synchronous voltage source as it also generates three-phase AC voltages with controllable amplitudes and phases at the desired fundamental frequency. It also prefers a synchronous compensator as it can create or absorb reactive power from a power system and it can, independently from the reactive power, create or absorb real power if an energy storage device rather than a DC capacitor is utilized in the SSSC.

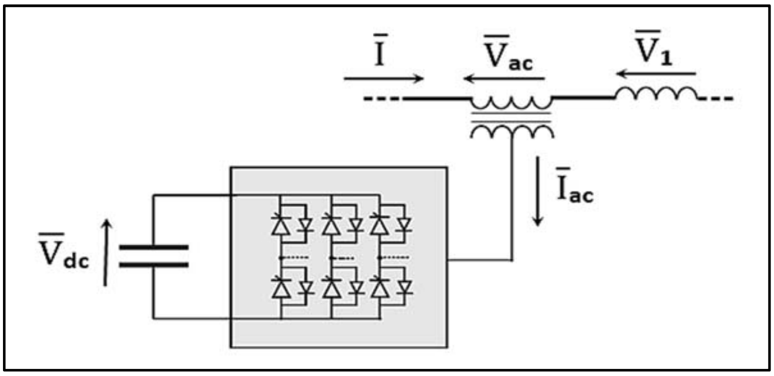


Figure 2.1: Basic SSSC structure.

2.2 Configuration, Topology and Principle of Operation

The SSSC controller contains a solid-state voltage source converter with many GTO thyristors or similar semiconductor switches with intrinsic turn-off capability, a DC capacitor, a transformer and a controller.

Many of these VSCs can be linked through a complex transformer that can be custom made in most cases. The desired quality of the SSSC generated waveforms affects the configuration of the transformer and the number of valves to be used. Another approach involves PWM-controlled VSCs where the quality of the AC output waveforms depends on the switching frequency.

Series reactive power compensation is obtained by controlling the equivalent impedance of a transmission line so as to regulate the power inflow along the transmission lines. The series connection of capacitor banks was the first method of series compensation. However, the impossibility to control in real time the level of compensation and the risk of initiating potentially dangerous resonances constitute serious drawbacks to this solution.

The SSSC can be defined as a static synchronous generator that acts as a series compensator with a fully controllable output voltage, which is independent of the transmission line current. It is preserved in quadrature with the line current in order to decrease or increase the voltage drop at the transmission line to control the power flow.

The basic structure of an SSSC and its connection with the network is depicted in Figure (2.1). SSSC operation is illustrated by the equivalent circuit of a lossless transmission line of Figure (2.2), where the compensator injects a voltage Vq.

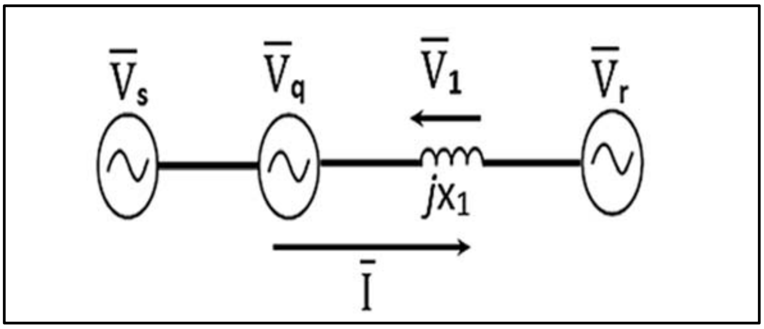


Figure 2.2: SSSC operation equivalent circuit of a lossless line.

The corresponding phasor diagram is depicted in Figure (2.3). Series injected voltage Vq is in quadrature with respect to transmission line current and it can supply either capacitive or inductive compensation where V_s and V_r are the values of the receiving and sending end voltages, respectively. δ (defined as the load corner) is the angle in the midst the receiving and sending end voltages.

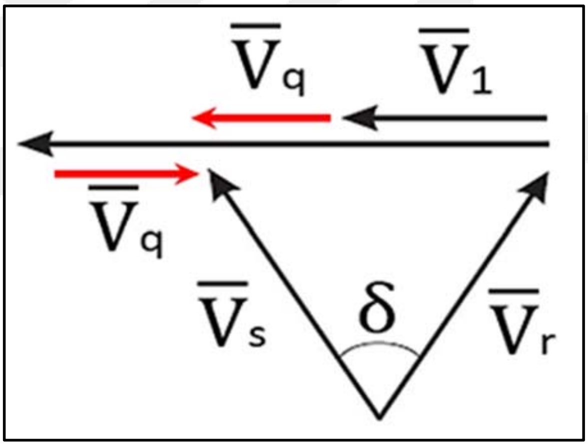


Figure 2.3: SSSC phasor diagram.

2.3 Modes of Operation

It is well known that series capacitive compensation using fixed dielectric capacitors improves synchronizing and damping powers; therefore, it increases the steady-state and transient stability limits of a radial power system. However, because of Sub Synchronous Resonance (SSR) instability, the use of series capacitors has been limited to power systems where series capacitors cannot cause SSR instability. For power systems with SSR instability, the capacitors can be replaced entirely by, or partially by, TCSC or SSSC. Since the SSSC is the subject of this thesis, the study focuses on the SSSC only. Figure (2.4) shows the SSSC device in voltage injection mode.

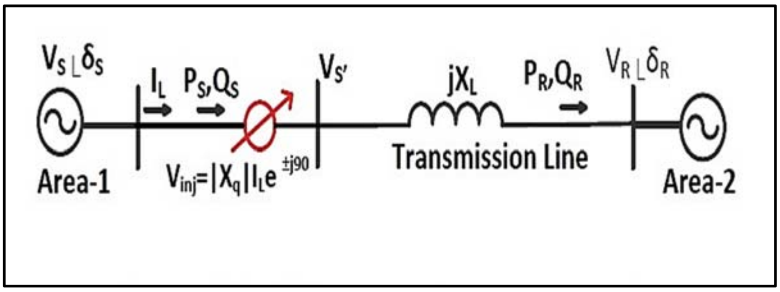


Figure 2.4: The SSSC device in voltage injection mode.

Figure (2.5a) below explains the various operating methods in a steady state case for an SSSC composite in the easy two-machine electrical power system manner. The no compensation manner of employment of the SSSC ($V_{sssc} = 0$) is illustrated as in Figure (2.5b). Figure (2.5c) explains the capacitive compensation mode where, as an effect of the SSSC inserted voltage ($V_{sssc} = -j\,V_{sssc}\,(\zeta)\,\frac{I}{I}$), the effective inductive reactance between the two buses is reduced and the line current is increased. This results in growth of the transferred power. Figure (2.5d) displays the SSSC's inductive manner of operation where the transferred power is reduced due to the insertion of ($V_{sssc} = +j\,V_{sssc}\,(\zeta)\,\frac{I}{I}$), where ζ is defined as a selection control parameter, and I is defined as the line current [18].

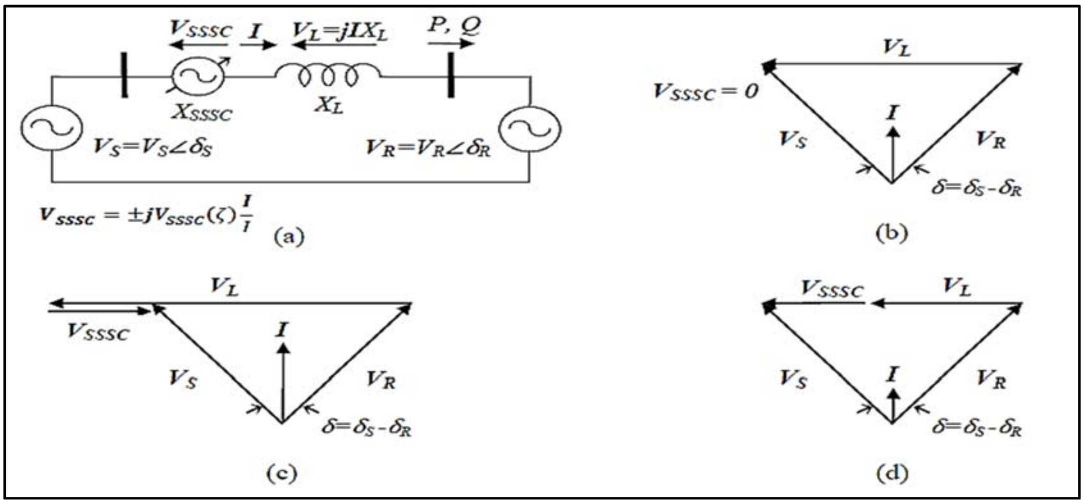


Figure 2.5: (a) Phasor diagrams of SSSC employment styles in a two-machine electric power system (b) without compensation, (c) the compensation is capacitive, and (d) the compensation is inductive.

The injected AC voltage (Vq) in Figure (2.2) also contains a small portion of the voltage that is in phase with the transmission line currents, causing a loss of power in the converter. The ability of the SSSC to instantaneously change the injected voltage will dynamically affect the power flow in the transmission line.

As mentioned above, the addition of an energy source (operating in an impedance controller) allows the control of both the active and reactive power transmitted by the line. To reach the maximum power flow, the injected voltage always lags the line current, so the level of compensation in the transmission line will increase (capacitive model). If the objective is a reduction in the power flow, the line current is driven by the injected voltage and the compensation level in the transmission line will decrease (inductive mode). The receiving end power set by the SSSC reactive compensation (Xq) is expressed by the following equations [10]:

$$P_R = \frac{V_s V_R}{X_L\left(1 - \frac{X_q}{X_L}\right)} (\sin\delta)$$

$$Q_R = \frac{V_s V_R}{X_L\left(1 - \frac{X_q}{X_L}\right)} (1 - \cos\delta)$$

The relation between the mode of operation and the resultant sending and receiving end powers with the level of compensation are depicted in Figure (2.6).

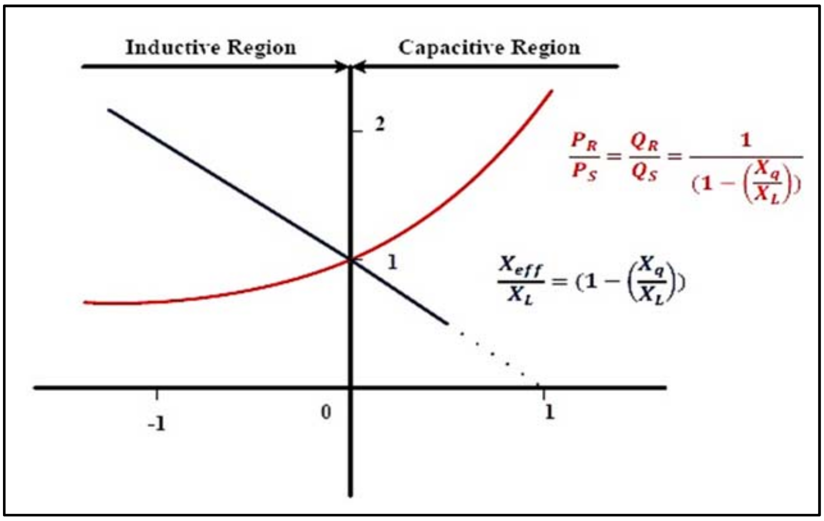


Figure 2.6: SSSC modes of operation.

In the general system, the active and reactive power flow on a line between two ends is a function of the magnitude of the voltage at both ends, the line impedance and the load angle. The equations are written thus [15]:

$$P = \frac{V_s\, V_r\, sin\delta}{X_L}$$

$$Q = \frac{V_s\, V_r\, (1 - cos\delta)}{X_L}$$

Where: V_s and V_r are the magnitudes of the voltage at the two ends $|V_s| = |V_r| = |V|$, X_L is the line impedance (assumed purely inductive) and $\delta = \delta_s - \delta_r$,which is the load angle.

2.4 Analysis and Modelling

Similarly, to the static phase shifter, the SSSC inserts voltage in quadrature with the transmission line current for active power flow regulation in the steady state. However, as the SSSC does not require reactive power from the system, it is much more effective and versatile than the static phase shifter. The DC capacitor of the SSSC provides its own reactive power. This feature enables the SSSC to regulate both the active and the reactive power flow. Figure (2.7) illustrates the SSSC schematic representation and its equivalent circuit [9].

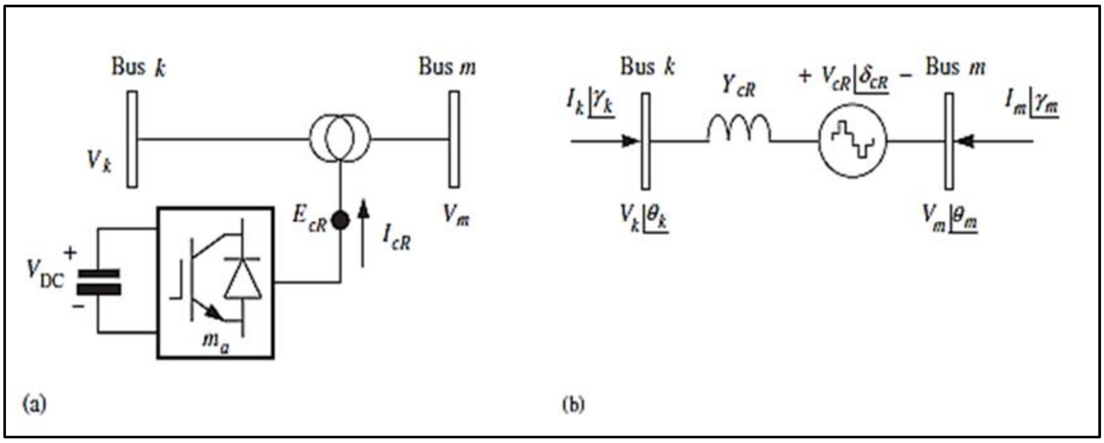


Figure 2.7: Solid-state series compensator (SSSC) system: (a) voltage source converter (VSC) connected to the AC network using a series transformer, and (b) series solid-state voltage source.

The series voltage source of the three-phase SSSC may be represented by:

$$E_{cR}^{\rho} = V_{cR}^{\rho}\left(\cos\delta_{cR}^{\rho} + j\sin\delta_{cR}^{\rho}\right)$$

Where ρ indicates phase quantities, a, b and c.

The magnitude and phase angle of the SSSC model is adjusted using any suitable iterative algorithm to satisfy a specified active and reactive power flow across the SSSC. Maximum and minimum limits will exist for the voltage magnitude V_{cR}, which are functions of the SSSC capacitor rating. On the other hand, the voltage phase angle δ_{cR} can take any value between 0 and 2π radians.

Based on the tantamount circuit appearing in Figure (2.7b), and assuming 3-Ø parameters, the next transfer admittance equation can be written as [8]:

$$\begin{bmatrix} I_k \\ I_m \end{bmatrix} = \begin{bmatrix} Y_{cR} & -Y_{cR} & -Y_{cR} \\ -Y_{cR} & Y_{cR} & Y_{cR} \end{bmatrix} \begin{bmatrix} V_k \\ V_m \\ E_{cR} \end{bmatrix}$$

The following quantities can also be defined:

$$I_m^{\rho} = [I_m^a\angle\gamma_m^a \quad I_m^b\angle\gamma_m^b \quad I_m^c\angle\gamma_m^c]^T$$

$$V_m^{\rho} = [V_m^a\angle\theta_m^a \quad V_m^b\angle\theta_m^b \quad V_m^c\angle\theta_m^c]^T$$

$$E_{CR}^{\rho} = [V_{cR}^a\angle\delta_{cR}^a \quad V_{cR}^b\angle\delta_{cR}^b \quad V_{cR}^c\angle\delta_{cR}^c]^T$$

$$Y_{cR}^{\rho} = \begin{bmatrix} Y_{cR}^{aa} & 0 & 0 \\ 0 & Y_{cR}^{bb} & 0 \\ 0 & 0 & Y_{cR}^{cc} \end{bmatrix}$$

In an SSSC device, the VSC is linked to the system in sequence with the transmission line. The SSSC manager inserts voltage in quadrature with one of the line-end voltages in order to adjust the real power. However, since the VSC has its own reactive power provision in the form of a DC capacitor, it makes the SSSC device capable of regulating both P and Q power inflow within limits imposed by its rating. From the principles of operation, the SSSC device might adequately be represented by a complex voltage source in sequence with the transformer impedance. Therefore, the equivalent circuit is offered in Figure (2.8).

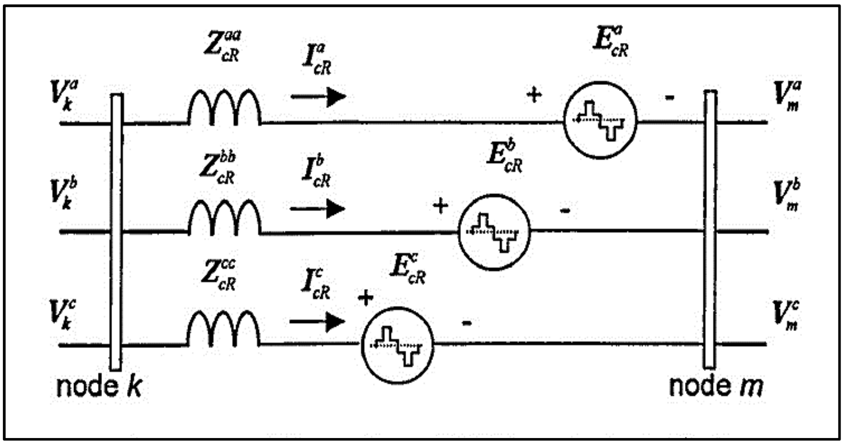


Figure 2.8: 3-phase SSSC equivalent circuit.

We can express the VSC station complex voltage sources within the SSSC in polar coordinates as:

$$E_{cR}^{\rho} = V_{cR}^{\rho} \angle \delta_{cR}^{\rho}$$

2.5 Power Oscillation Damping Controller

A great deal of relevant research in this area is based on a small perturbation analysis that greatly depends on the linearization of the involved system. It should be noted that linearization techniques cannot always capture the complex dynamics of the system appropriately, especially in the case of main turbulences. This fact creates difficulties in change of the FACTS managers, as managers adjusted to provide the desired act during small signal situations do not guarantee a satisfactory act in cases with main turbulences.

In an effort to mitigate such limitations, 3-Ø models of both the SSSC and power system components are used in this thesis. A conventional LL controller is mostly favored by the power system operating services due to the ease of its online setting as well as its assurance of stability. A comprehensive appreciation of the special effects of SSSC-based damping managers for power system stabilization enhances multi-machine power system operation. A simple lead-lag (LL) construction based organizer for the SSSC is suggested in Figure (2.9).

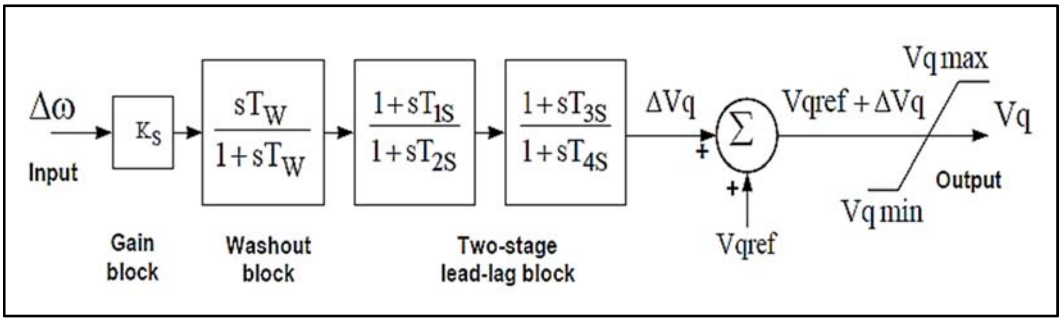


Figure 2.9: Lead-Lag block of the SSSC-based damping manager [31].

The block of an SSSC-based damping manager modifies the SSSC inserted voltage Vq. The construction contains a gain block with gain K_S, a signal washout block and a two-stage phase compensation block as displayed in the figure. The signal washout block serves as a high-pass filter, with the time constant T_W, which is sufficiently high to allow signals associated with oscillations in the input signal to pass unchanged. From the viewpoint of the washout function, the value of T_W is not critical and it might be in the range of 1 to 20 seconds [28].The phase compensation blocks (time constants T_{1S}, T_{2S}, T_{3S}, T_{4S}) provide the appropriate phase-lead features to compensate for the phase lag between input and the output signals. Vqref represents the reference inserted voltage as desired by the steady state power inflow regulate loop. The steady state power inflow loop acts quite slowly in practice and therefore, in the present study, Vqref is supposed to be constant throughout large disruption transient periods.

The usually used lead-lag block is selected in this survey as an SSSC-based organizer. The block of the SSSC manager is presented in Figure (2.9). It contains a gain block with gain K_T, a signal washout block, and a two-stage phase compensation block. The phase compensation block provides the appropriate phase-lead features to compensate for the phase lag between the I/p and O/p signals. The signal washout block serves as a high-pass filter, with the time constant T_{WT}, sufficiently high to allow signals associated with oscillations in the I/p signal to pass unchanged.

2.6 Discussion

Variable Series Compensation has been presented to be very strong effective not only in power inflow control but also as an improvement in stability [7]. By injecting control voltages in sequence with the line, SSSC provides virtual compensation to the line impedance. This virtual reactance provided by the injected voltage affects the electrical power inflow in the line and it is independent of the value of the transmission line current. The system is very stable with bidirectional power flows. Moreover, the SSSC’s response time is excellent and it has a continuous and perfectly smooth transition between positive, negative or zero voltage injection modes. Furthermore, since in all practical cases the line reactance will be superior and intrinsically limited by the injected compensation voltage, it is not possible to tune the SSSC with a finite transmission line inductance to have a conventional resonance at the major frequency. In order to suppress the oscillation of the power system, the SSSC power flow control function can also be superimposed on an auxiliary signal for stabilization purposes.

CHAPTER THREE

SIMULATION AND RESULTS FOR SSSC

3.1 Introduction

An SSSC not only damps power oscillations during system disturbances; it can also efficiently control real and reactive power in a transmission line. For inductive or capacitive compensation cases, the reference voltage that the SSSC takes as the injected or recommended scalar voltage can, in reality, be either positive or negative only. The reference voltage will always conform to the anticipated control parameter, such as when it is the real power to be controlled in the transmission line, the input of the controller will be the real power that is measured at the output, whereas the reference voltage will follow the difference between the setpoint and the line power. In an effort to attain a lower generator oscillation to avoid synchronism problems, the rate of change in the angular velocity of the generator (i.e., derivative $d\omega$) can also be fed into the controller.

3.2 Simulation Environment

The damping controller design for the SSSC and all the simulations being performed are accomplished with the software simulation environment Simscape Power Systems, a product of Simulink family from Mathworks. Simscape Power Systems is a modern design tool that allows users to build models rapidly and easily and simulate power systems. Simscape Power Systems operates in the Simulink environment. The Simscape Power Systems' main library, "Powerlib," contains three-phase models of typical power equipment, such as machines, governors, excitation systems, and transformers, lines and FACTS devices. The Powergui block is necessary for simulation of any Simulink model containing Simscape Power Systems blocks. It provides a useful graphical user interface (GUI) tools for the analysis of simulated models. The library also contains the Powergui block that opens a GUI for the steady-state analysis of electrical circuits. It performs load flows and initializes the three-phase networks containing three-phase machines so that the simulation starts in a steady state.

Simscape Power Systems provides component libraries and analysis tools for modeling and simulating electrical power systems. It comprises models of electrical power components, counting 3-Ø machines, electric drives, and components for requests such as FACTS and renewable energy systems. Harmonic analysis, the calculations of total harmonic distortion (THD), load inflow and other key electrical power system analyses are automated, thereby helping to investigate the performance of the design.

Simscape Power Systems aid to advance and regulate systems as well as examine system-level performance. Models can be parameterized using MATLAB variables and expressions, and be designed to regulate systems for simulated electrical power systems in Simulink. Mechanical, hydraulic, thermal, and other physical systems can be integrated into the model using components from the Simscape family of products. To deploy models in other simulation environments, including hardware-in-the-loop (HIL) systems, Simscape Power Systems supports C-code generation.

Key features can be summarized as:

1. Application-specific models, including common AC and DC electric drives, FACTS and renewable energy systems.
2. Phasor simulation models for faster model execution.
3. Ideal switching algorithms for accelerated simulation of power electronic devices.
4. Analysis methods for obtaining state-space representations of circuits and for computing machine load flows.
5. Basic models for developing key electrical technologies.
6. MATLAB based Simscape language for creating custom component models.
7. Support for C-code generation (with the Simulink Coder).

3.3 Design of the Main Simulation Circuit (Parts and Parameters)

The SSSC, a major member of the family of FACTS devices, is comprised of a voltage controlled converter and a transformer linked in sequence with the line. The SSSC device emulates an inductive or capacitive reactance by injecting a changeable magnitude voltage in quadrature with the transmission line current. The transferred electric power can then be influenced by the emulated changeable reactance that is in sequence with the transmission lines. By following this operation principle, the SSSC is utilized in damping the power oscillation after a three-phase fault occurs in a power grid. A snapshot of the simulated configuration is depicted in Figure (3.1) (first location).

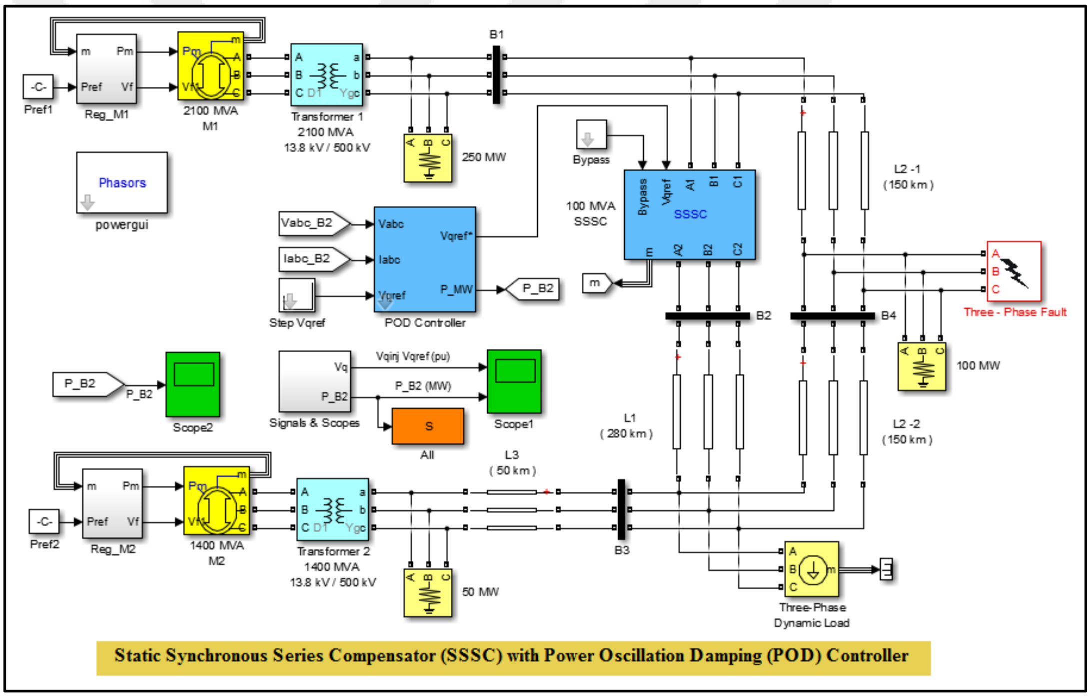


Figure 3.1: SSSC configuration simulated in the first location.

3.3.1 Power Generation

The power system grid model consists of generation plants that are simulated to be comprised of two power generation substations, M1 and M2. The first generator is connected to transformer T_1 (13.8/500 kv) in series rated at 2100 MVA and the second generator is connected to transformer T_2 (13.8/500 kv) in series rated at 1400 MVA. In addition, one main load middle point is situated at bus bar (B3).

Power Generation Station 1:

The first-generation substation plant (M1) had its capacity and generation rated at 2100 MVA and 13.8 kv, respectively, as shown in Figure (3.2).

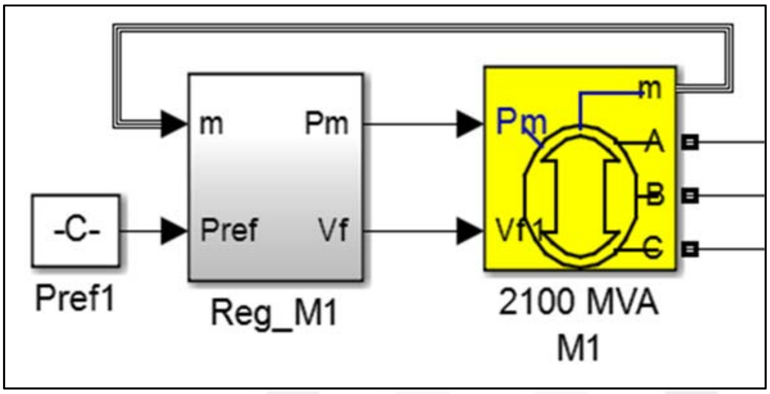


Figure 3.2: Power generation substation-1.

Power Generation Station 2:

The second-generation substation plant (M2) had its capacity and generation rated at 1400 MVA and 13.8 kv, respectively, as shown in Figure (3.3).

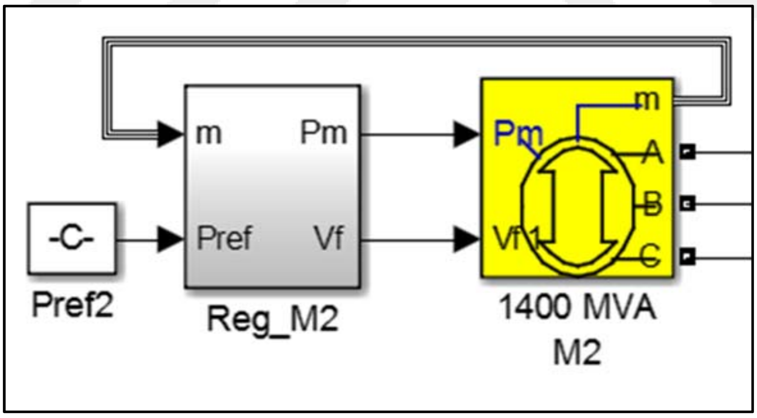


Figure 3.3: Power generation substation-2.

3.3.2 Load Center

The three-phase main load center is rated at approximately at 2200 MW and 100 MVAR at bus bar (B3), as shown in Figures (3.4) and (3.5). The dynamic load center is sited at bus-3 near to the second generation substation plant (M2), which is designated as a Dynamic Load Model (DLM) type in which the active and reactive power absorbed is a function of the system voltage. Transmission lines L1 and L2 connect this load to the generation substation M1. Transmission line L3 connects the load to generation substation M2.

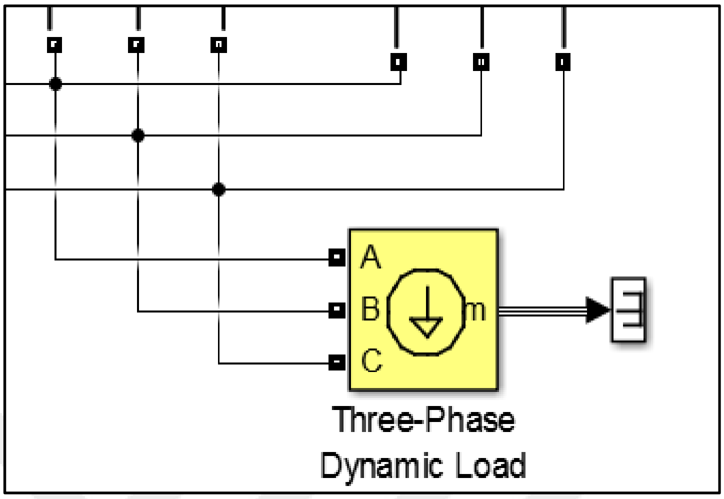
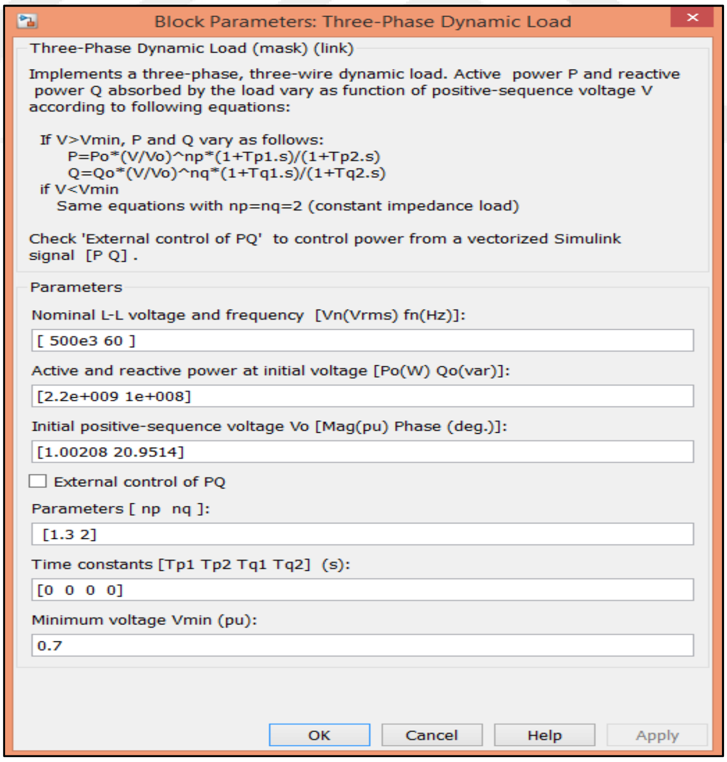


Figure 3.4: Three-phase dynamic load.



Three-Phase Dynamic Load (mask) (link)

Implements a three-phase, three-wire dynamic load. Active power P and reactive power Q absorbed by the load vary as function of positive-sequence voltage V according to following equations:

```
  If V>Vmin, P and Q vary as follows:
       P=Po*(V/Vo)^np*(1+Tp1.s)/(1+Tp2.s)
       Q=Qo*(V/Vo)^nq*(1+Tq1.s)/(1+Tq2.s)
  if V<Vmin
     Same equations with np=nq=2 (constant impedance load)
```

Check 'External control of PQ' to control power from a vectorized Simulink signal [P Q] .

Parameters

Nominal L-L voltage and frequency [Vn(Vrms) fn(Hz)]: [500e3 60]

Active and reactive power at initial voltage [Po(W) Qo(var)]: [2.2e+009 1e+008]

Initial positive-sequence voltage Vo [Mag(pu) Phase (deg.)]: [1.00208 20.9514]

☐ External control of PQ

Parameters [np nq]: [1.3 2]

Time constants [Tp1 Tp2 Tq1 Tq2] (s): [0 0 0 0]

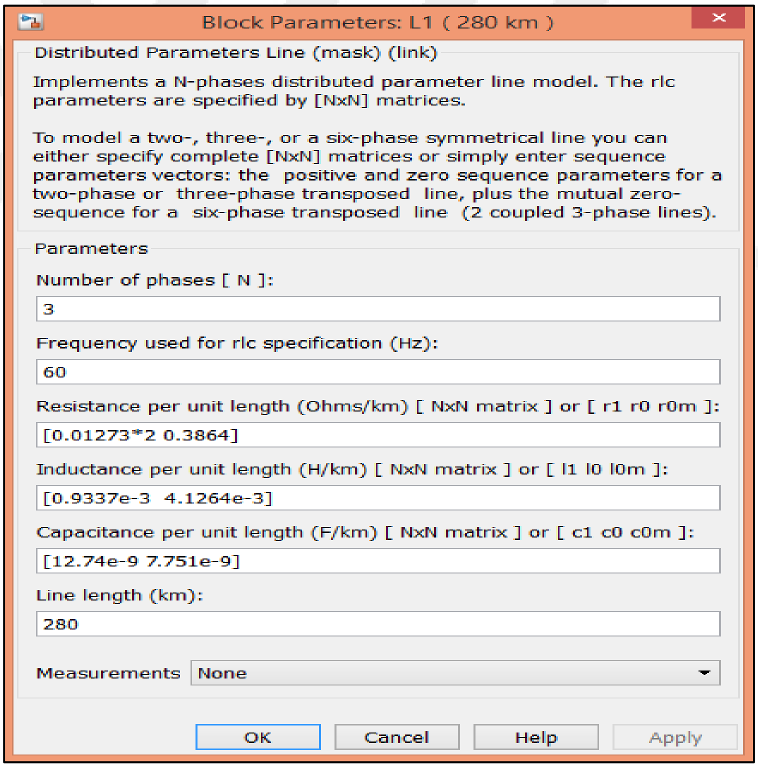
Minimum voltage Vmin (pu): 0.7

Figure 3.5: Three-phase dynamic load block parameters.

3.3.3 Transmission Lines

Power transmission lines in this simulation design include different length values, which are expressed as follows:

1- Transmission Line-1 (L1): 280 km is given in Figure (3.6).
2- Transmission Line-2 (L2): 300 km is divided into two sections with the same parameters as follows below. They simulate a 3Ø short circuit fault with the help of the fault breaker at the middle point of this line. This is explained in Figure 3.7.
    a- L2-1 = 150 km
    b- L2-2 = 150 km
3- Transmission Line-3 (L3): 50 km, shown in Figure (3.8).


Block Parameters: L1 (280 km)

Distributed Parameters Line (mask) (link)

Implements a N-phases distributed parameter line model. The rlc parameters are specified by [NxN] matrices.

To model a two-, three-, or a six-phase symmetrical line you can either specify complete [NxN] matrices or simply enter sequence parameters vectors: the positive and zero sequence parameters for a two-phase or three-phase transposed line, plus the mutual zero-sequence for a six-phase transposed line (2 coupled 3-phase lines).

Parameters

Number of phases [N]: 3

Frequency used for rlc specification (Hz): 60

Resistance per unit length (Ohms/km) [NxN matrix] or [r1 r0 r0m]: [0.01273*2 0.3864]

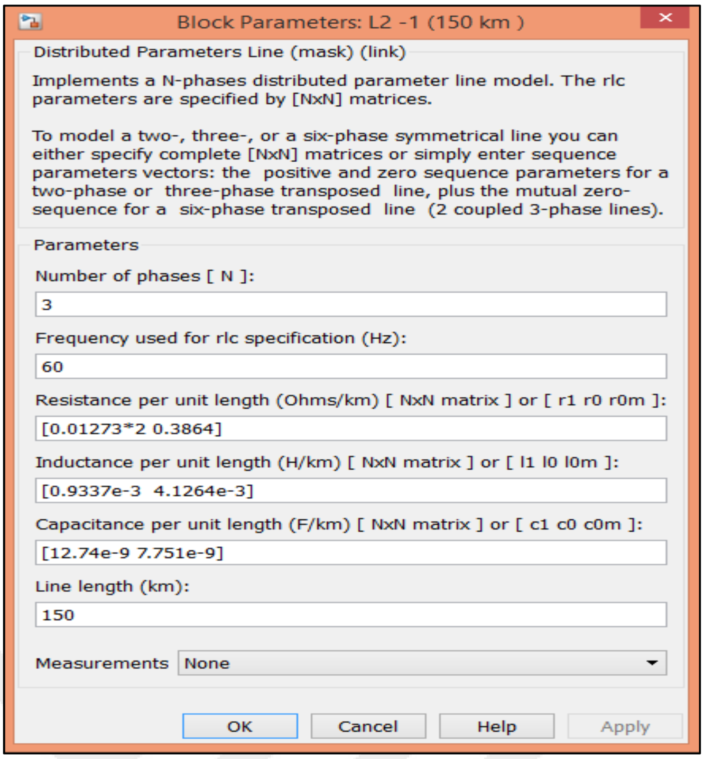
Inductance per unit length (H/km) [NxN matrix] or [l1 l0 l0m]: [0.9337e-3 4.1264e-3]

Capacitance per unit length (F/km) [NxN matrix] or [c1 c0 c0m]: [12.74e-9 7.751e-9]

Line length (km): 280

Measurements: None

Figure 3.6: Transmission line-1 block parameters.


Block Parameters: L2 -1 (150 km)

Distributed Parameters Line (mask) (link)

Implements a N-phases distributed parameter line model. The rlc parameters are specified by [NxN] matrices.

To model a two-, three-, or a six-phase symmetrical line you can either specify complete [NxN] matrices or simply enter sequence parameters vectors: the positive and zero sequence parameters for a two-phase or three-phase transposed line, plus the mutual zero-sequence for a six-phase transposed line (2 coupled 3-phase lines).

Parameters

Number of phases [N]: 3

Frequency used for rlc specification (Hz): 60

Resistance per unit length (Ohms/km) [NxN matrix] or [r1 r0 r0m]: [0.01273*2 0.3864]

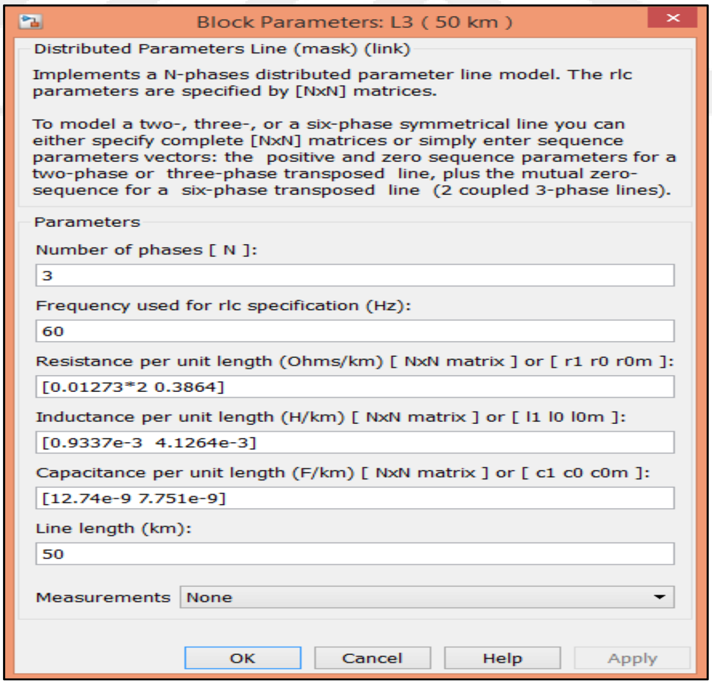
Inductance per unit length (H/km) [NxN matrix] or [l1 l0 l0m]: [0.9337e-3 4.1264e-3]

Capacitance per unit length (F/km) [NxN matrix] or [c1 c0 c0m]: [12.74e-9 7.751e-9]

Line length (km): 150

Measurements: None

Figure 3.7: Transmission line-2 block parameters.


Block Parameters: L3 (50 km)

Distributed Parameters Line (mask) (link)

Implements a N-phases distributed parameter line model. The rlc parameters are specified by [NxN] matrices.

To model a two-, three-, or a six-phase symmetrical line you can either specify complete [NxN] matrices or simply enter sequence parameters vectors: the positive and zero sequence parameters for a two-phase or three-phase transposed line, plus the mutual zero-sequence for a six-phase transposed line (2 coupled 3-phase lines).

Parameters

Number of phases [N]: 3

Frequency used for rlc specification (Hz): 60

Resistance per unit length (Ohms/km) [NxN matrix] or [r1 r0 r0m]: [0.01273*2 0.3864]

Inductance per unit length (H/km) [NxN matrix] or [l1 l0 l0m]: [0.9337e-3 4.1264e-3]

Capacitance per unit length (F/km) [NxN matrix] or [c1 c0 c0m]: [12.74e-9 7.751e-9]

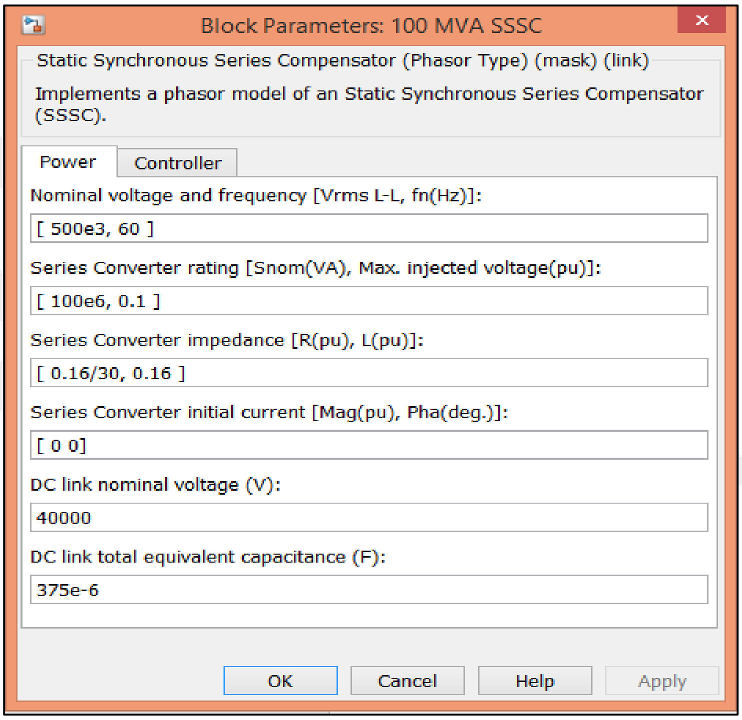
Line length (km): 50

Measurements: None

Figure 3.8: Transmission line-3 block parameters.

3.3.4 SSSC Model

The SSSC model is located at bus bar (B1) (first location). This component has the ability to inject ten percent of the nominal system voltage rated at 100 MVA. It is in sequence with line L1 and situated at bus bar (B1). As illustrated in Figure (3.9), the SSSC model used in the simulation has a nominal DC-link voltage of 40 kv and an equivalent capacitance of 375 μF. It is a 3-level pulse width modulation phasor model of the SSSC.



Static Synchronous Series Compensator (Phasor Type) (mask) (link)

Implements a phasor model of an Static Synchronous Series Compensator (SSSC).

Nominal voltage and frequency [Vrms L-L, fn(Hz)]: [500e3, 60]

Series Converter rating [Snom(VA), Max. injected voltage(pu)]: [100e6, 0.1]

Series Converter impedance [R(pu), L(pu)]: [0.16/30, 0.16]

Series Converter initial current [Mag(pu), Pha(deg.)]: [0 0]

DC link nominal voltage (V): 40000

DC link total equivalent capacitance (F): 375e-6

Figure 3.9: SSSC properties.

The total equivalent impedance at the AC side is 0.16 (p.u) at 100 MVA. This impedance denotes the phase reactor of the insulated-gate bipolar transistor (IGBT) bridge together with the leakage reactance of the transformer.

3.3.5 POD controller

The output of the POD is connected to the Vqref input to set the injected voltage reference of the SSSC, as shown in Figure (3.10).

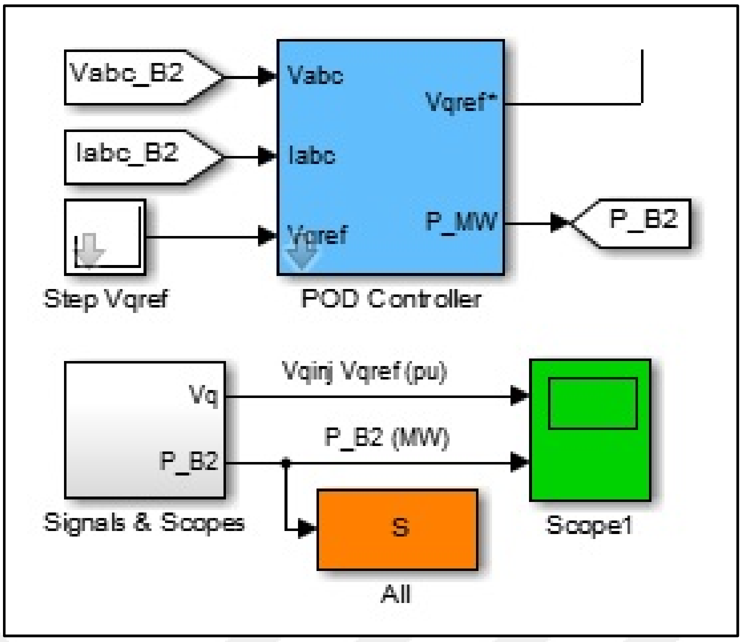


Figure 3.10: POD controller.

The POD controller is comprised of an active power measurement, gain, low-pass filter, high-pass (washout) filter, lead compensator and output limiter stages. The current in line L1 and the voltage on bus B2 are fed into the POD as inputs. In detail, the diagram of the POD control can be seen in Figure (3.11).

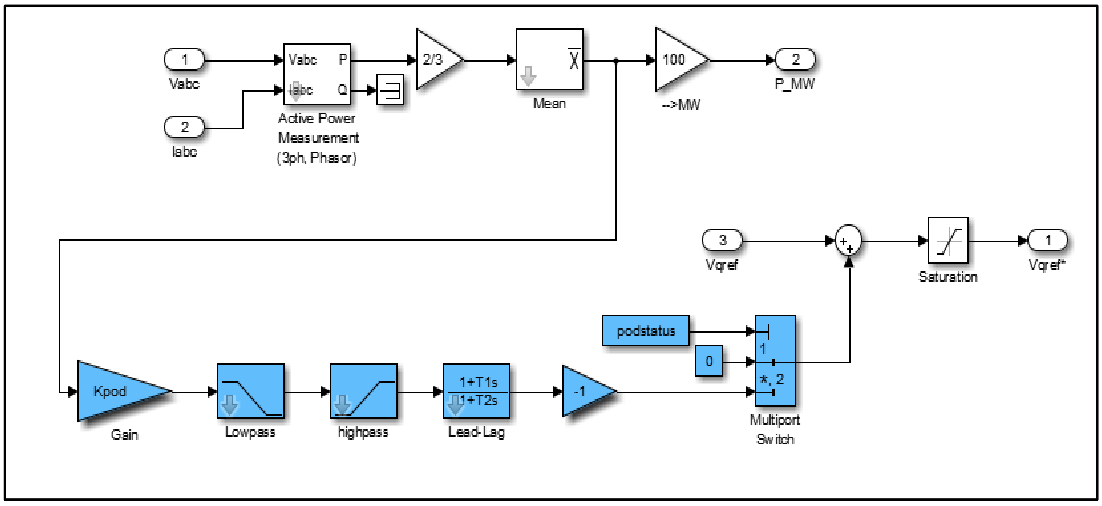


Figure 3.11: POD controller block diagram.

3.4 Case Studies

In this research, we looked at different studies that simulated design. Through this study, we also explain the importance of the work of SSSC compensation and how to control it. We present the following case studies:

3.4.1 Varying the Real Power (MW)

This case study demonstrates model validity followed by the ability of the SSSC to control power transfer on Line-1 (L1). It consists of three simulations: a system without the SSSC; power is increased and decreased on the Line-1 (L1) at B2 by the SSSC.

1- In the beginning is the first case explanation. We designed the simulation circuit model without an SSSC compensator and without control for the POD unit under the fault conditions, as seen in Figure (3.12).

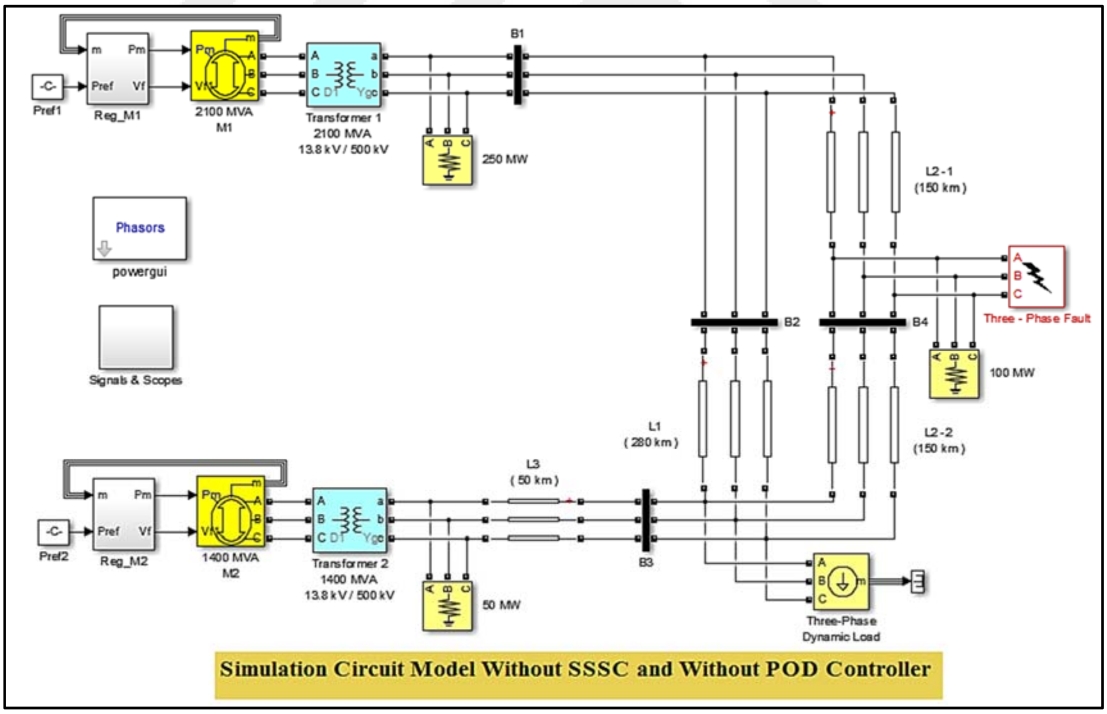


Figure 3.12: Simulation circuit model without the SSSC and without the POD controller.

When the 3-phase fault is not activated, the active power flows measured at the buses are distributed toward this main load, as summarized below:

a) B1 measurement: voltage (p.u) and 1338 MW, as given in Figure (3.13), respectively. We can find it from within the block (Signals and Scopes) from the red (Scope 4).

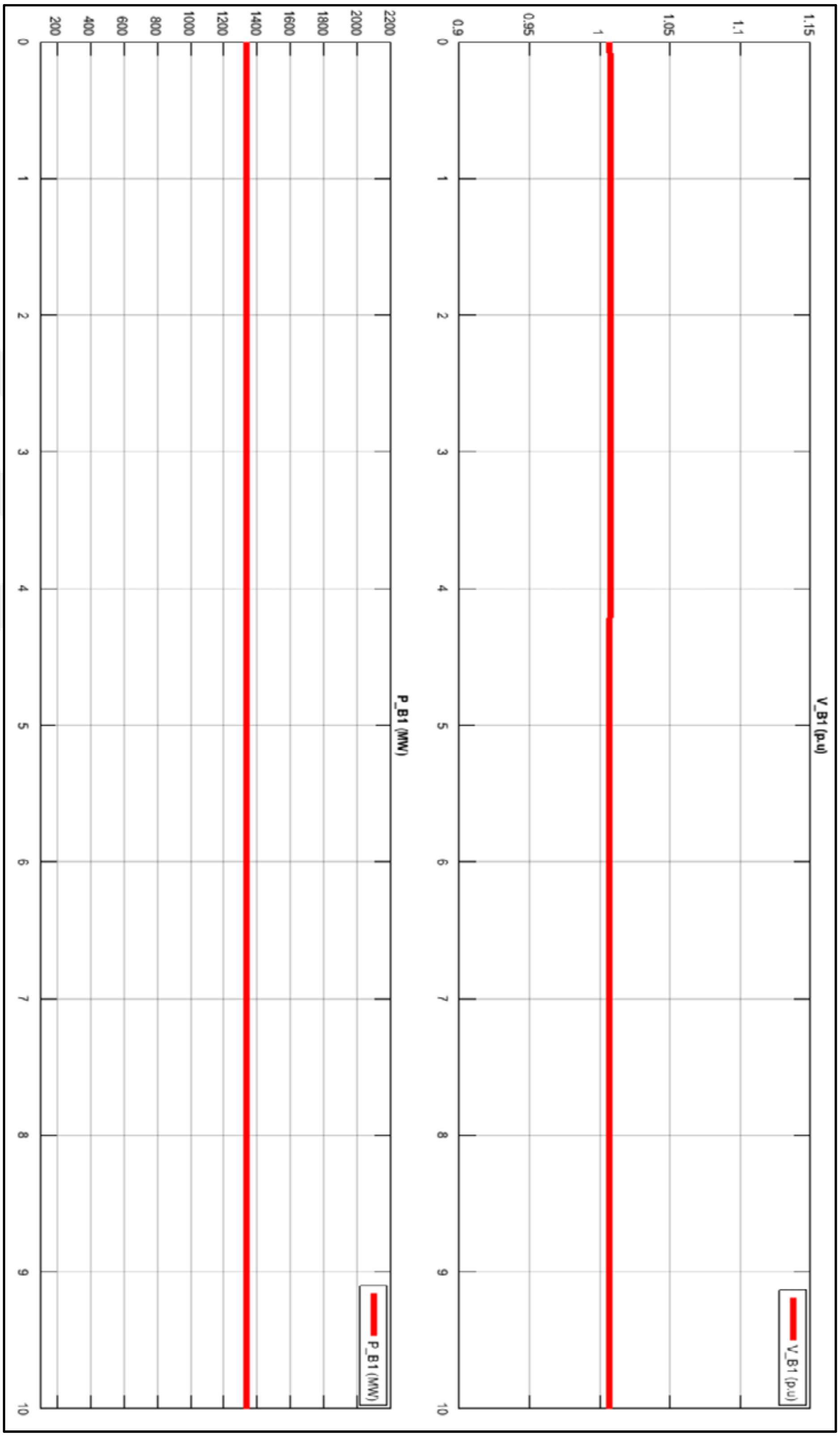


Figure 3.13: Signals of V_B1 (p.u) and P_B1 (MW) without (SSSC, POD, fault).

b) B2 measurement on Line-1: voltage (p.u) and 664 MW are given in Figure (3.14). We can find it from within the block (Signals and Scopes) from the red (Scope 2).

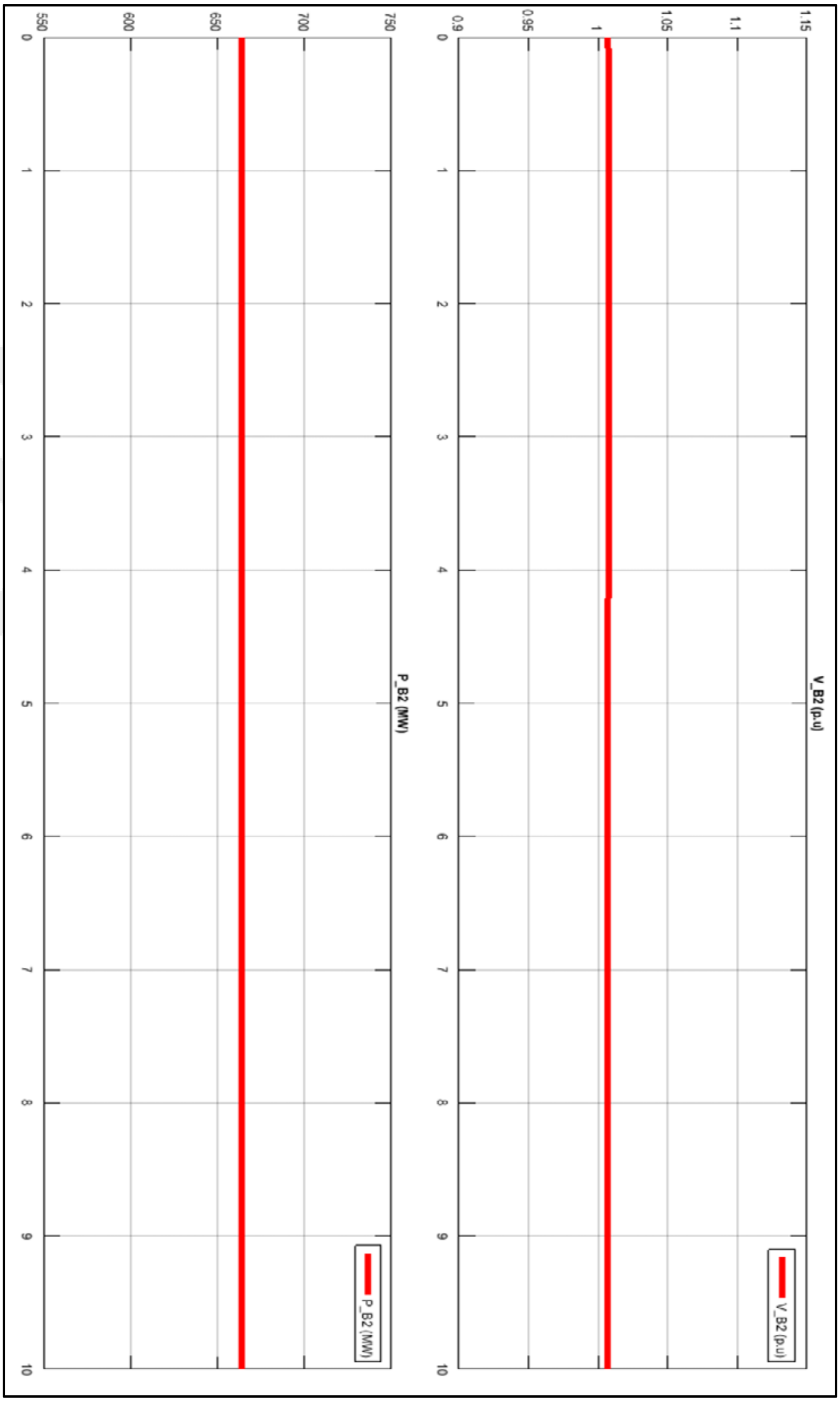


Figure 3.14: Signals of V_B2 (p.u) and P_B2 (MW) without (SSSC, POD, fault).

c) B3 measurement on the Line-3: voltage (p.u) and 990 MW, as explained in Figure (3.15). In addition, we can find it from within the block (Signals and Scopes) from the red (Scope 1).

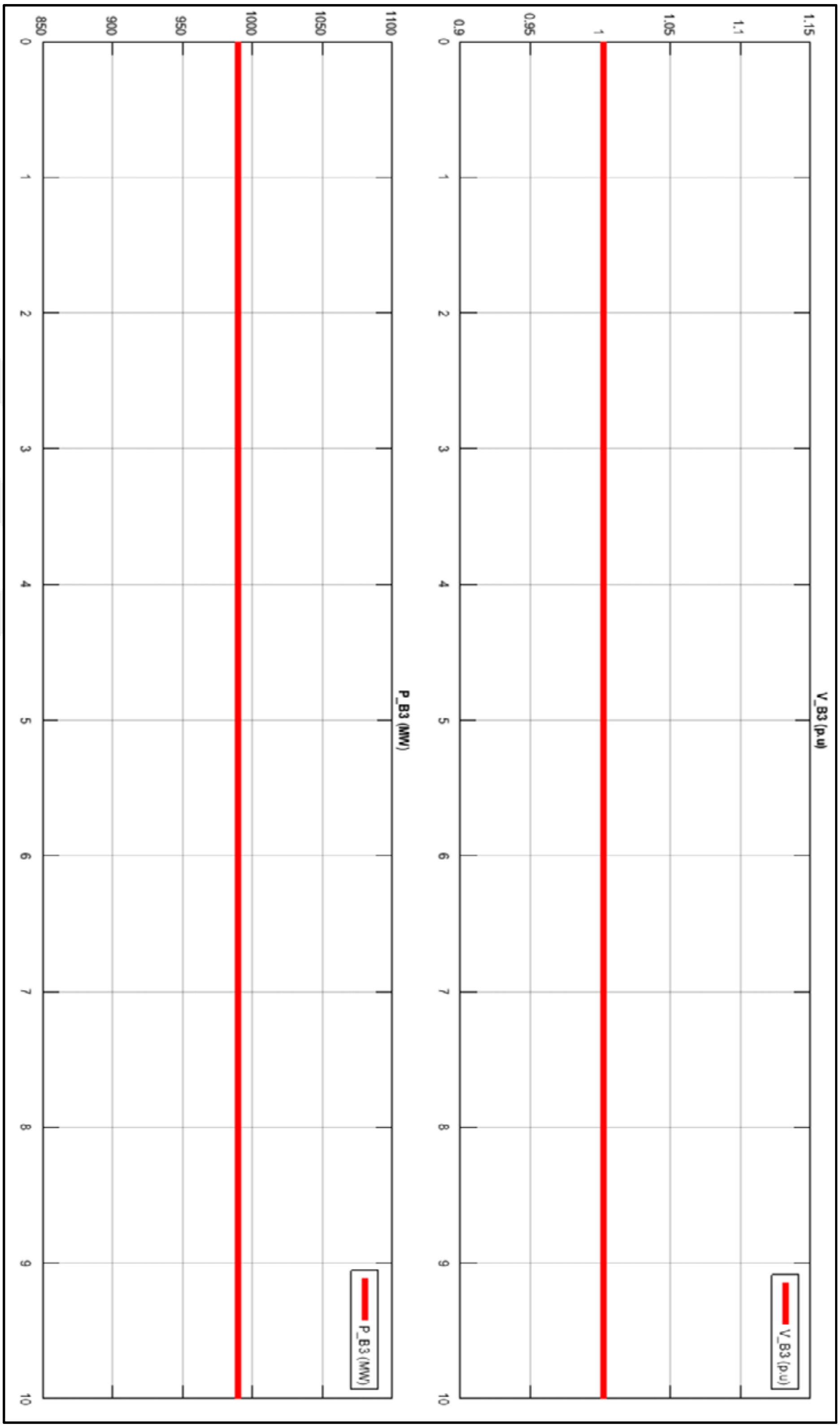


Figure 3.15: Signals of V_B3 (p.u) and P_B3 (MW) without (SSSC, POD, fault).

d) B4 measurement on Line-2: voltage (p.u), (563MW) as seen in Figure (3.16) respectively. Finally, look inside the block (Signals & Scopes) then red (Scope 3).

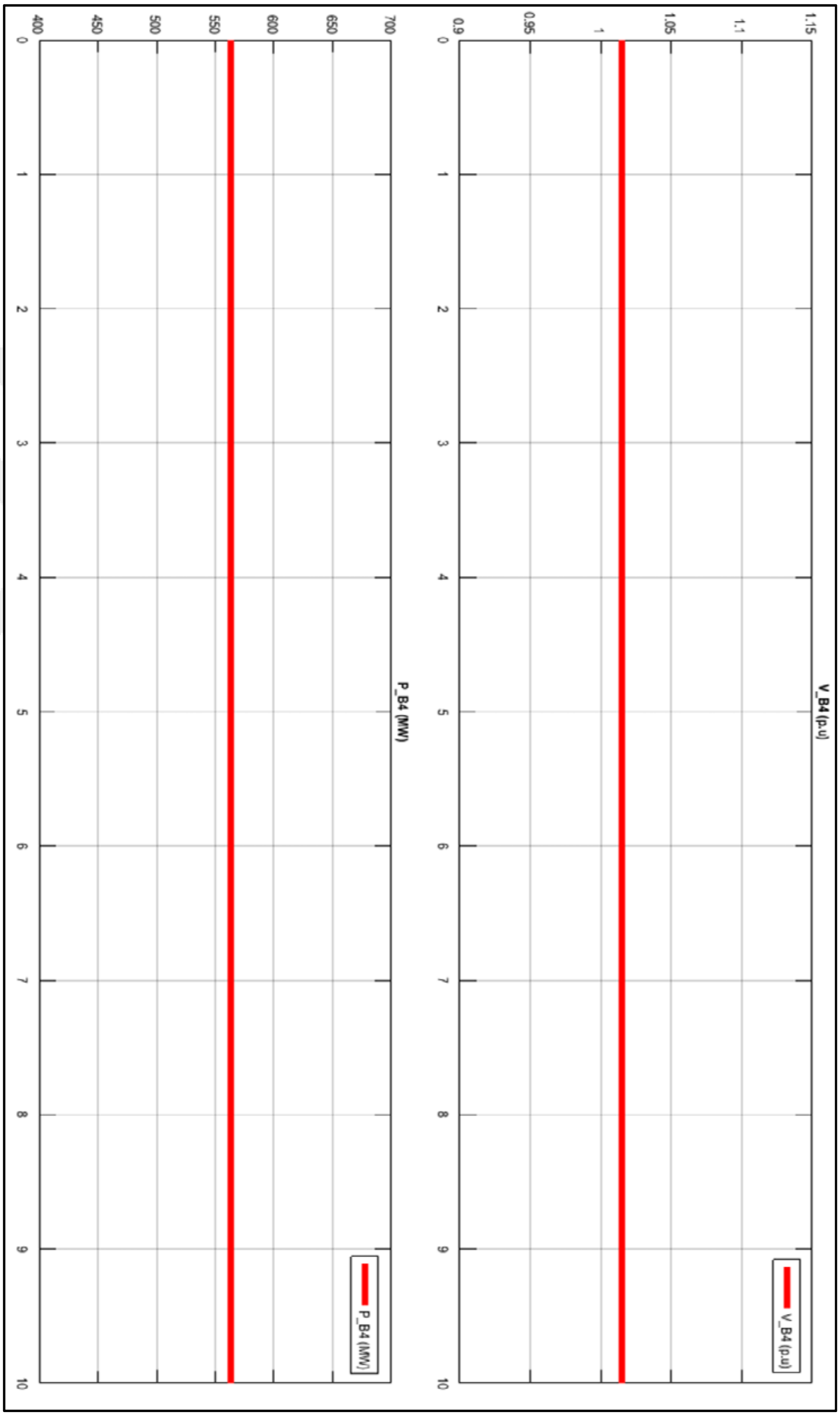


Figure 3.16: Signals of V_B4 (p.u) and P_B4 (MW) without (SSSC, POD, fault).

2- Now, we repeat the same previous applications, but this time when the 3-Ø fault is activated. To activate the simulation of the 3-phase fault, “Switching of phase A, B and C” are selected with the transition times: [20/60 30/60] + 1. This means that the fault will be started from 1.33 s to 1.5 s; that is mean will last for 10 cycles as follows:

a) B1 measurement: voltage (p.u), 1338 MW, as given in Figure (3.17). We can obtain this from within the block (Signals & Scopes) from the red (Scope 4).

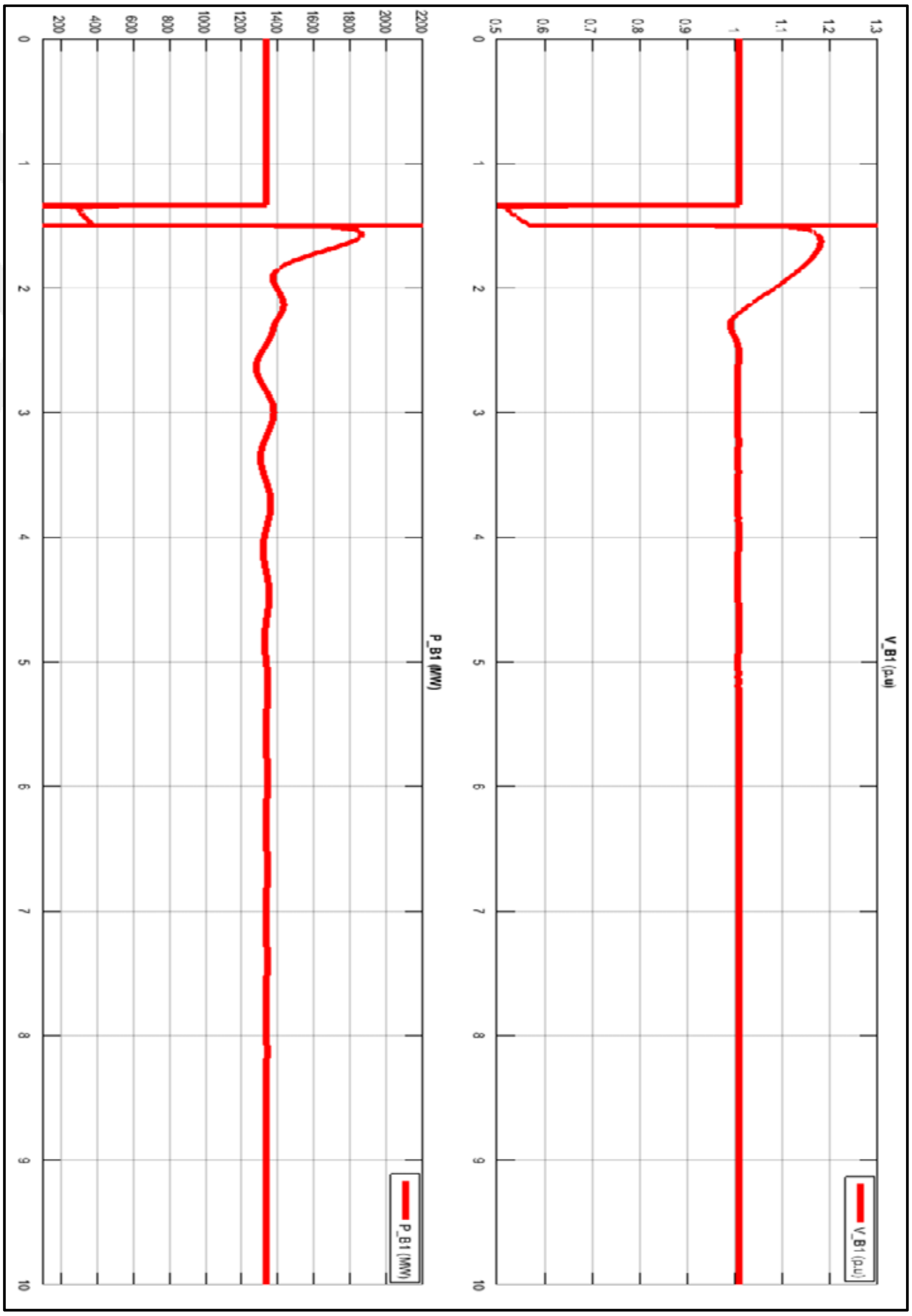


Figure 3.17: Signals of V_B1 (p.u) and P_B1 (MW) without (SSSC, POD) and with fault.

b) B2 measurement on the Line-1: voltage (p.u), 664 MW. Figure (4.18) shows oscillations, changes in waves, and the effects of the fault period.

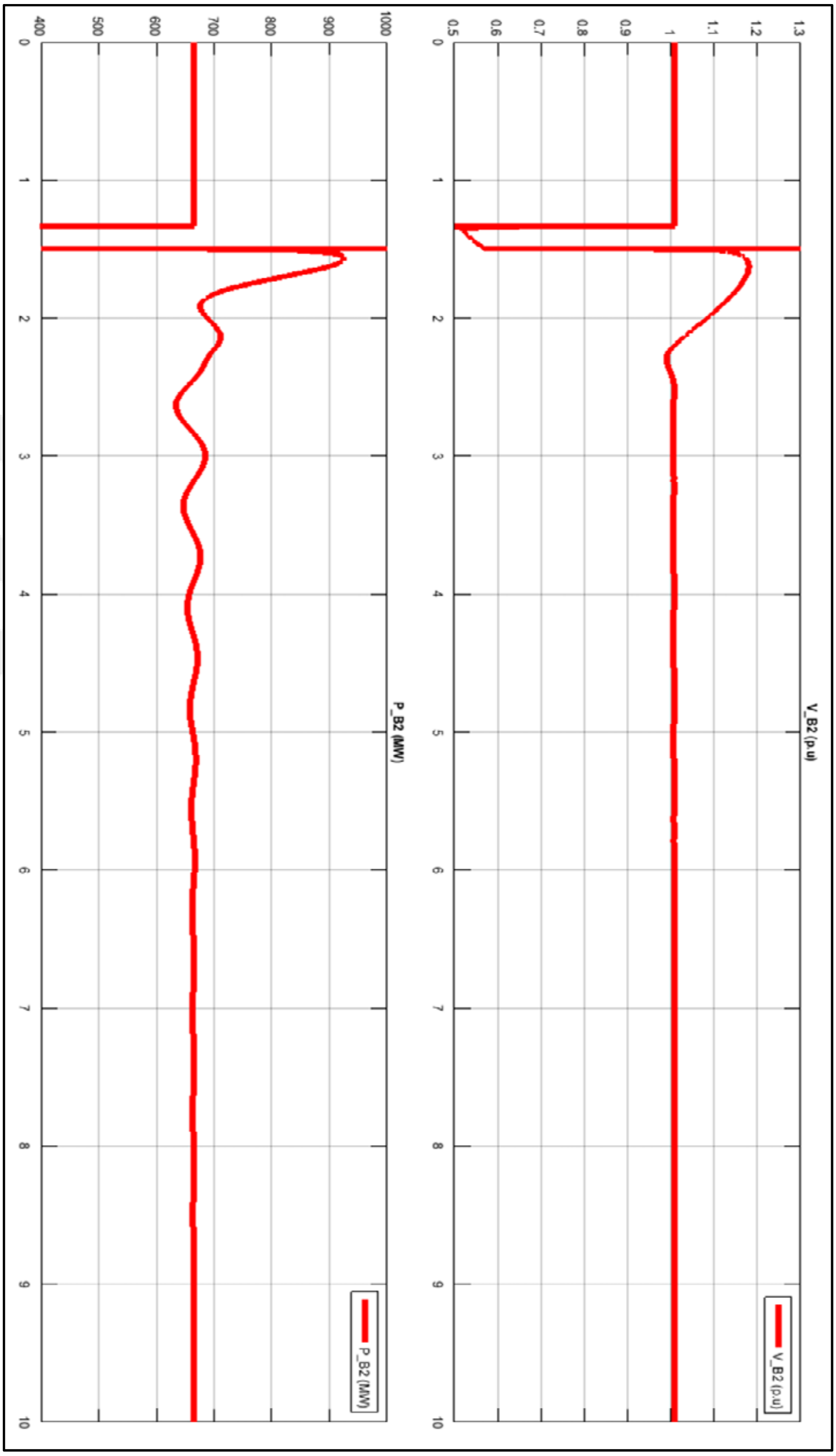


Figure 3.18: Signals of V_B2 (p.u) and P_B2 (MW) without SSSC, POD and with fault.

c) B3 measurement on the Line-3: voltage (p.u), 990 MW, as explained in Figure (3.19), with changes in the signals.

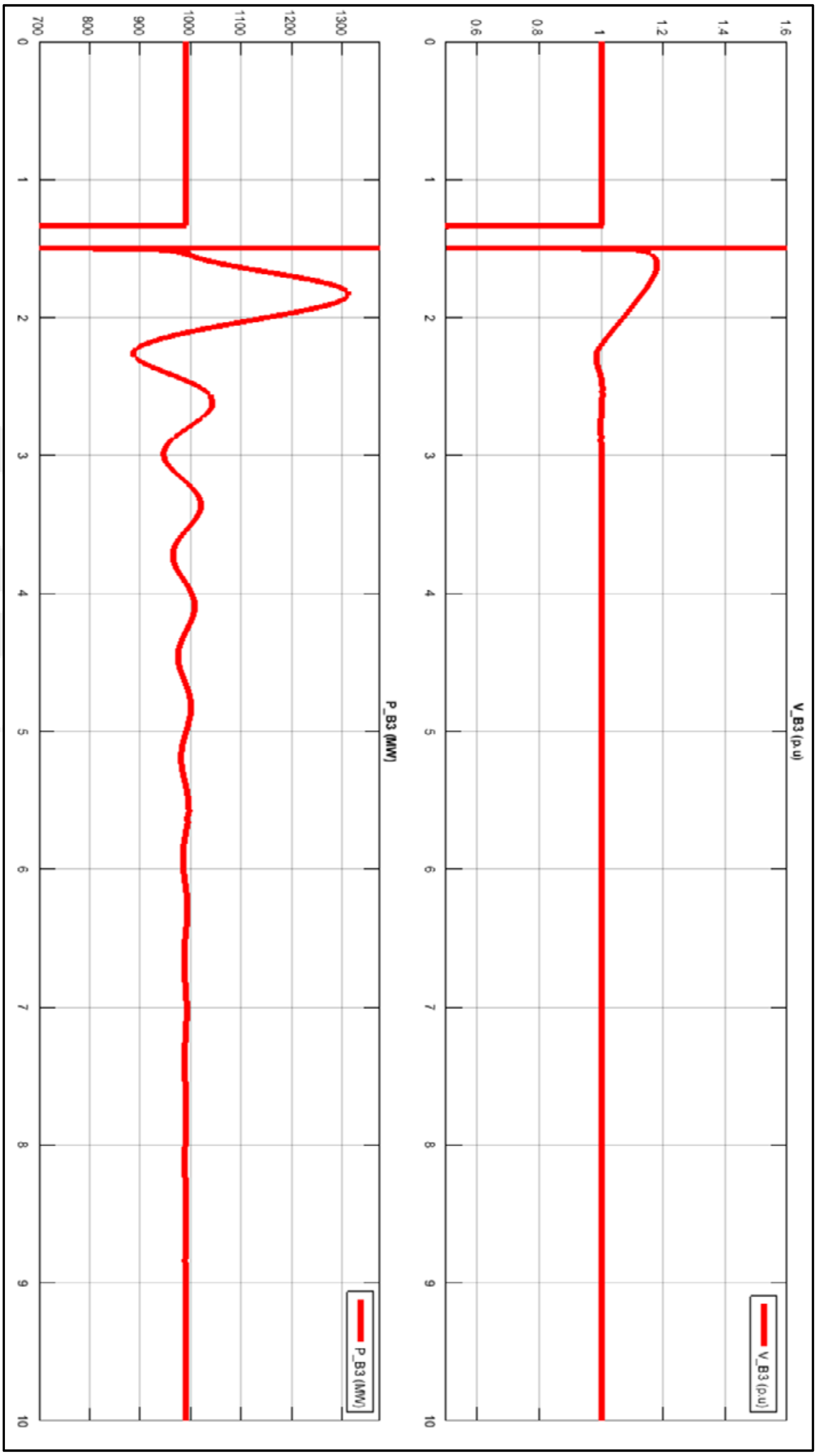


Figure 3.19: Signals of V_B3 (p.u) and P_B3 (MW) without SSSC, POD and with fault.

d) B4 measurement on Line-2: voltage (p.u), 563 MW, as seen in Figure (3.20). Again, we can look inside the block (Signals & Scopes) at the red (Scope 3).

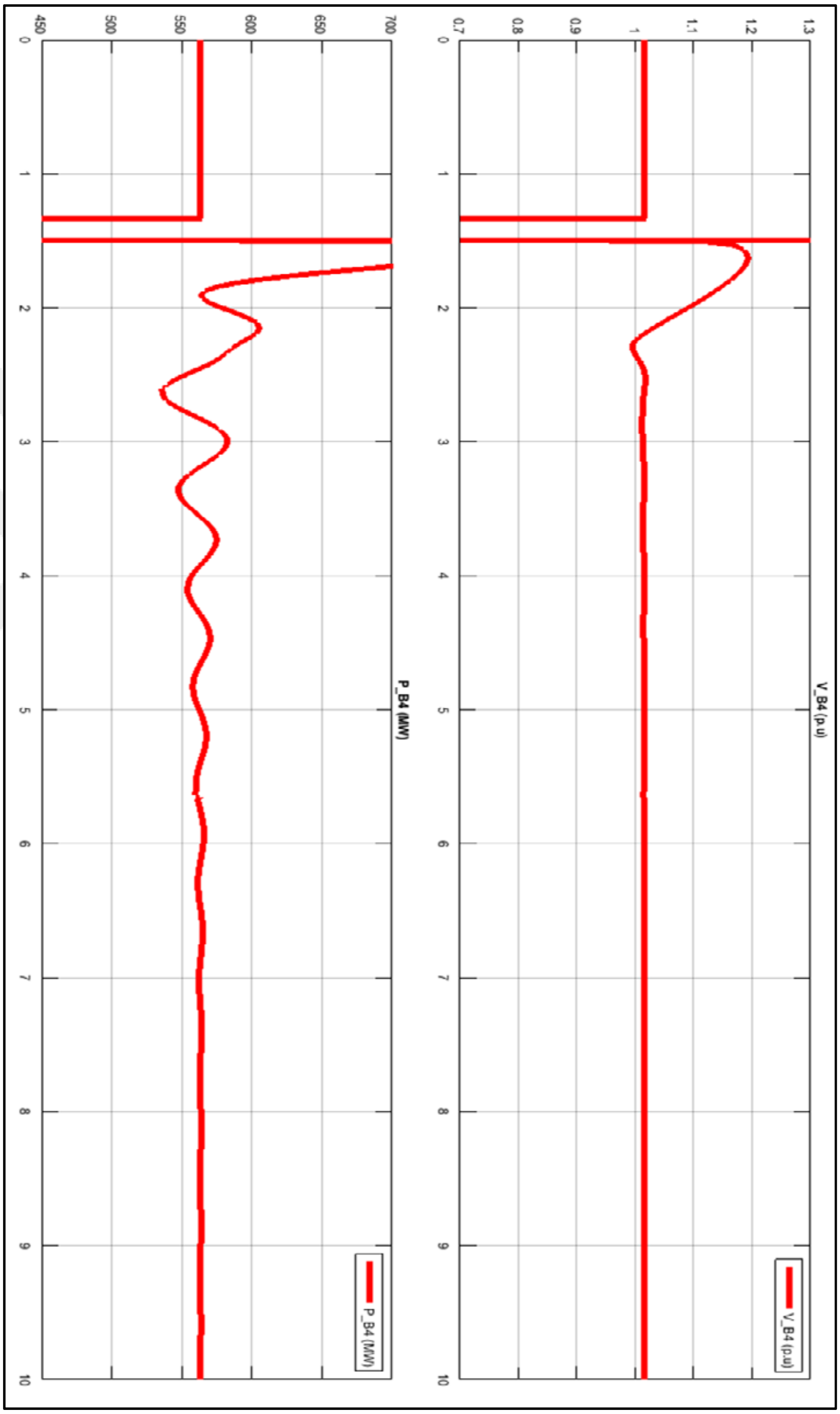


Figure 3.20: Signals of V_B4 (p.u) and P_B4 (MW) without SSSC, POD and with fault.

Finally, from the above, all the results have been obtained by simulation. We can compare the active powers with and without fault and the oscillations resulting because of the fault. Where we see more oscillation through the fault and more time to stability, the stability of the active powers begins from 5 sec. as shown in Figure (3.21).

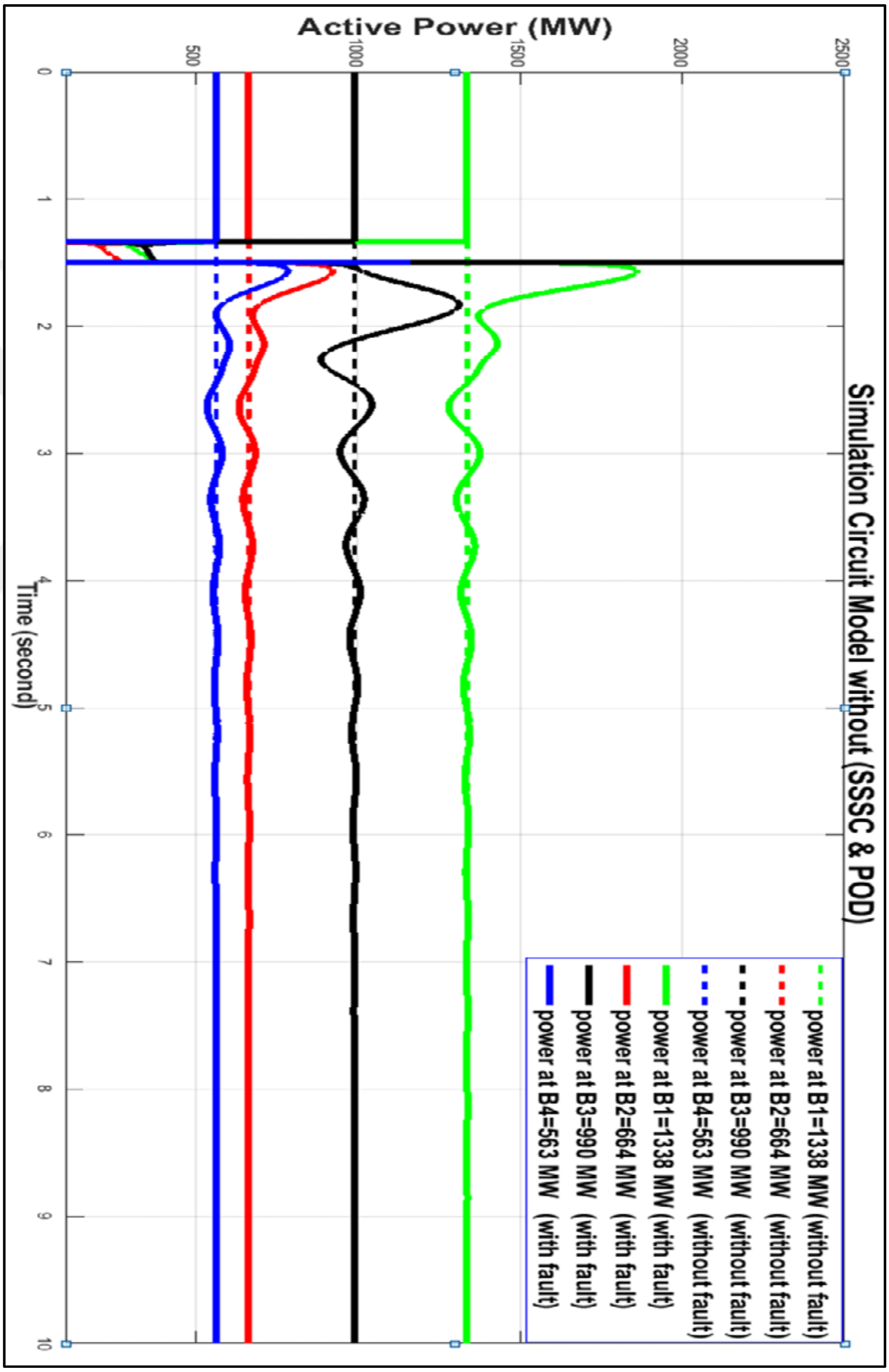


figure 3.21: All signals of active power (MW) at B1, B2, B3, B4 (with and without fault) and without SSSC, POD.

3- In the design given in Figure (3.22), we connect the SSSC compensator (phasor model) in the first location to the electrical grid and locate it at bus B1 and sequentially with Line-1. In addition, we have connected the POD control.

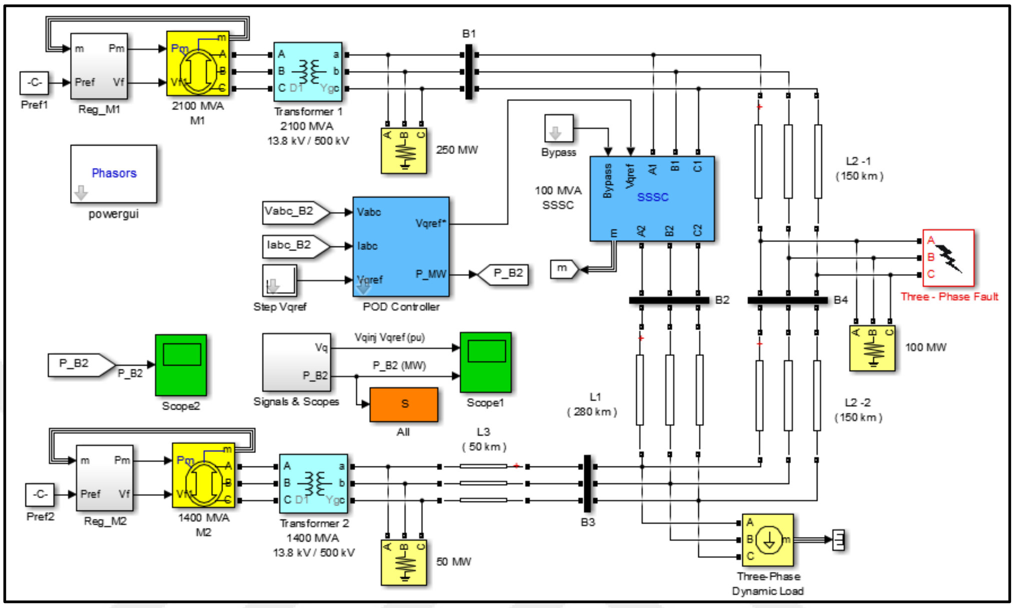
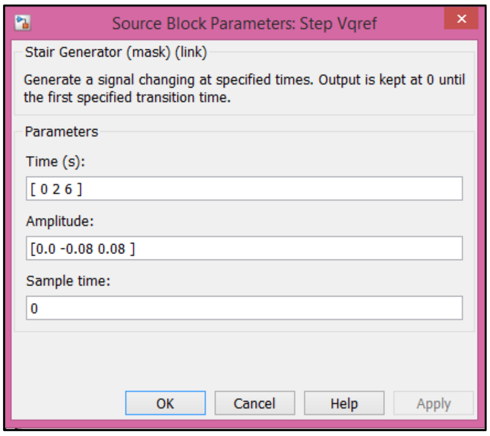


Figure 3.22: Simulation circuit model with the SSSC compensator in the first location and POD control and fault.

We start with the dynamic response for the SSSC. It is necessary to set Vqref in order to verify our model. Figure (3.23) shows the settings response, where the amplitude of Vqref = 0.0 (p.u) at time(s) = 0, amplitude of Vqref = –0.08 (p.u) at time(s) = 2 (SSSC emulating inductive) and amplitude of Vqref = 0.08 (p.u) at time(s) = 6 (SSSC emulating capacitive).


Source Block Parameters: Step Vqref

Stair Generator (mask) (link)

Generate a signal changing at specified times. Output is kept at 0 until the first specified transition time.

Parameters

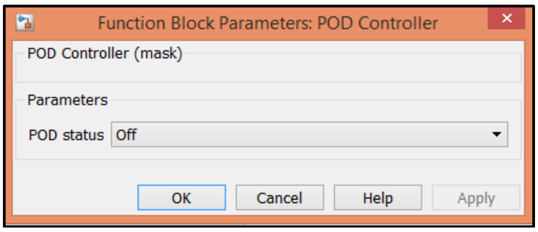
Time (s):
[0 2 6]

Amplitude:
[0.0 -0.08 0.08]

Sample time:
0

Figure 3.23: Step Vqref block parameters.

When the POD controller is in a turn-off state and the three-phase fault is initially inactive as given below in Figures (3.24) and (3.25); we can obtain several signals at bus B2 as follows:

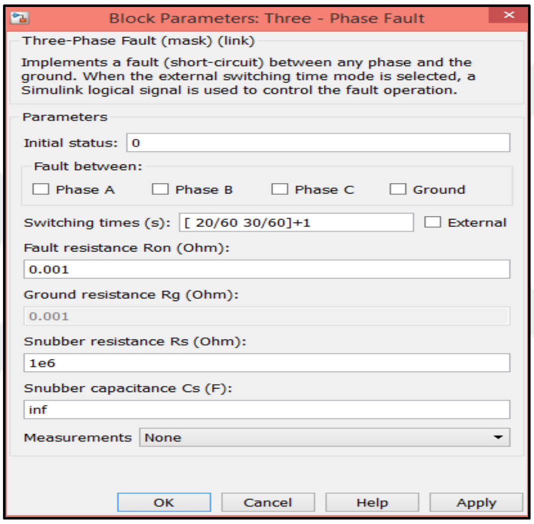

Function Block Parameters: POD Controller

POD Controller (mask)

Parameters

POD status: Off

Figure 3.24: POD Controller in a Turn-Off state.


Block Parameters: Three - Phase Fault

Three-Phase Fault (mask) (link)

Implements a fault (short-circuit) between any phase and the ground. When the external switching time mode is selected, a Simulink logical signal is used to control the fault operation.

Parameters

Initial status: 0

Fault between:

☐ Phase A ☐ Phase B ☐ Phase C ☐ Ground

Switching times (s): [20/60 30/60]+1 ☐ External

Fault resistance Ron (Ohm): 0.001

Ground resistance Rg (Ohm): 0.001

Snubber resistance Rs (Ohm): 1e6

Snubber capacitance Cs (F): inf

Measurements: None

Figure 3.25: Fault is initially inactive.

a) B2 measurement on Line-1: Initially, we adjusted the maximum rate of change of the reference voltage (p.u/s) to 3 inside of SSSC block. Then we reran the simulation. Firstly, we can see displays of the Vqref (p.u) (red indicated signal) along with the inserted voltage Vqinj (p.u) (blue signal) by the SSSC. One can observe that the SSSC organizer closely follows Vqref very well. Secondly, the voltage (V_B2) (p.u). Thirdly, depending on the inserted voltage, the active power inflow (P_B2) (red signal) on this line swings between 575 MW and 750 MW. This case represents a decrease and increase for the active power on Line-1 at B2; thereby emulating an inductive or capacitive reactance, as shown in Figure (3.26). We look for these signals within a block (Signals and Scopes) on the red (Scope 3).

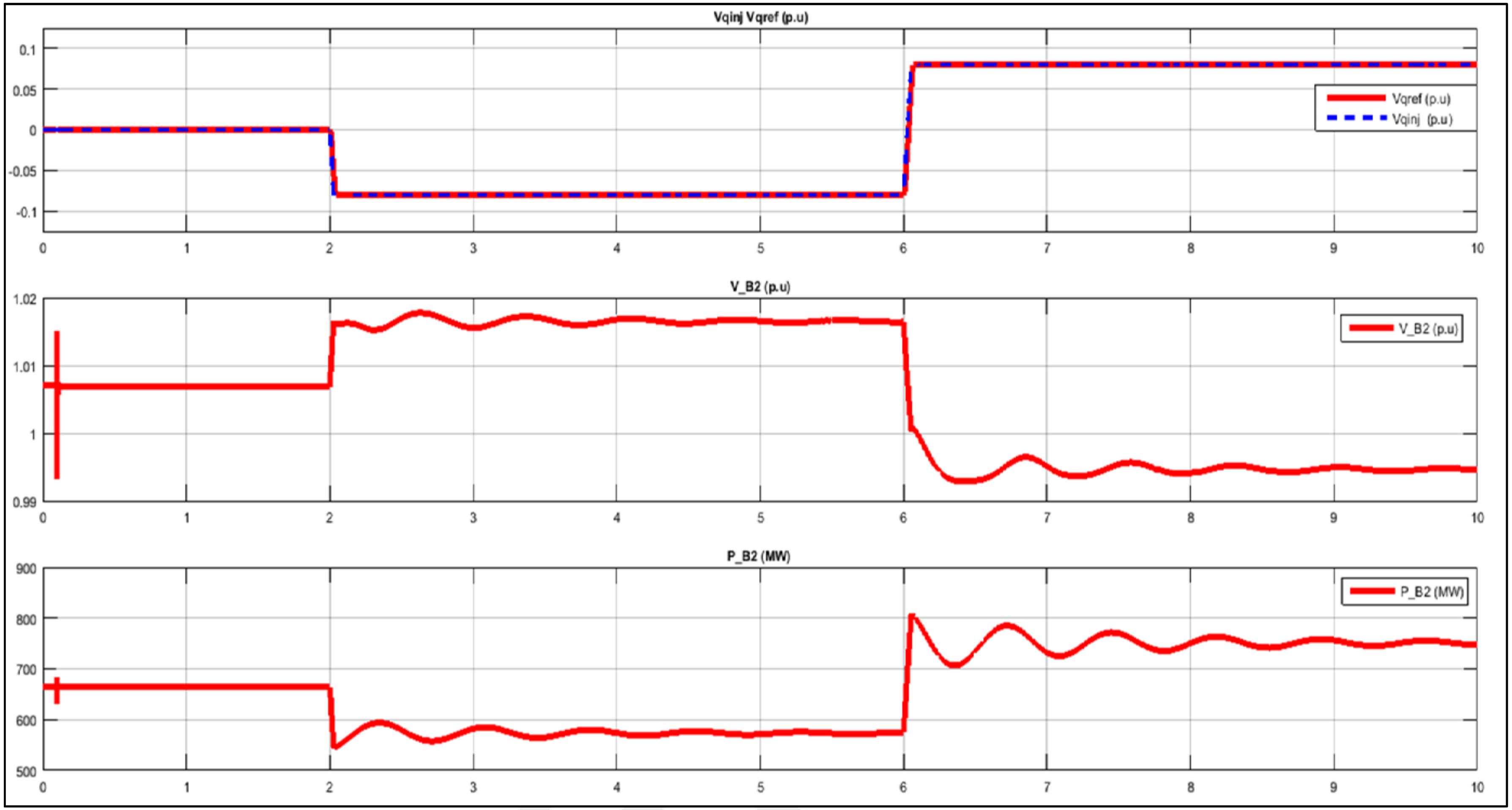


Figure 3.26: Signals of Vqinj Vqref and V_B2 (p.u) and P_B2 (MW) with the SSSC in the first location – Max. rate of change of Vqref (pu/s = 3) and without POD, fault.

b) B2 measurement on Line-1: In order to treat the oscillation, we have to decrease the maximum rate of change of the reference voltage (p.u/s) to 0.2 and restart the simulation. We look again at the signals. The Vqref (p.u) (red signal) along with the injected voltage Vqinj (p.u) (blue signal) from the SSSC. The second wave represents a voltage at bus B2 (V_B2) (p.u) (the red signal). The last graph (P_B2) (red signal) explains the active power flow at line L1, which varies between 575 MW and 750 MW and represents the down and high of active power value on this Line, as seen below in Figure (3.27). We can see this by following the same path as before.

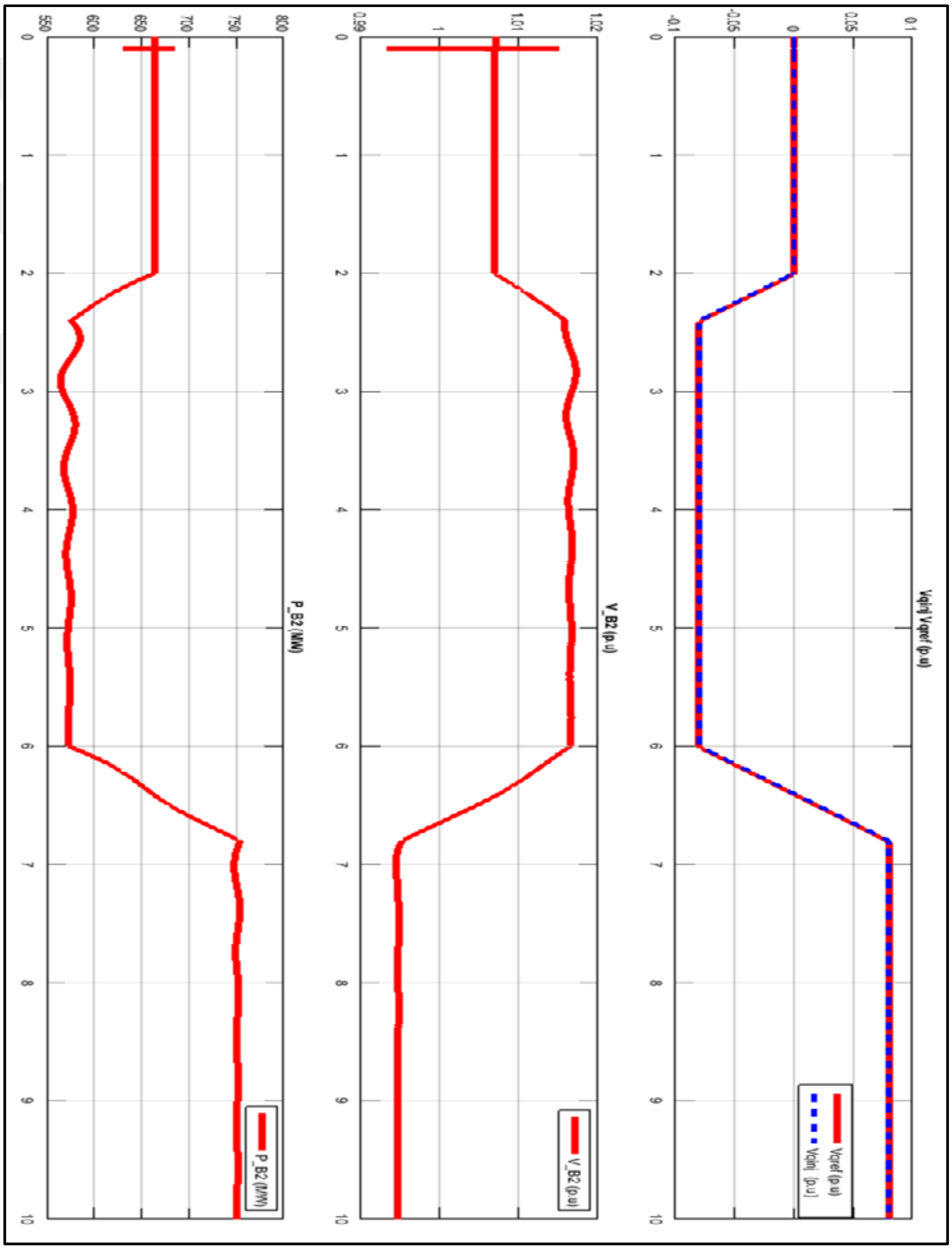


Figure 3.27: Signals of Vqinj Vqref and V_B2 (p.u) and P_B2 (MW) (with the SSSC in the first location – Max. rate of change of Vqref (pu/s = 0.2) and without POD, fault.

c) B2 measurement on Line-1: We continue to decrease the maximum rate of change of the reference voltage (p.u/s) at 0.05. We see again more change in the output waves of Vqref (p.u) (red signal) along with the injected voltage Vqinj (p.u) (blue signal) by the SSSC. The voltage at bus B2 (V_B2) (p.u) (red signal) and lastly in the active power flow (P_B2) (red signal) at line-1 with the power oscillation on the active power that should now be very small. Their values range from 575 MW to 750 MW and represent the upper and lower limits of the active power value on Line-1, as shown in Figure (3.28).

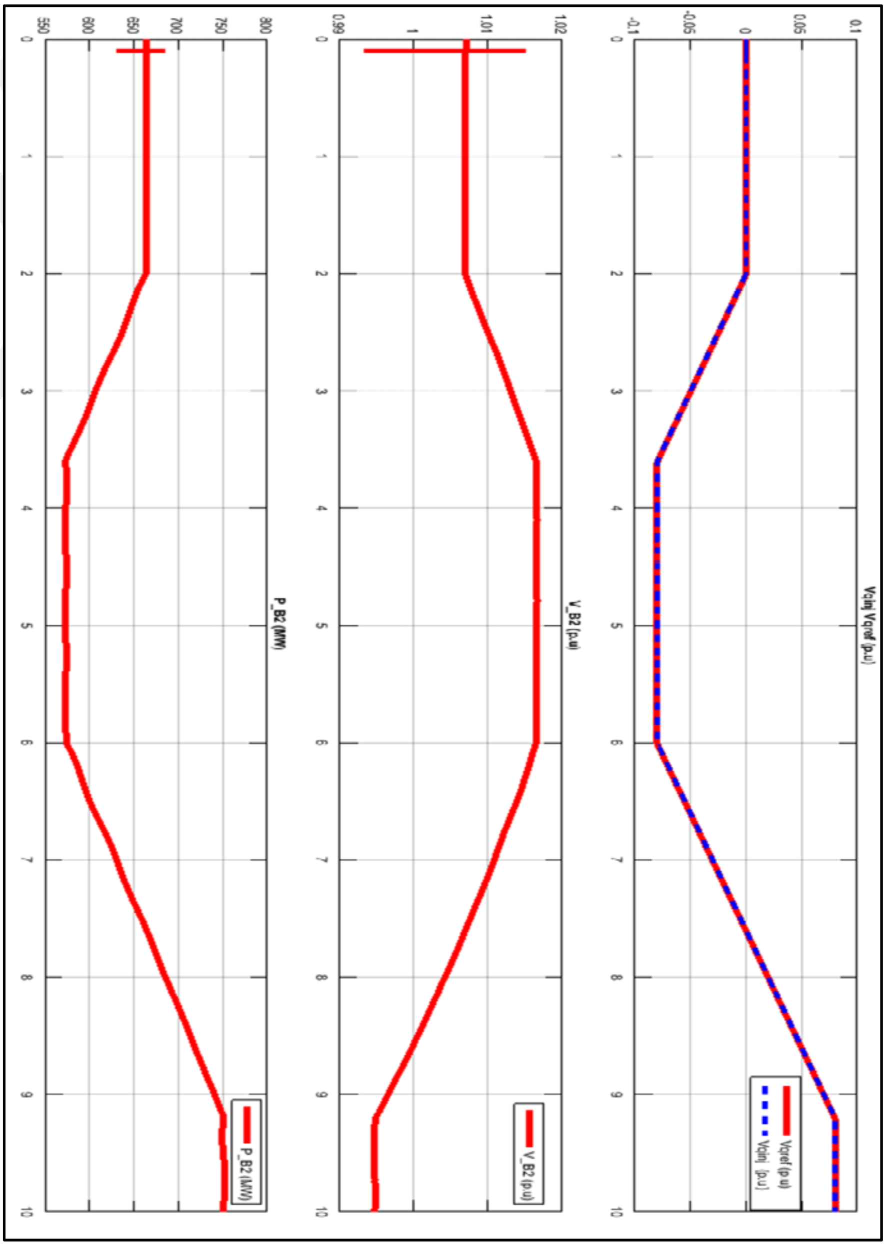


Figure 3.28: Signals of Vqinj Vqref and V_B2 (p.u) and P_B2 (MW) with the SSSC in the first location – Max. rate of change of Vqref (pu/s) = 0.05) and without POD, fault.

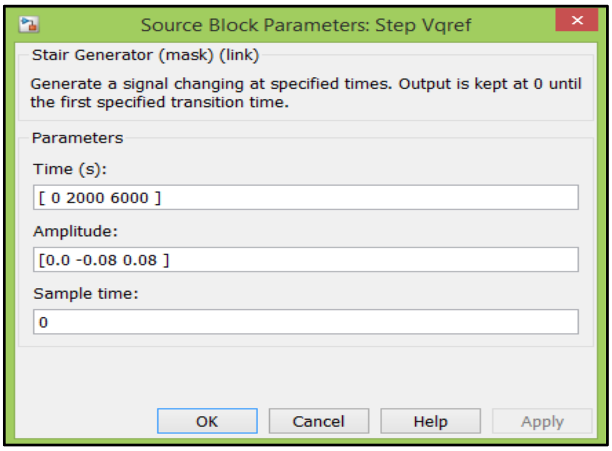
Finally, we concluded with the strong impact of the SSSC in the injection voltage (Vqinj) in the electrical transmission networks and the possibility of tracking the reference voltage (Vqref), in the case of increases and decreases, for power (inductive or capacitive modes) as being very good since it can regularly keep track of reference indicator signals (Vqref). Depending on the inserted voltage (Vqinj), the power transfer on the line differs according to different values. Moreover, a quick response to the injection of voltage and the possibility of obtaining and to control the best real power (active power) at least oscillations and will tend to vanish in order avoid the power oscillation on the active power should now be very small. This means that the SSSC is ideal for fast responses and is an effective tool for power transmission networks.

3.4.2 Damping Real Power (MW)

After achieving and validating the ability of the SSSC to control the real power (active power), this case presents another crucial feature of the SSSC, which is power damping during severe power system faults. The following procedure is followed in order to simulate and test SSSC operations with and without POD control:

a) Tuning the Time Vector for the Reference Voltage (Vqref).

We start working by going to Block “Step Vqref” in our simulation. We open it and make a change to the old values of time to new values [0 2000 6000] to disable the Vqref variations, as shown below in Figure (3.29). In addition, the fault breaker’s parameters “Switching of phase A, B and C” must be not selected now and the POD block is (Off), as shown in Figures (3.30) and Figure (3.31), respectively.



Source Block Parameters: Step Vqref

Stair Generator (mask) (link)

Generate a signal changing at specified times. Output is kept at 0 until the first specified transition time.

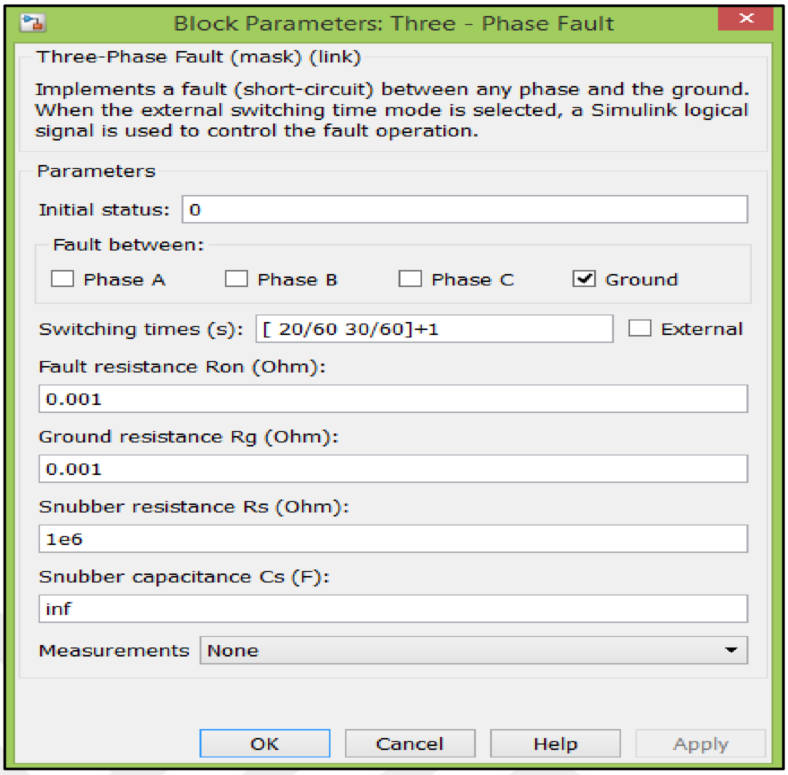
Parameters

Time (s): [0 2000 6000]

Amplitude: [0.0 -0.08 0.08]

Sample time: 0

Figure 3.29: Modified Vqref time vector.



Three-Phase Fault (mask) (link)

Implements a fault (short-circuit) between any phase and the ground. When the external switching time mode is selected, a Simulink logical signal is used to control the fault operation.

Parameters

Initial status: 0

Fault between:

☐ Phase A ☐ Phase B ☐ Phase C ☑ Ground

Switching times (s): [20/60 30/60]+1 ☐ External

Fault resistance Ron (Ohm): 0.001

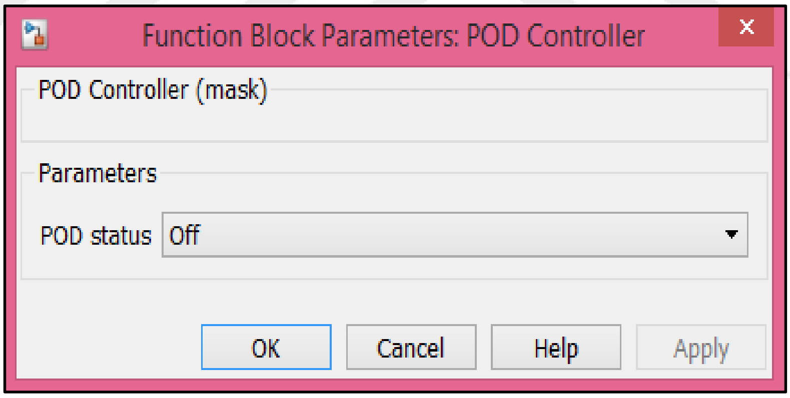
Ground resistance Rg (Ohm): 0.001

Snubber resistance Rs (Ohm): 1e6

Snubber capacitance Cs (F): inf

Measurements None

Figure 3.30: Three-phase fault inactivation.



POD Controller (mask)

Parameters

POD status Off

Figure 3.31: POD controller (off).

When we rerun a simulation again and open "Signals and Scopes block" and look at red scope 3, we obtain the wave form as Vqinj Vqref (p.u) equal to zero in order to diminish the reference voltage variations, voltage at B2 (p.u) and transfer active power to line-1 (L1) (664 MW), as shown in Figure (3.32).

In this case, we do not see any significant effect in the waveform and the real power (active power) is especially transferred in the first line (Line-1) at B2 because there is no effect of the fault (normal case).

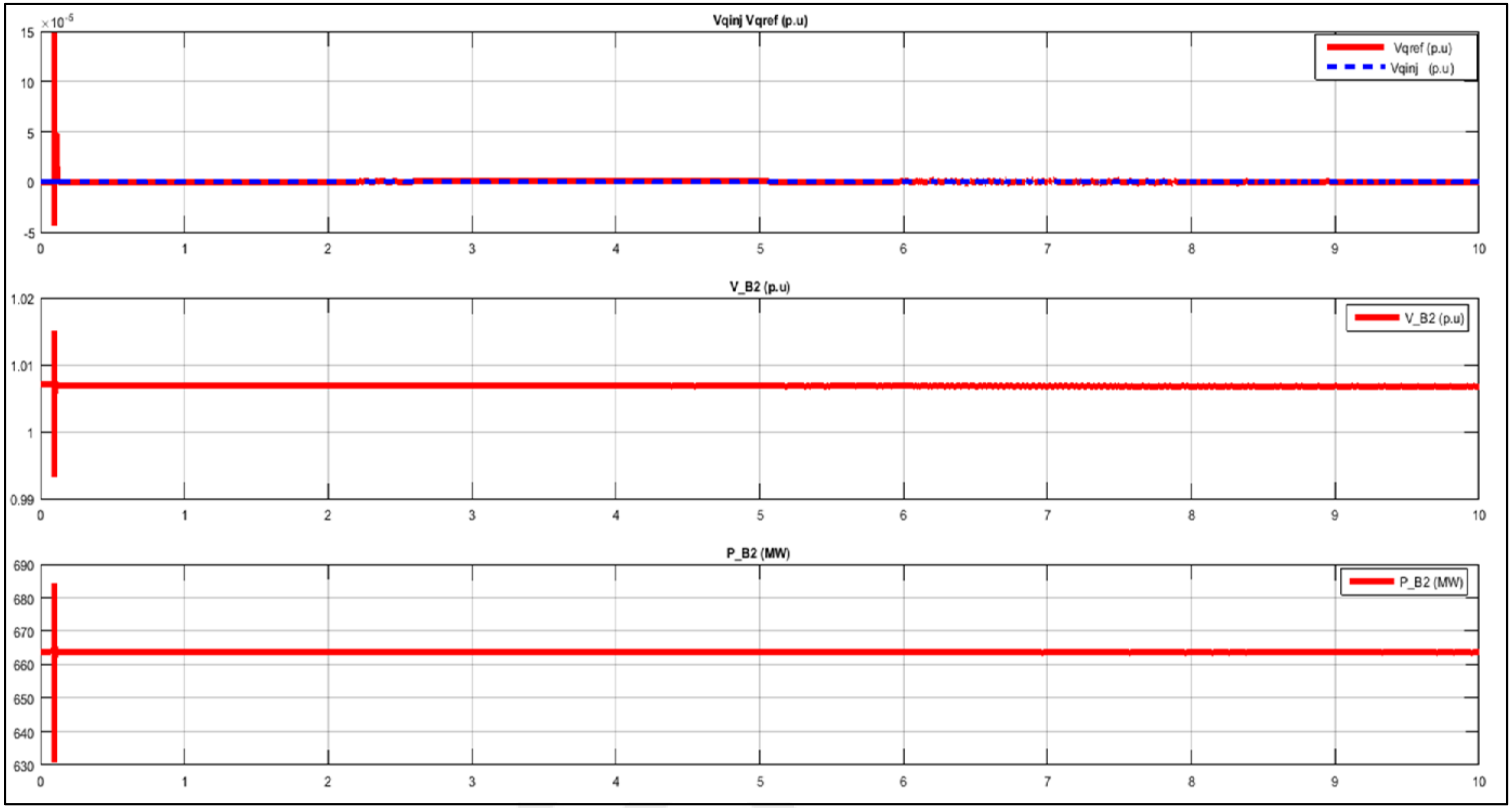


Figure 3.32: Signals of Vqinj Vqref and V_B2 (p.u) and P_B2 (MW) with the SSSC in the first location and without fault, POD and with time step Vqref [0 2000 6000] seconds.

b) SSSC in the first location without POD and with Fault.

In this case, we make the three-phase short circuit fault effective by selecting the “Switching of phase A, B and C” to “Ground” and restarting the simulators. We see the effect of the fault on all waves with high fluctuation (oscillations) in the stability of the power transferred on Line-1. This means that the power system is unstable at fault 1.33-1.5 seconds (10 cycles). We look for the signals in Figure (3.33) inside “Signals and Scopes block” and look at the red scope 5 to obtain the Vqinj Vqref (p.u) and observe the P_B2 (MW) on line-1(L1) following the three-phase fault.

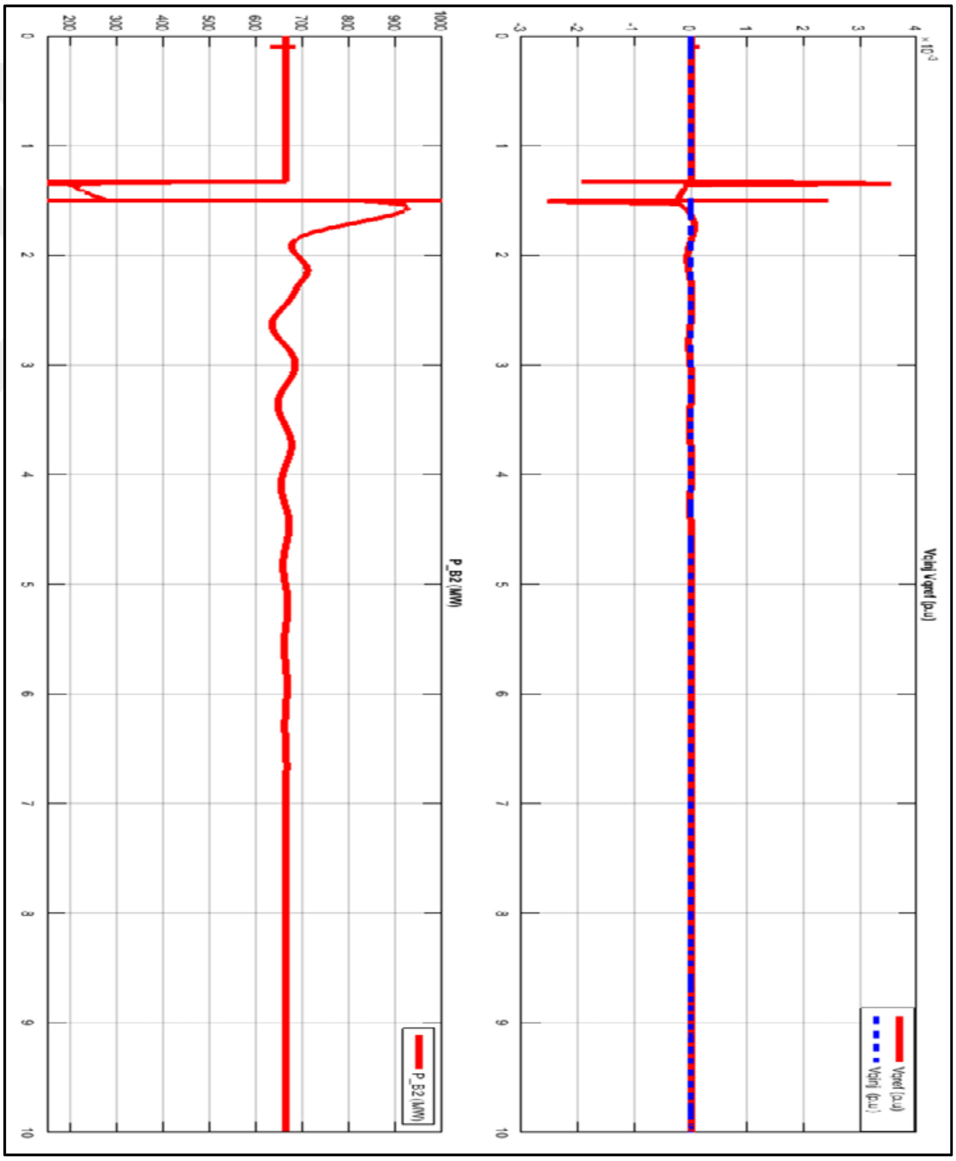


Figure 3.33: Signals of Vqinj Vqref (p.u) and P_B2 (MW) and with the SSSC in the first location, fault and without POD and with time step Vqref [0 2000 6000] seconds.

c) SSSC in the first location with POD and with Fault.

To see the effect of the POD controller, we will rerun the simulation with the POD controller in operation. We set the parameters for the POD into operation “On.” We start the operation and look at the results inside the “Signals and Scopes block” and look once more at red scope 5 for the purpose of obtaining the forms of the signals as V_{qinj} V_{qref} (p.u) and the active power on line-1 (L1) (P_B2) (MW) is depicted in Figure (3.34).

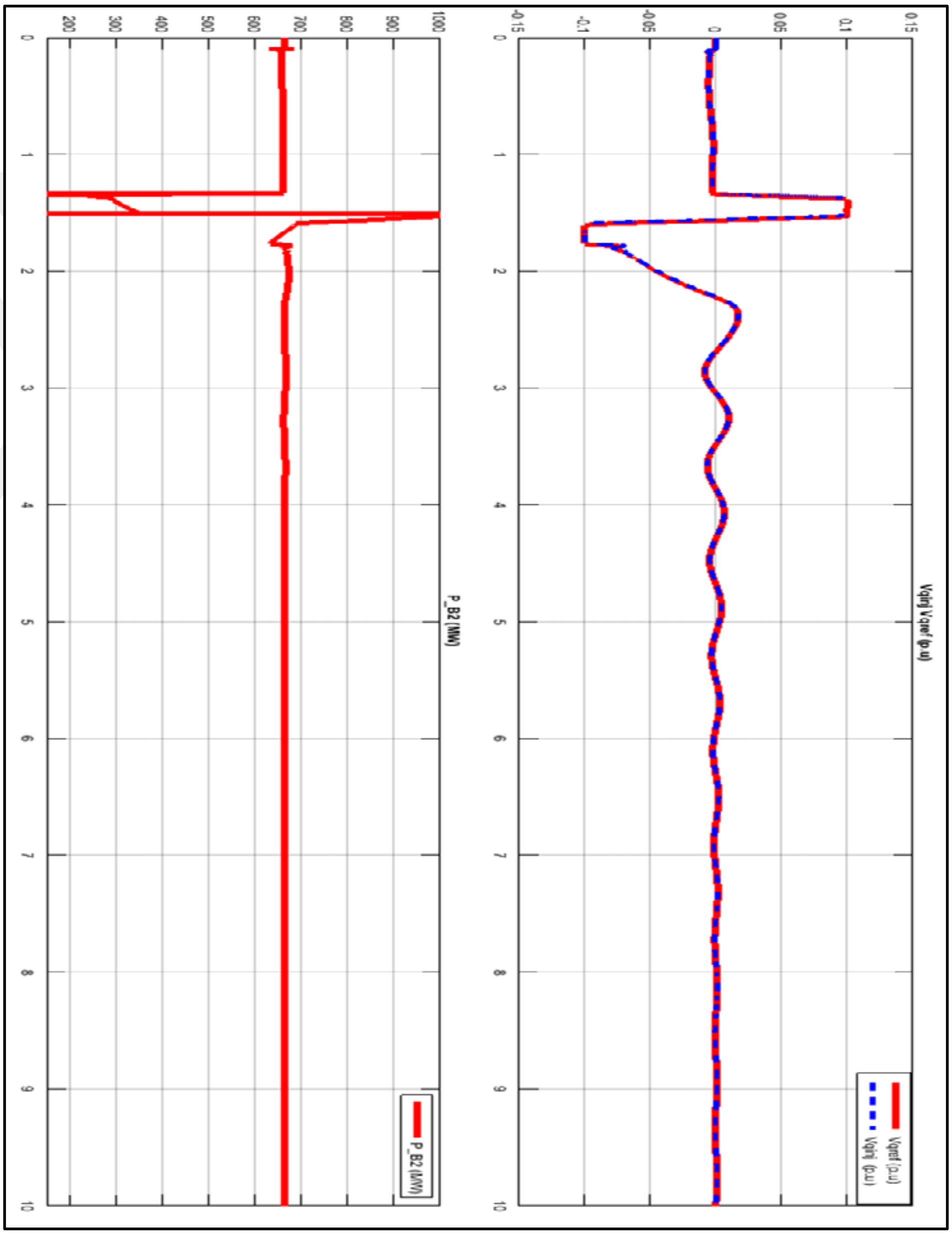


Figure 3.34: Signals of VqinjVqref (p.u) and P_B2 (MW) with the SSSC in the first location, fault, and POD and with time step Vqref [0 2000 6000] seconds.

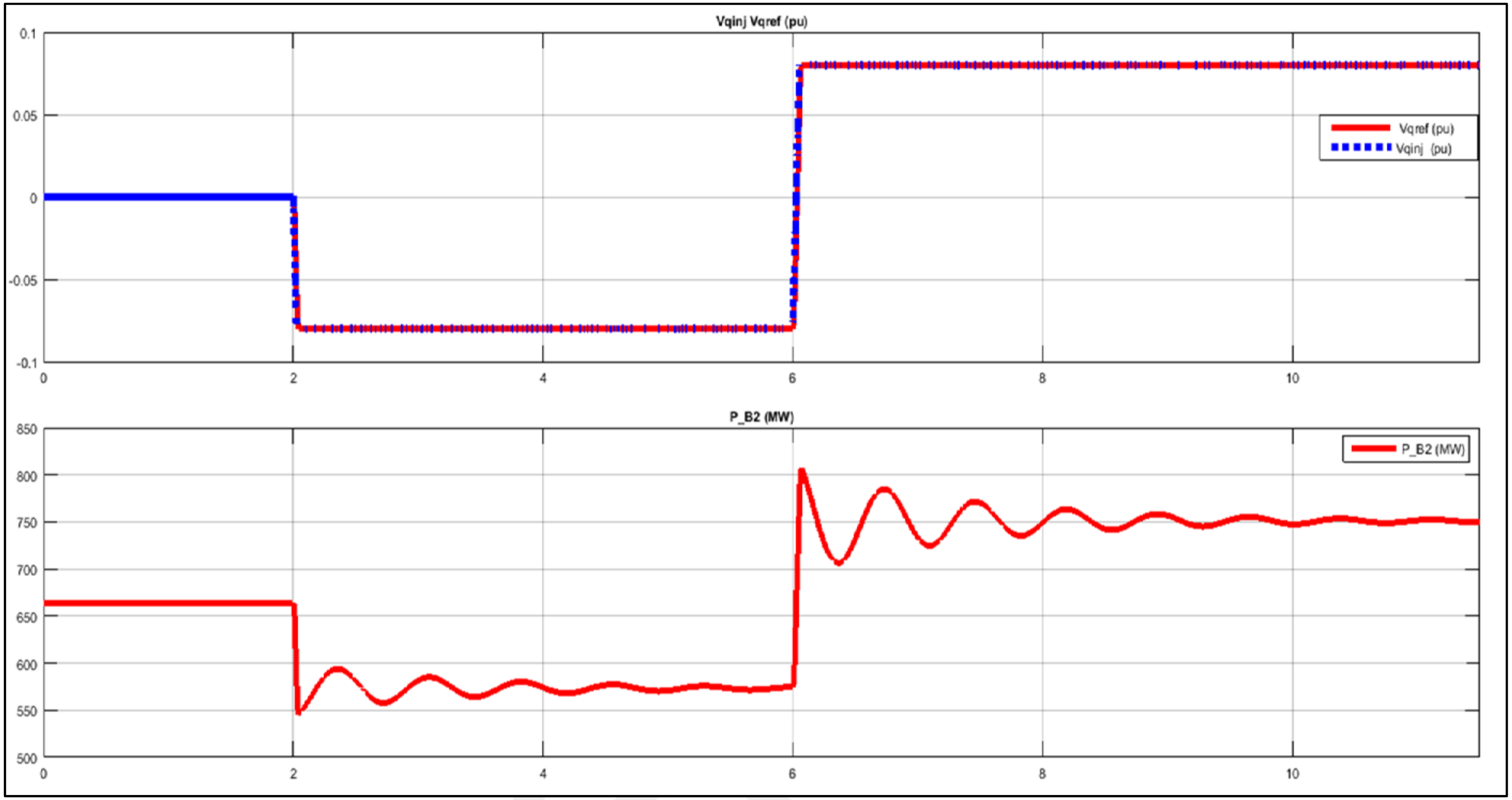
Finally, looking at the above power signals (P_B2) on line-1 from the red scope 5 in Figures (3.33) and (3.34) for comparison, we can see an SSSC in the first location with a POD controller that is a very strong, effective tool damping for power system oscillations of active power in the electric power transmission grid. This means there is fast response controlling the stability, power flow, and reduction of power oscillations in the system with fault conditions.

d) Other Comparisons.

These comparisons are also important in knowing the difference and changes that take place in the form of signals during, and controlled by, different conditions. We now show the important devices that have been used in the simulator model. The possibility of control and stability in the transfer of the real power (active power) on the transmission line-2 (L2) at B2 is as follows:

1- For example, we took the voltages Vqinj (the blue signal) (p.u) and Vqref (the red signal) (p.u) and P_B2 (MW) with time step Vqref [0 2 6] to compare between them in the natural state (normal inductive or normal capacitive emulation) during the time of the fault and during control and damping of the oscillation. To see the effect of the POD controller, we rerun the simulation with the POD controller during the operation. We set the parameters for the POD into operation “ON.” As the simulation is run with the POD controller in operation, power fluctuations are measured on the first transmission line L1 following the 3-Ø fault that can be observed at the output of “Scope 1” (green color) and seen from the P_B2 signal.

The first wave of blue color represents the injected voltage (Vqinj). This signal tracks the reference voltage (Vqref). It is red in color. In the same part below, we can also see the power flow. It is red in color as given in Figures (3.35), (3.36) and (3.37) below.



0Figure 3.35: Signals of VqinjVqref and V_B2 (p.u) and P_B2 (MW) with the SSSC in the first location and without fault, POD and with time step Vqref [0 2 6] seconds.

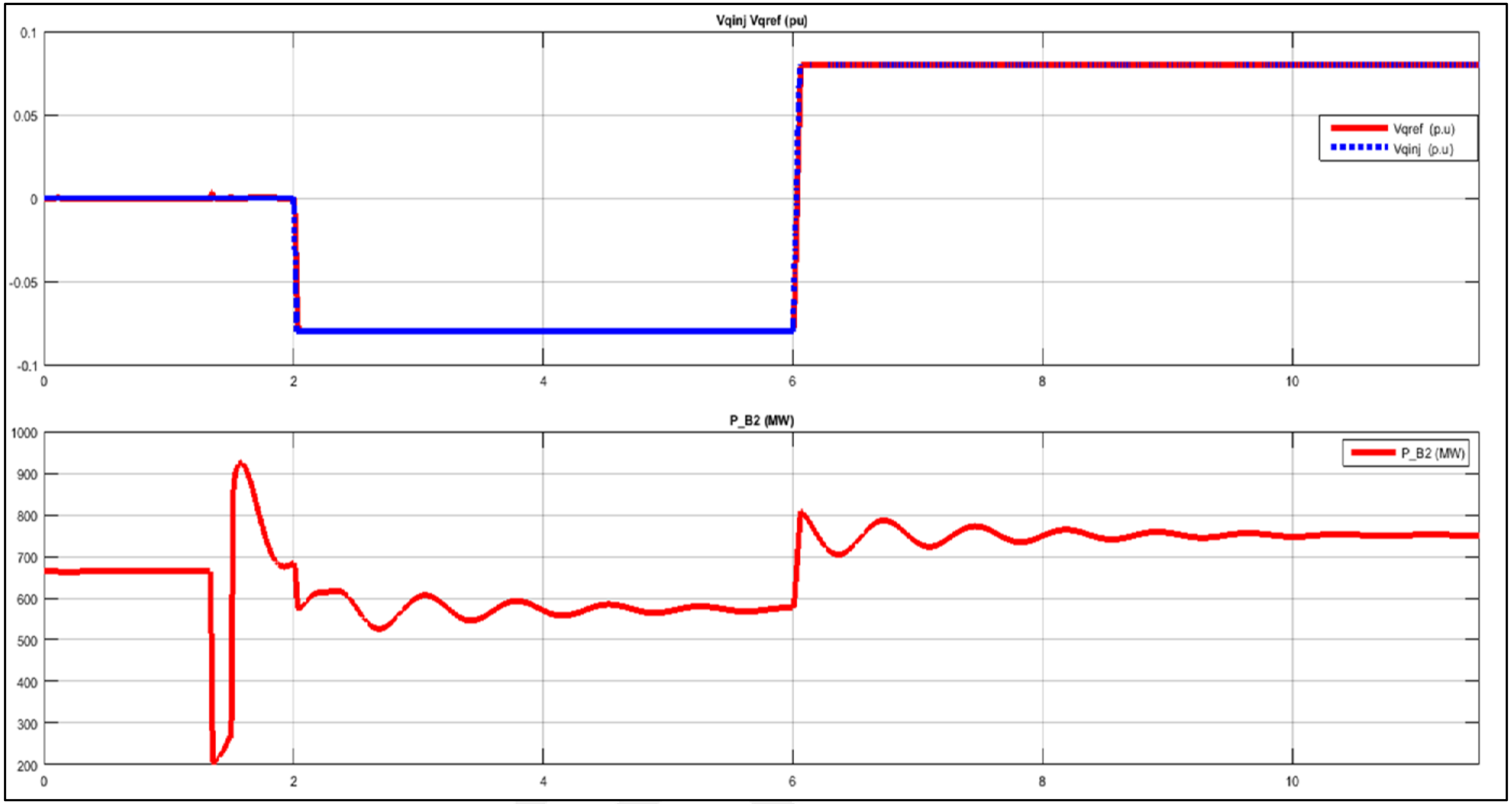


Figure 3.36: Signals of VqinjVqref and V_B2 (p.u) and P_B2 (MW) with the SSSC in the first location, fault without POD and with time step Vqref [0 2 6] seconds.

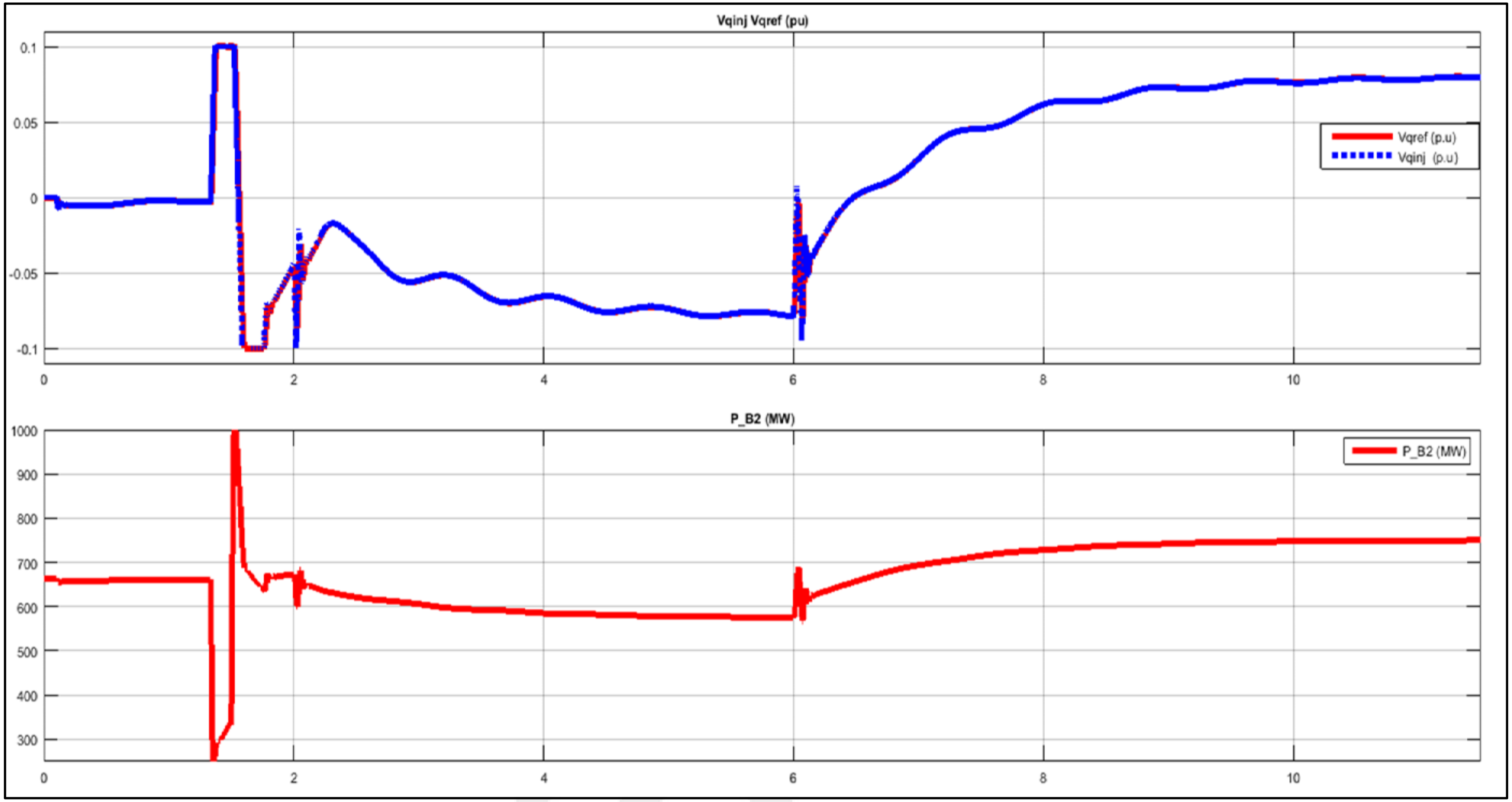


Figure 3.37: Signals of VqinjVqref and V_B2 (p.u) and (P_B2 (MW) and with the SSSC in the first location, fault, POD and with time step Vqref [0 2 6] seconds.

2- All SSSC operations (simulations) with and without fault and POD control can be simultaneously seen in Figures (3.38), (3.39), (3.40) and (3.41) for comparison between all the results obtains for active power on L1 at bus-B2 and voltage at B2. We conclude that the stability and damped oscillation of the active power is much faster with the SSSC and POD controller through time (2 sec to 6 sec).

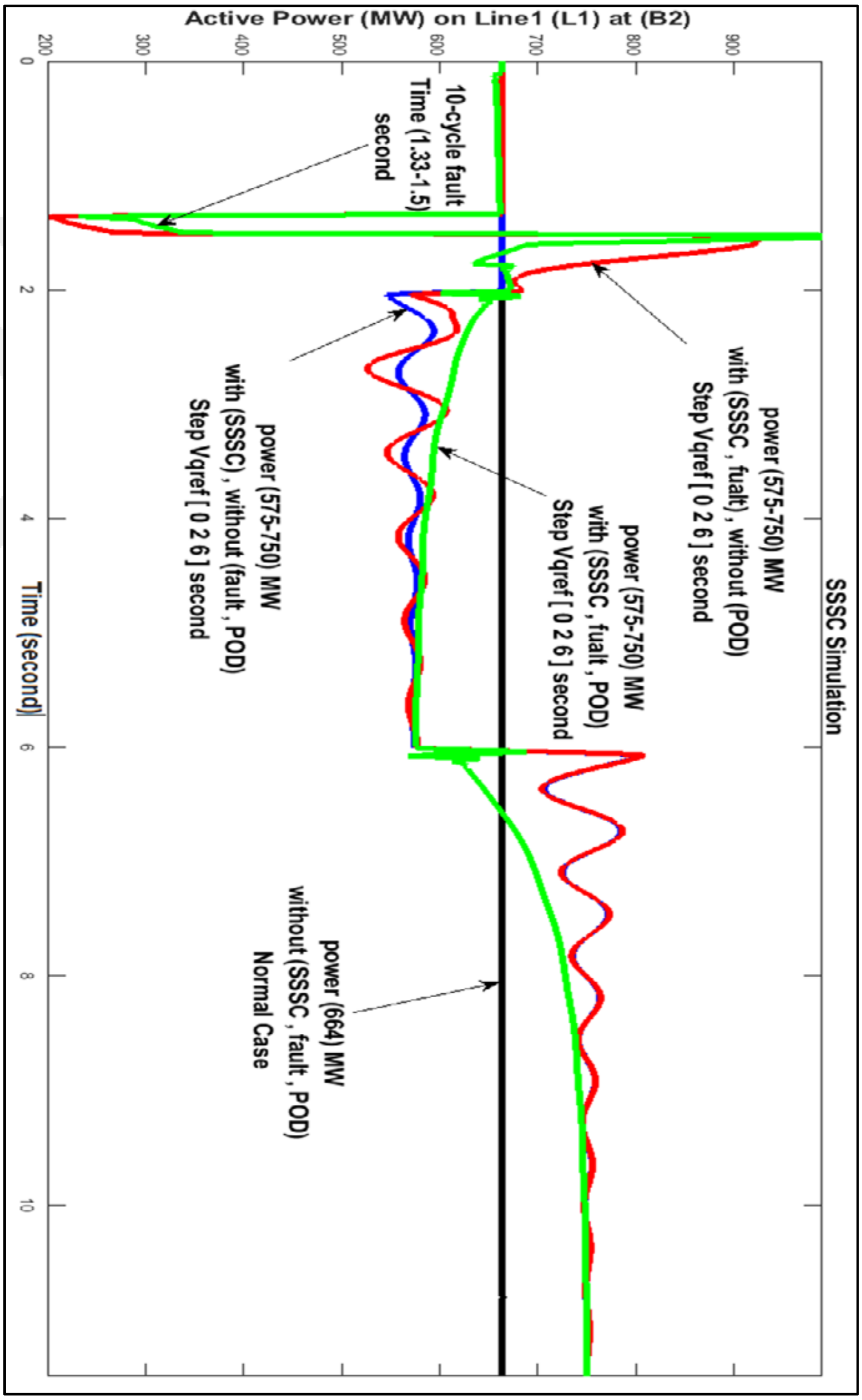


Figure 3.38: Signals of a normal case, SSSC in the first location with and without fault and POD when the step Vqref is [0 2 6] seconds.

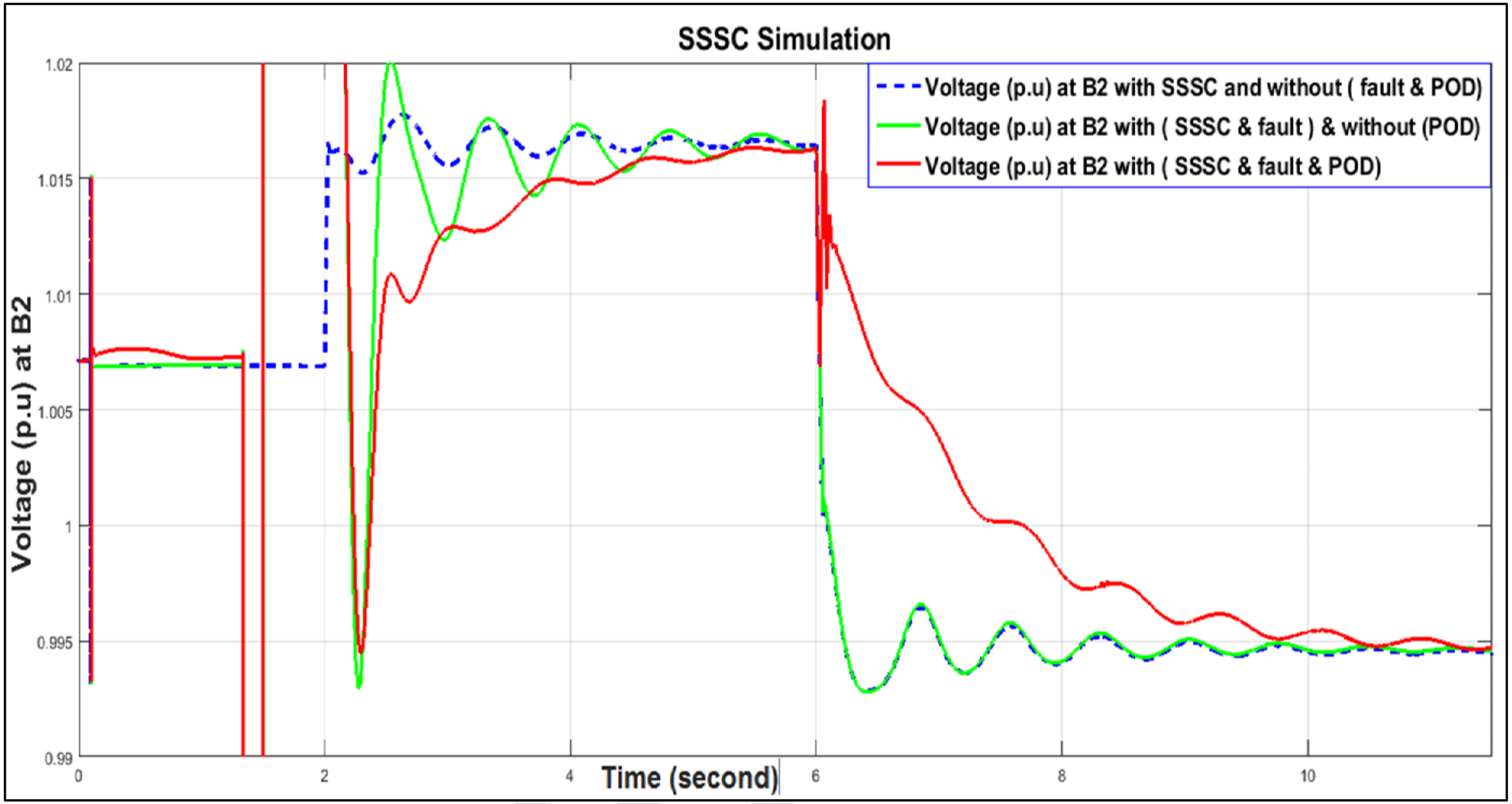


Figure 3.39: Voltage (p.u) at B2, SSSC in the first location with and without fault and POD when the step Vqref is [0 2 6] seconds.

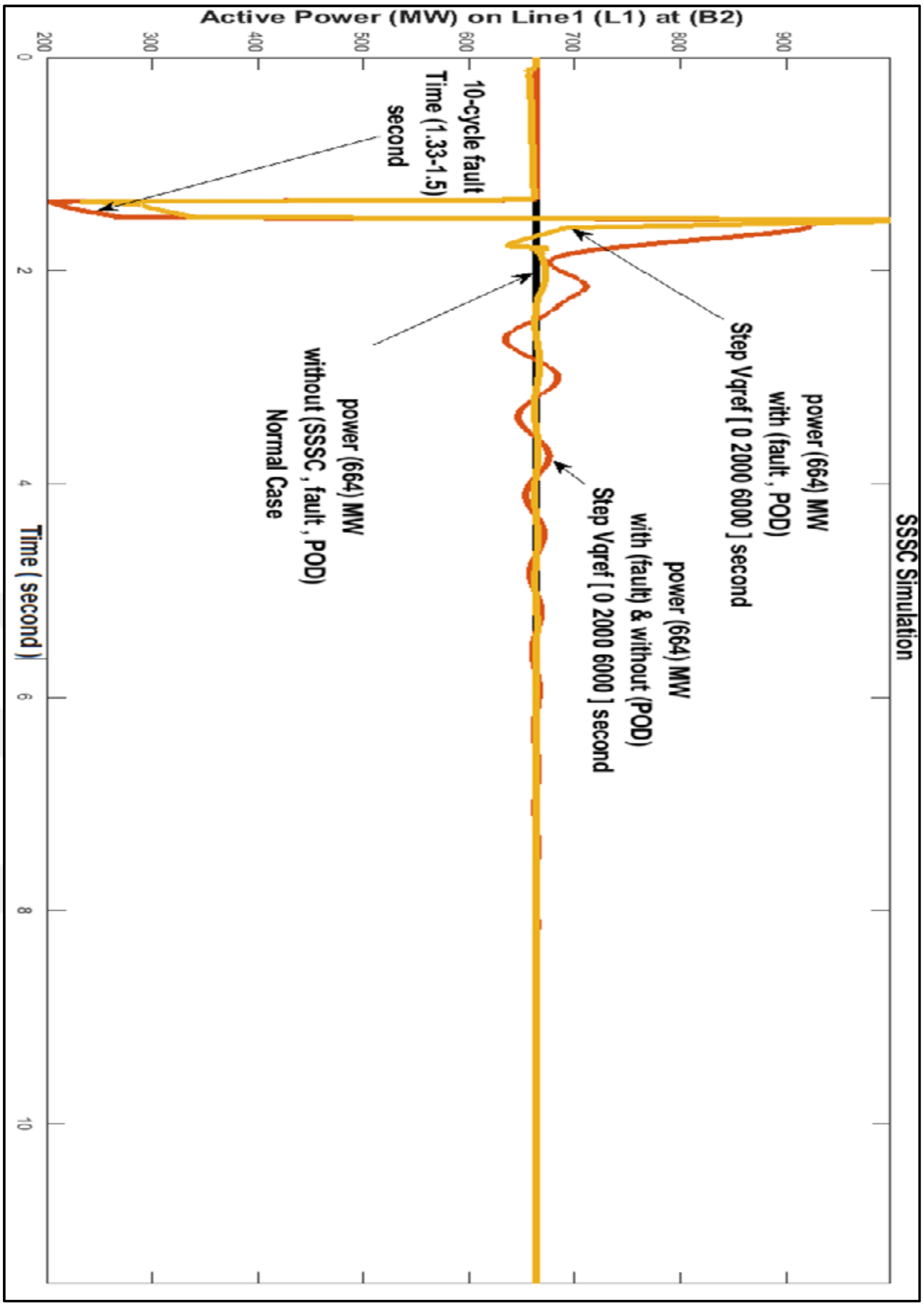


Figure 3.40: Signals of a normal case, SSSC in the first location with and without fault and POD when the step Vqref is [0 2000 6000] seconds.

The resultant damping behavior of the SSSC is outstanding (Figure 3.40). Line power drops to almost 200 MW during a fault while with SSSC compensation, it barely reaches 280 MW. After clearing the fault, line power overshoots, passing 900 MW and it falls to under 700 MW after 2.4 seconds, after which it continues oscillating for 7 seconds. On the other hand, when compensation is inactive, it rapidly damps down to below 700 at ~1.6 seconds, and then it smoothly reaches nominal line power (664 MW) in an oscillation-free manner.

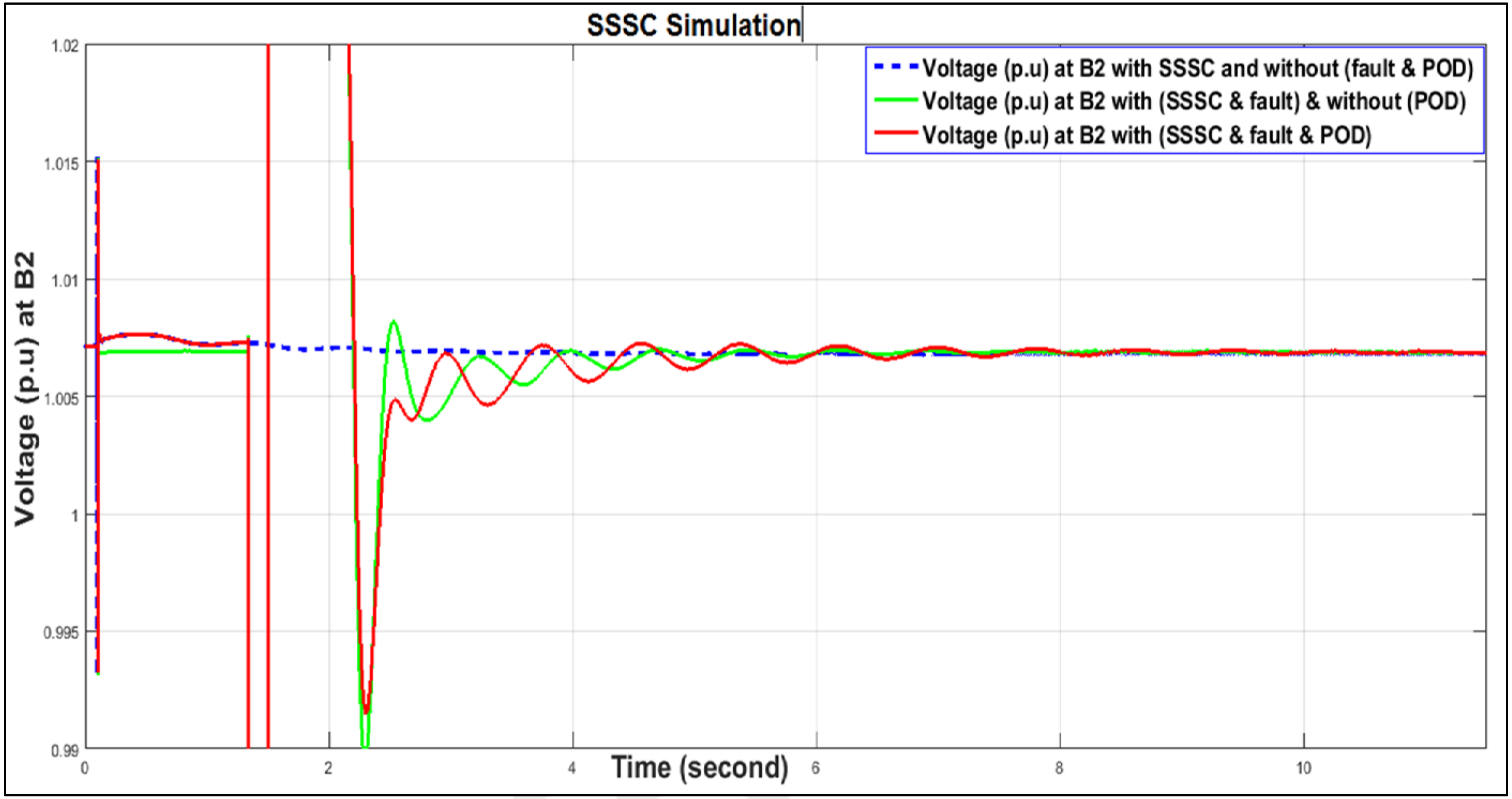


Figure 3.41: Voltage (p.u) at B2, SSSC in the first location with and without fault and POD when the step Vqref [0 2000 6000] second.

The simulation result shows after installing the SSSC at bus no. 1 in the first location, which is in series with line 1 (L1). The active power flow and power oscillation damper have been improved. The major objective of an SSSC component is to regulate power inflow in steady state cases, while this ability also enhances the transient stabilization of a power system. The main benefit is to use the SSSC to adjust active power (P) inflow in transmission lines.

In other words, the overall system stability has been improved. The SSSC has a powerful impact on every power transmission system. It minimizes oscillations which occur due to faults. The objective of its use was achieved to improve the highest stability and dampen oscillations. In addition, we notice in a few seconds the strong impact on all the buses (B1, B3, and B4) and the control to damp the oscillation and stability of the overall system of active power transfer, as shown in Figures (3.42), (3.43), (3.44), (3.45), (3.46), and (3.47), respectively.

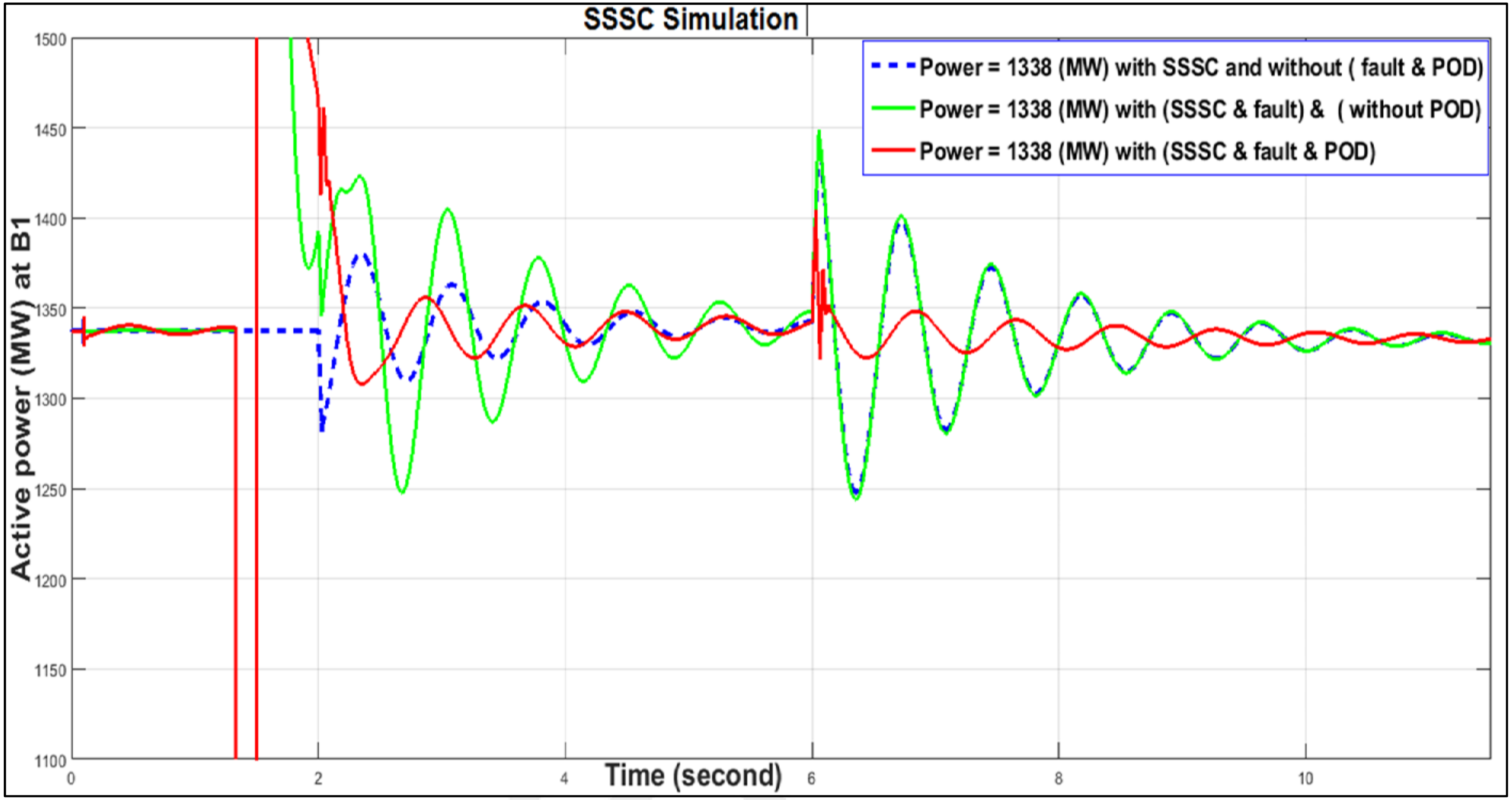


Figure 3.42: Active power at B1, SSSC in the first location with and without fault and POD.

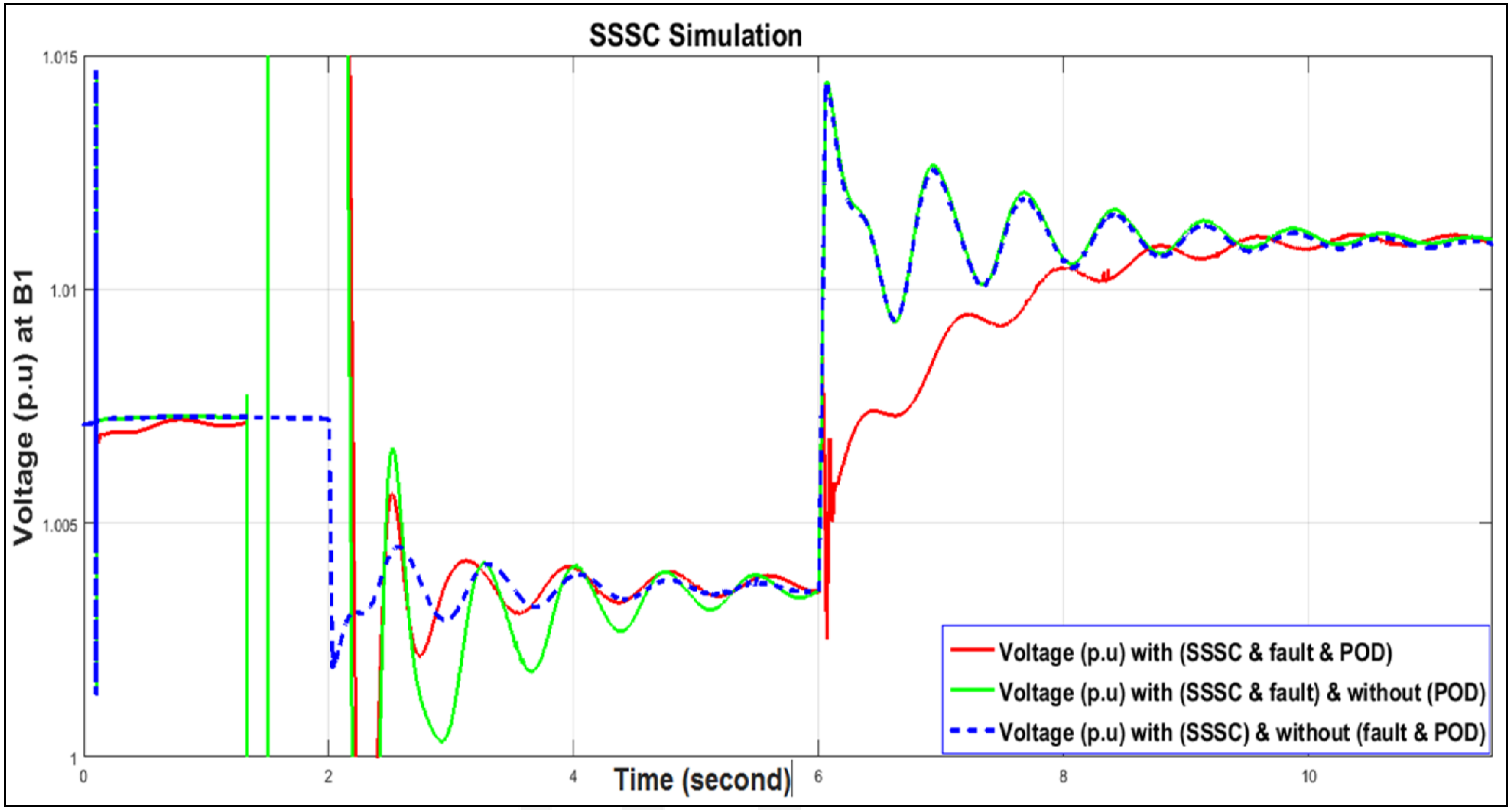


Figure 3.43: Voltage (p.u) at B1, SSSC in the first location with and without fault and POD.

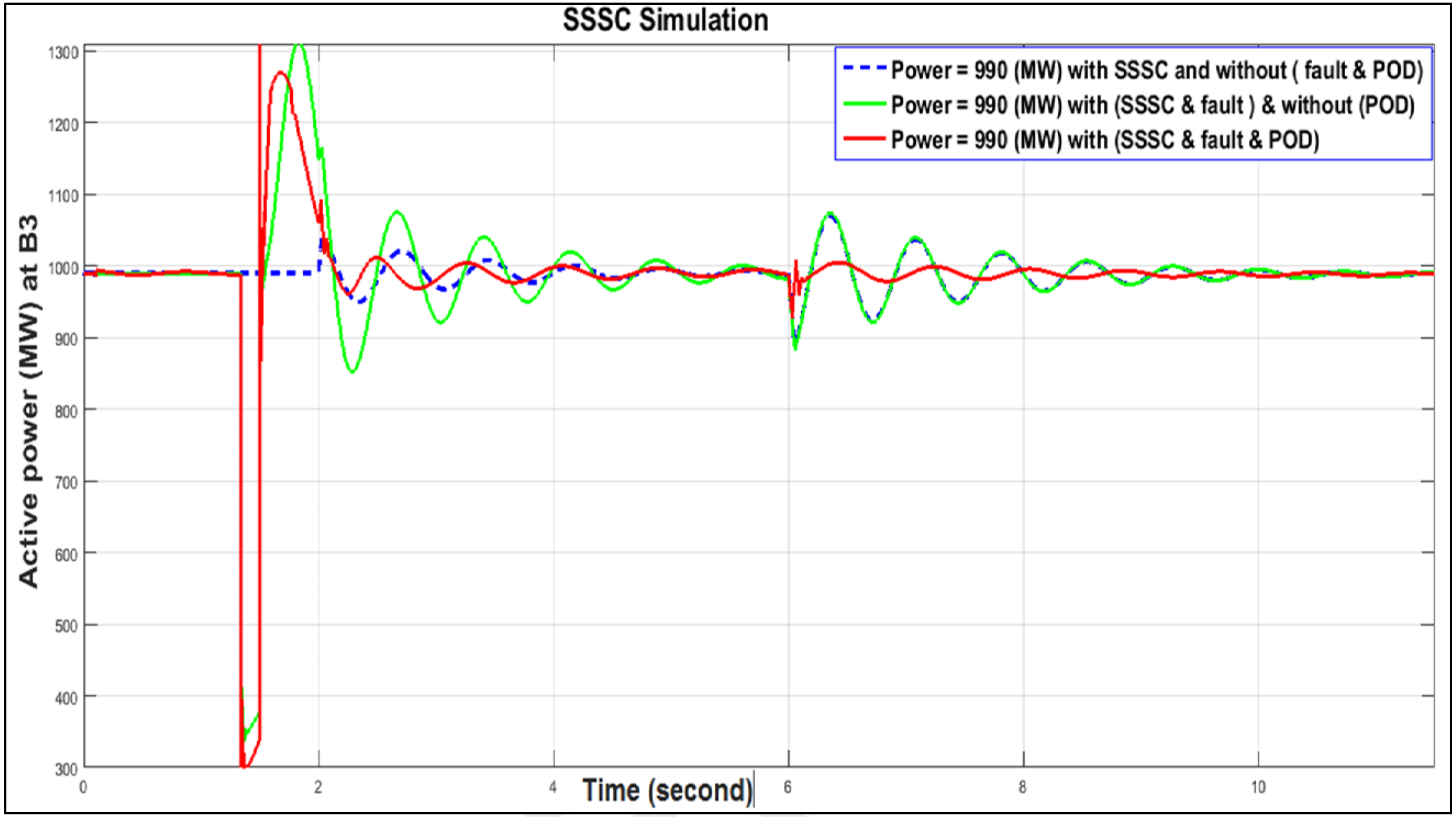


Figure 3.44: Active power at B3, SSSC in the first location with and without fault and POD.

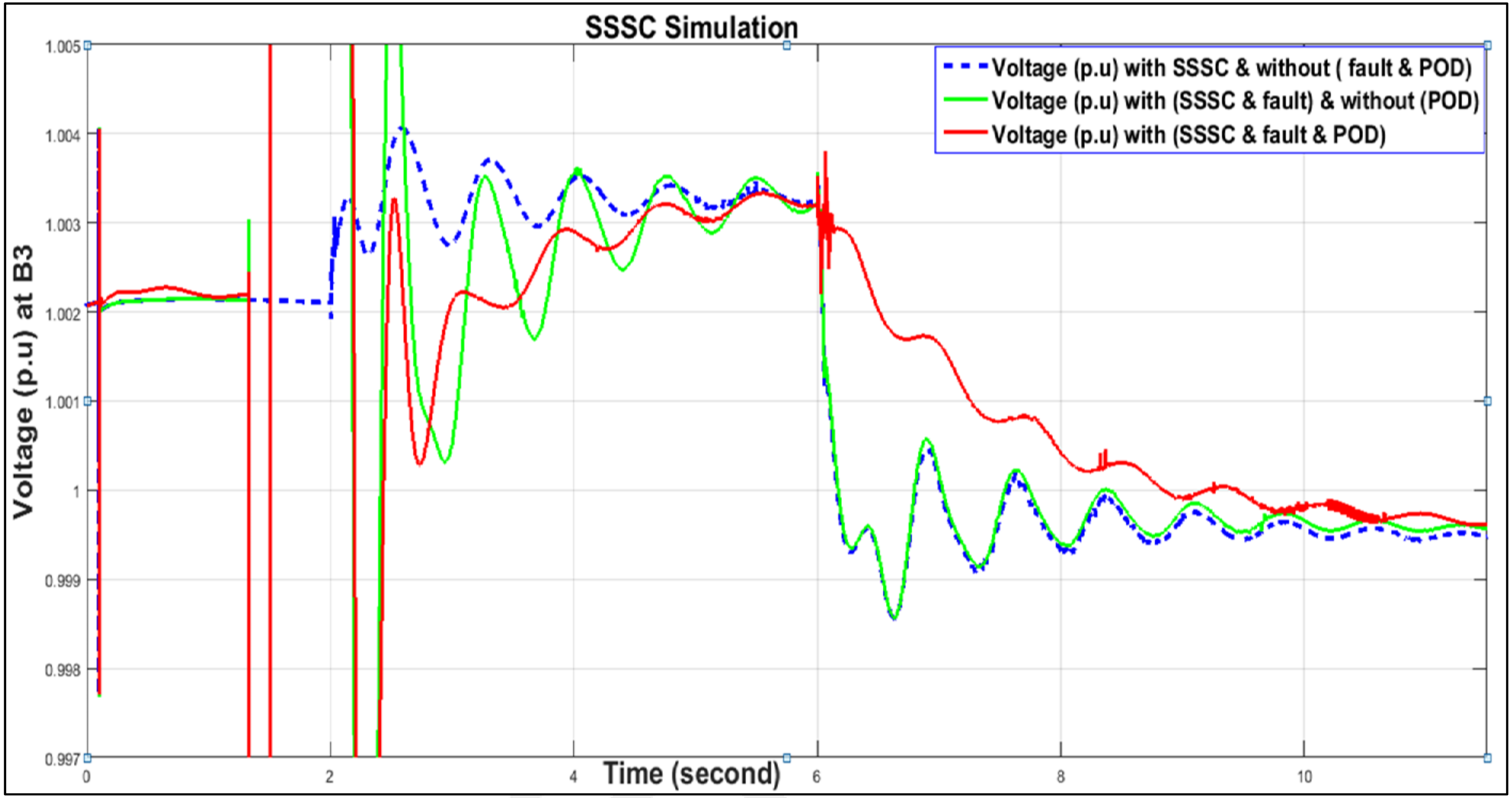


Figure 3.45: Voltage (p.u) at B3, SSSC in the first location with and without fault and POD.

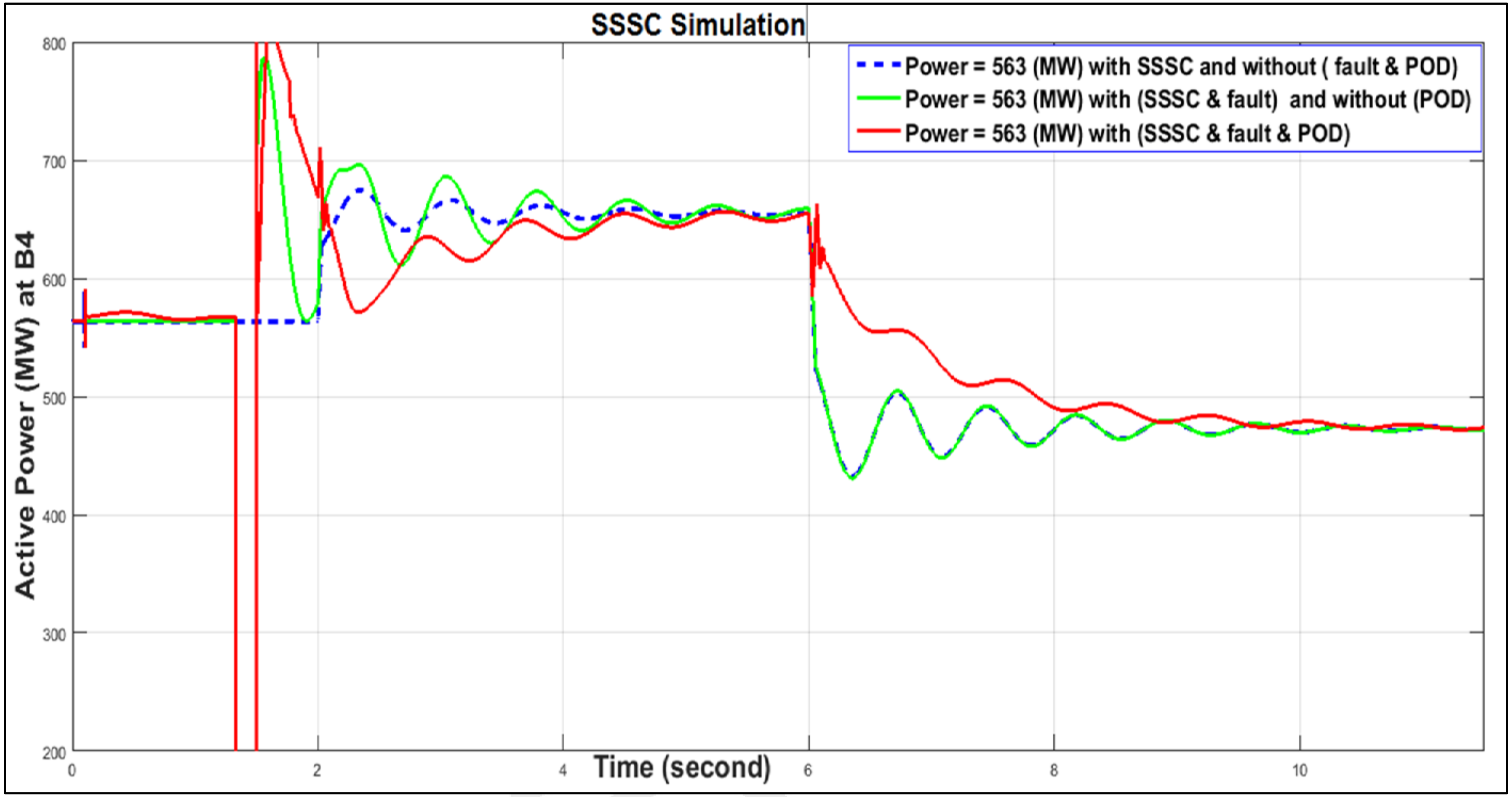


Figure 3.46: Active power at B4, SSSC in the first location with and without fault and POD.

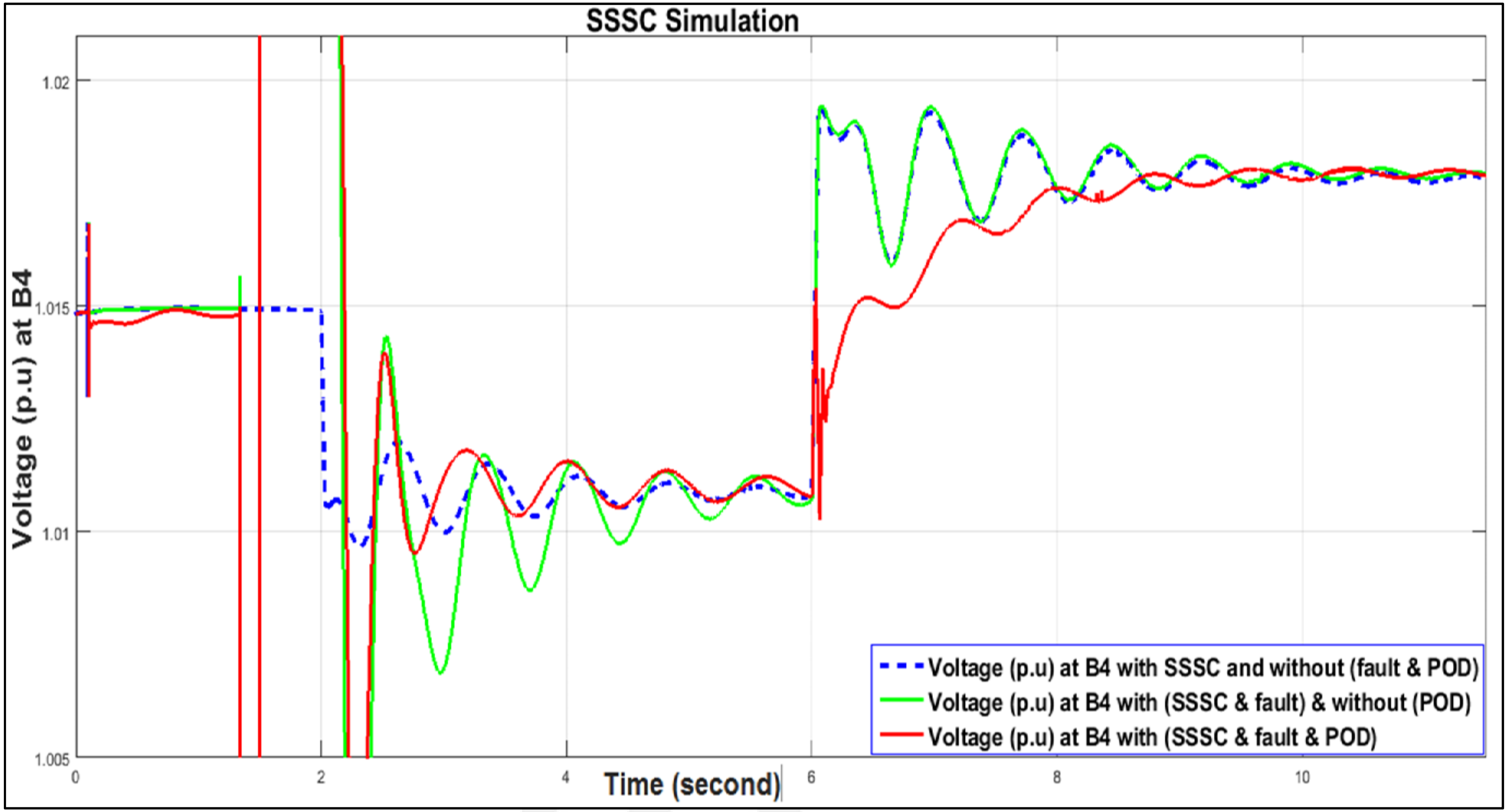


Figure 3.47: Voltage (p.u) at B4, SSSC in the first location with and without fault and POD.

3.4.3 Suggestion For a New Location (Second Location)

In this work and simulation, we have changed the location of the SSSC to another place in our grid to obtain new results, and use these results in comparison with the previous results as well as obtaining good results for damping the oscillation of the active power and stability of the overall system, as shown in Figure (3.48) below.

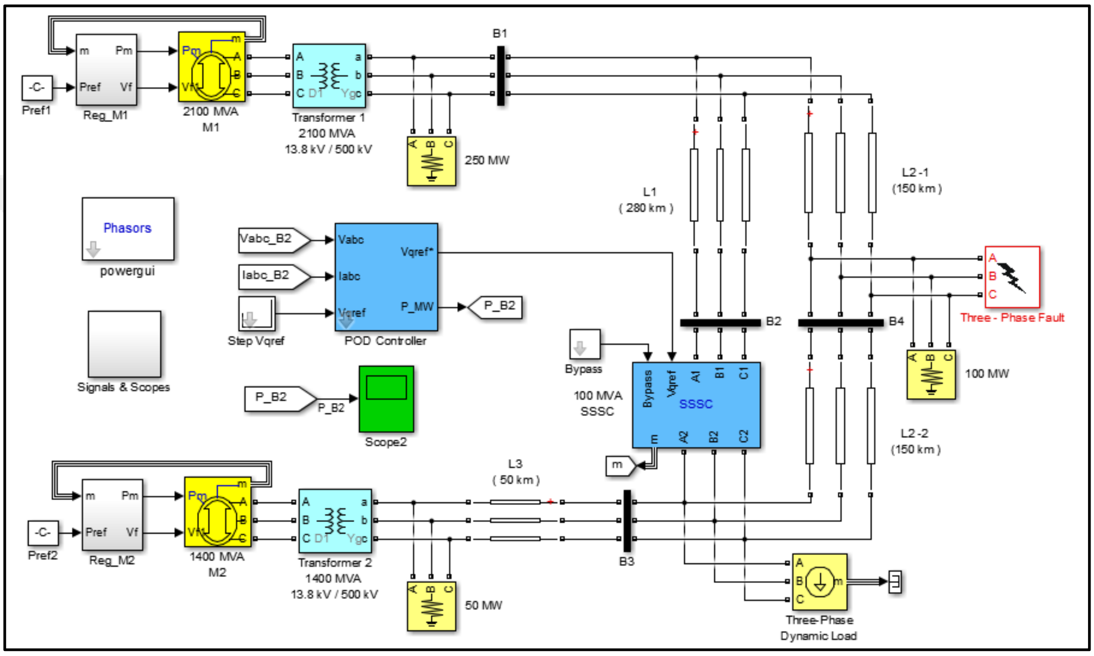


Figure 3.48: SSSC Configuration simulated in the second location.

Initially, we simulated the circuit and measured the active powers (MW) and voltages (p.u) at all buses in all cases (SSSC, fault, and POD) to see the new effect of the SSSC on the active powers and voltages under the conditions of faults and use the results to compare later with the first location of the hand of the voltage stability and damping of the oscillations that occur on the system and the powers transferred along the transmission lines of electrical power.

a) B1 measurement: Voltage (p.u) and active power (1338) (MW) as given in Figures (3.49) and (3.50) below in all cases.

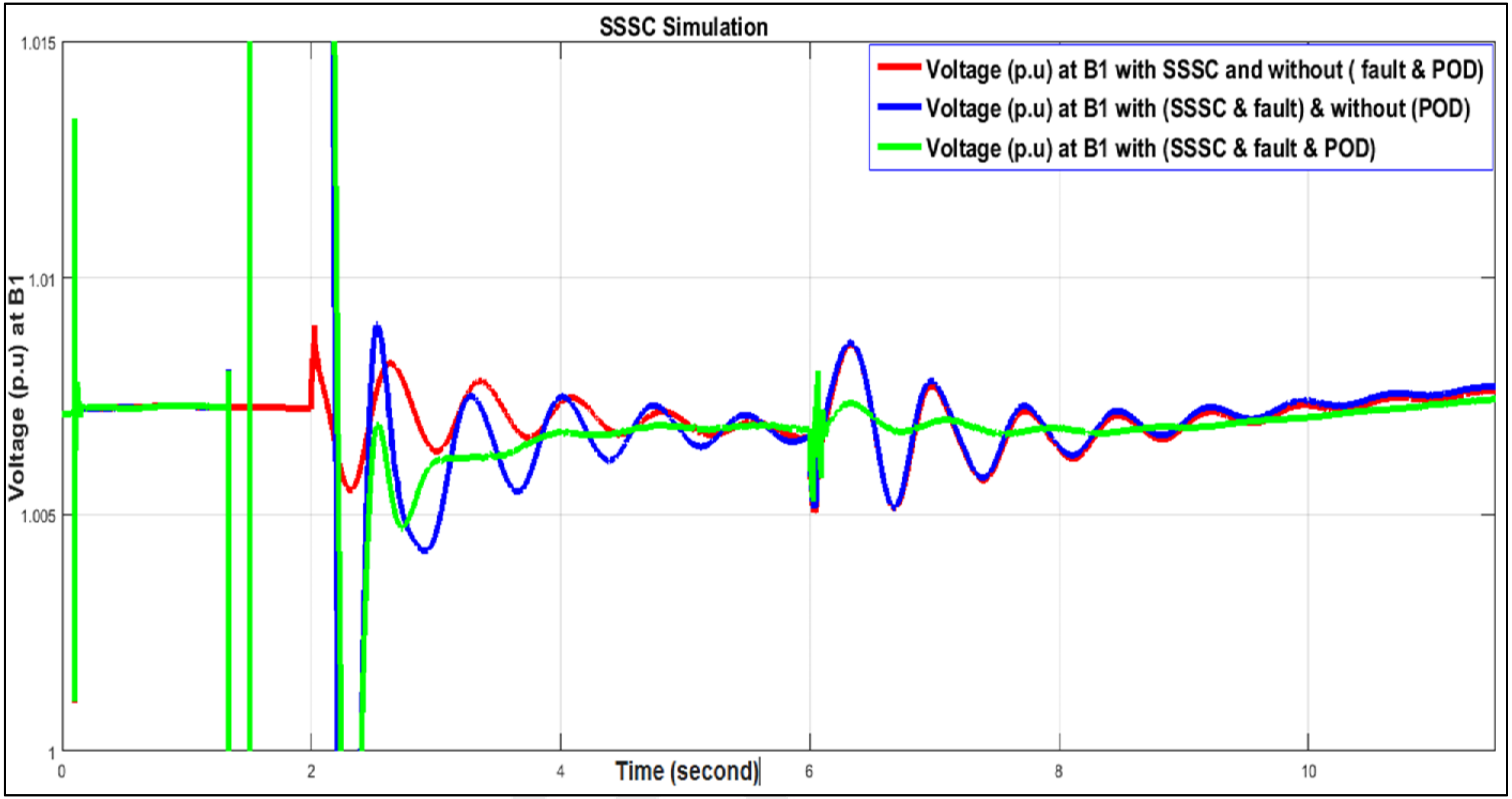


Figure 3.49: Voltage (p.u) at B1, SSSC in the second location with and without fault and POD.

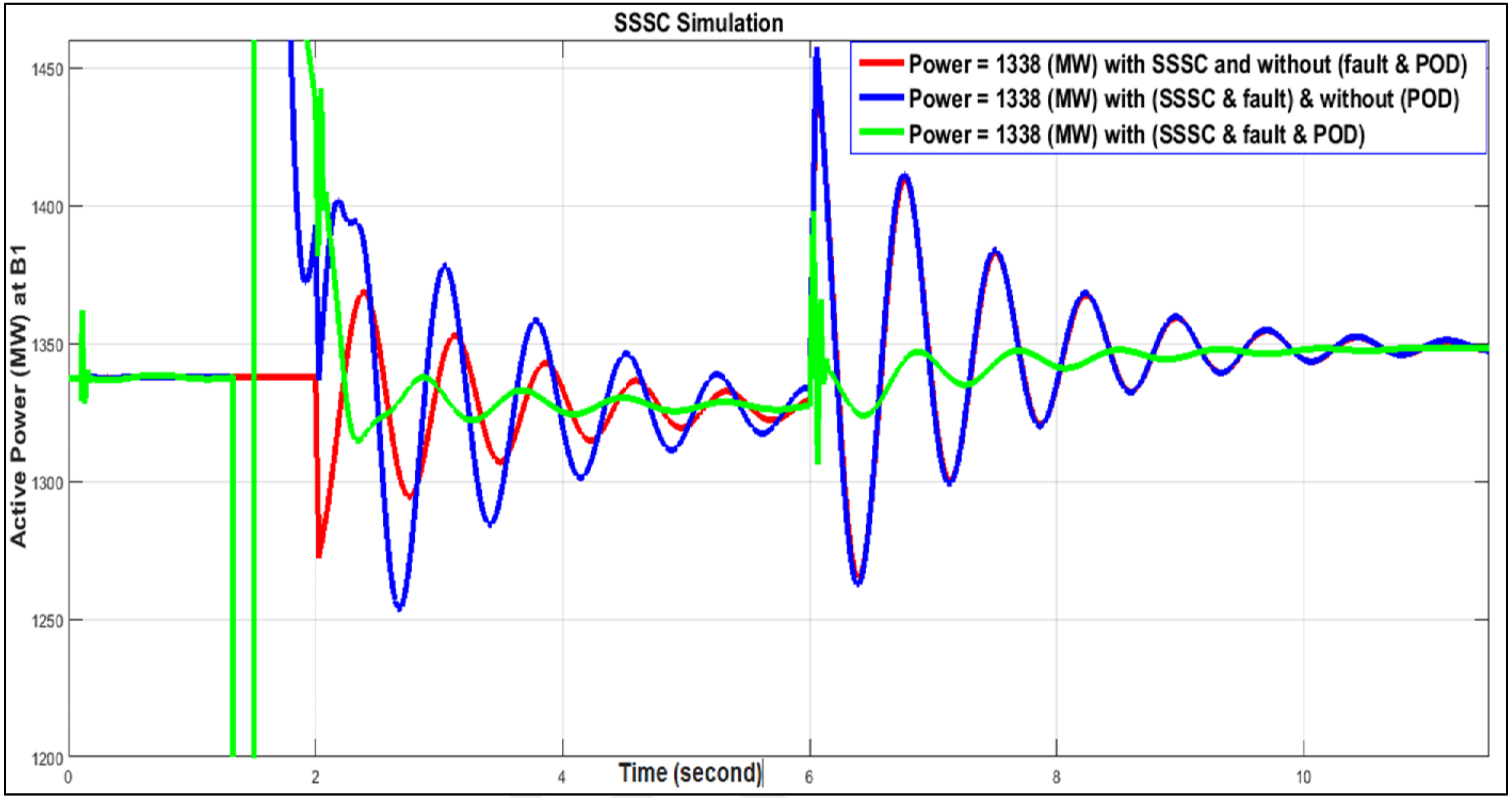


Figure 3.50: Active power at B1, SSSC in the second location with and without fault and POD.

b) B2 measurement: Voltage (p.u) and active power (650) (MW), as shown in Figure (3.51) and (3.52) below with all cases.

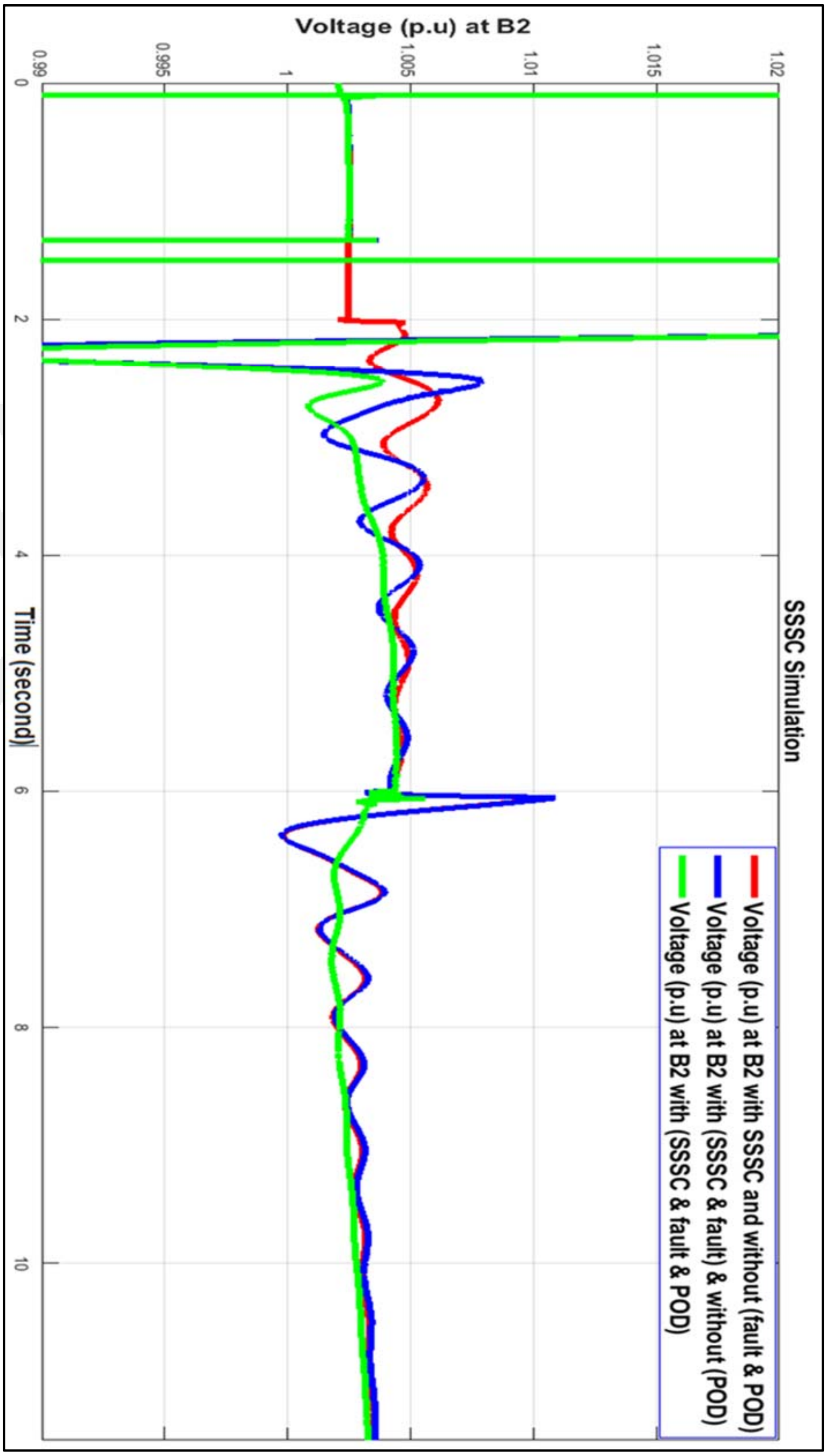


Figure 3.51: Voltage (p.u) at B2, SSSC in the second location with and without fault and POD.

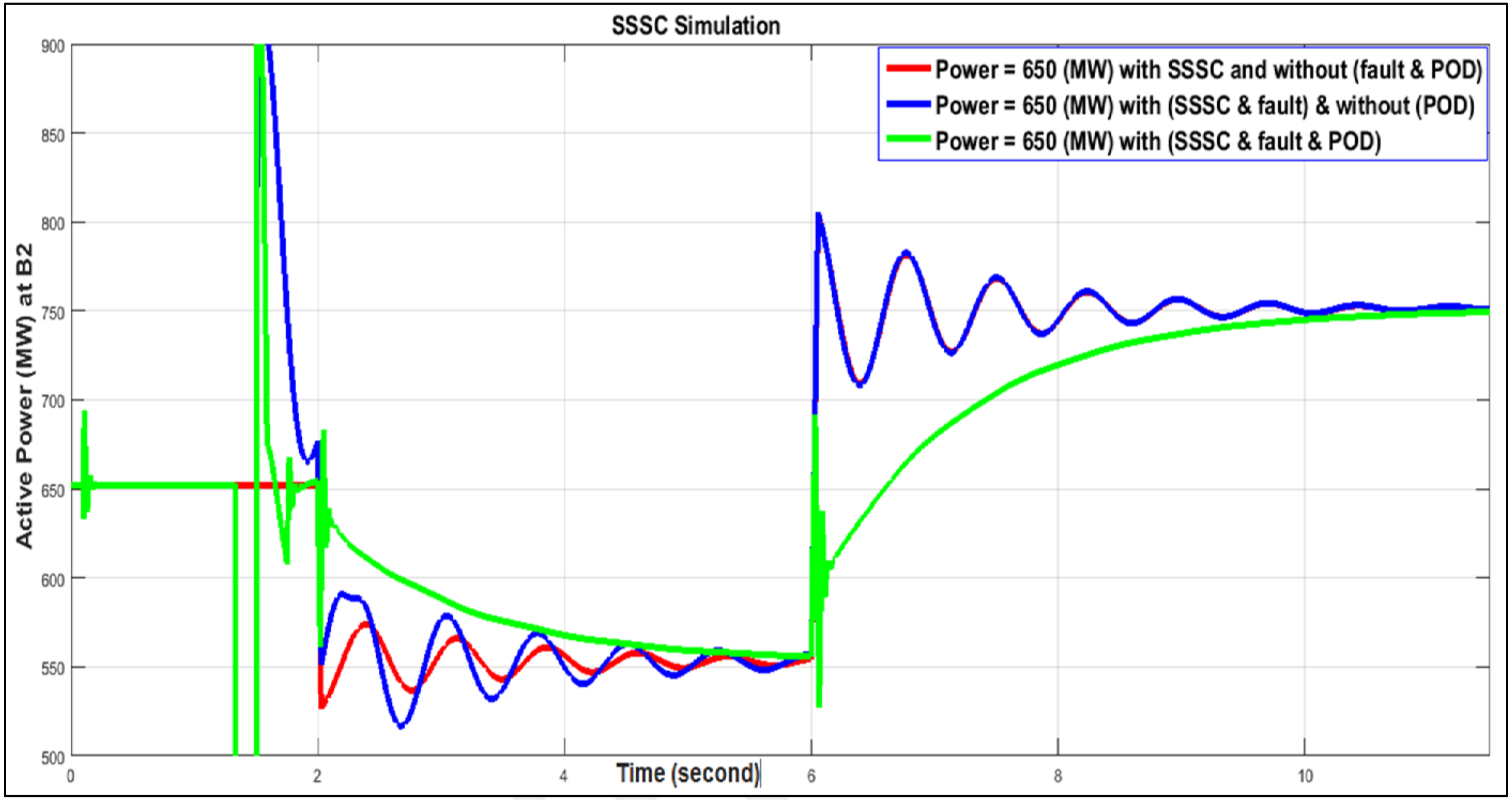


Figure 3.52: Active power at B2, SSSC in the second location with and without fault and POD.

c) B3 measurement: Voltage (p.u) and active power (990) (MW), as shown in Figures (3.53) and (3.54) below in all cases.

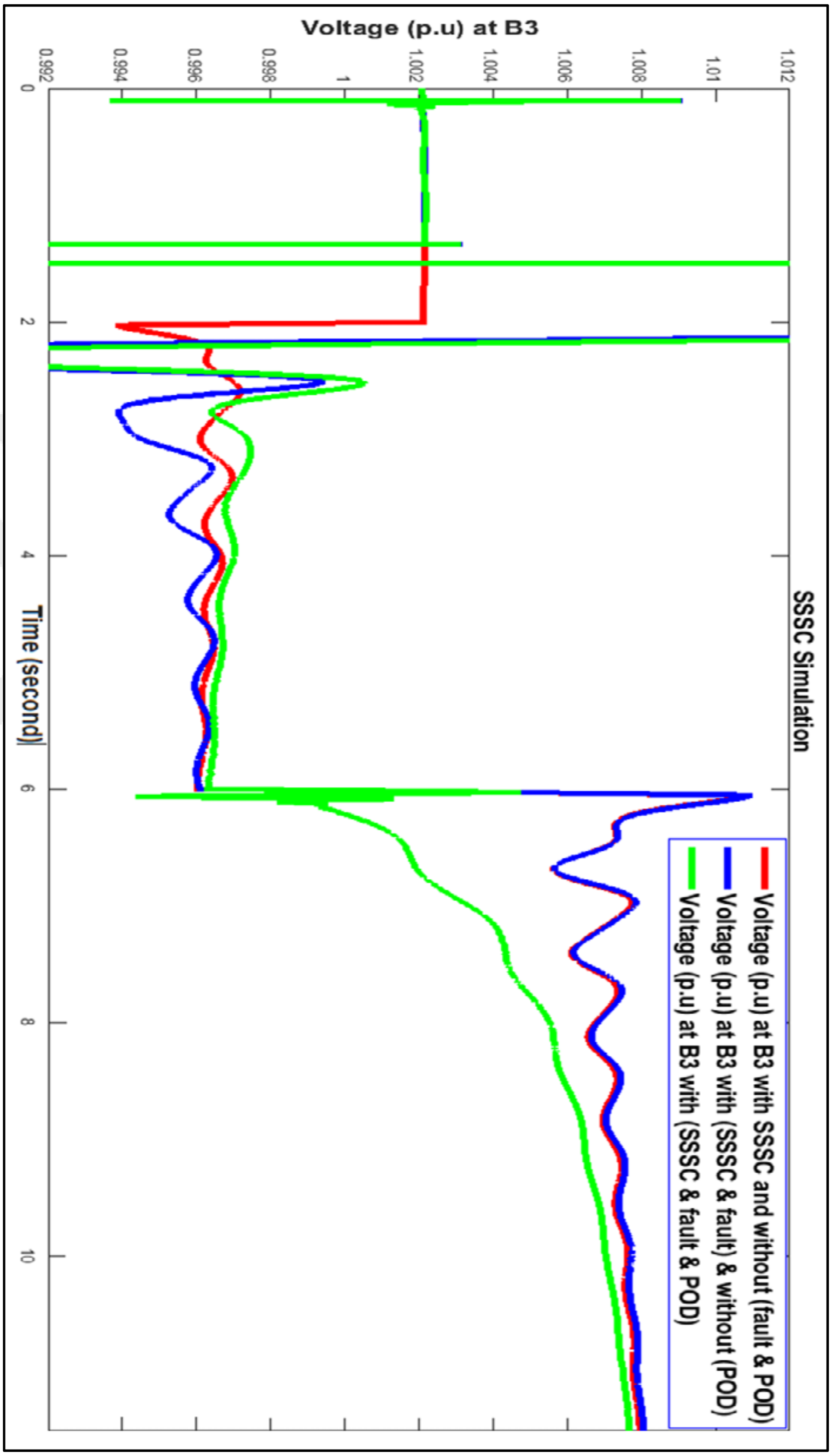


Figure 3.53: Voltage (p.u) at B3, SSSC in the second location with and without fault and POD.

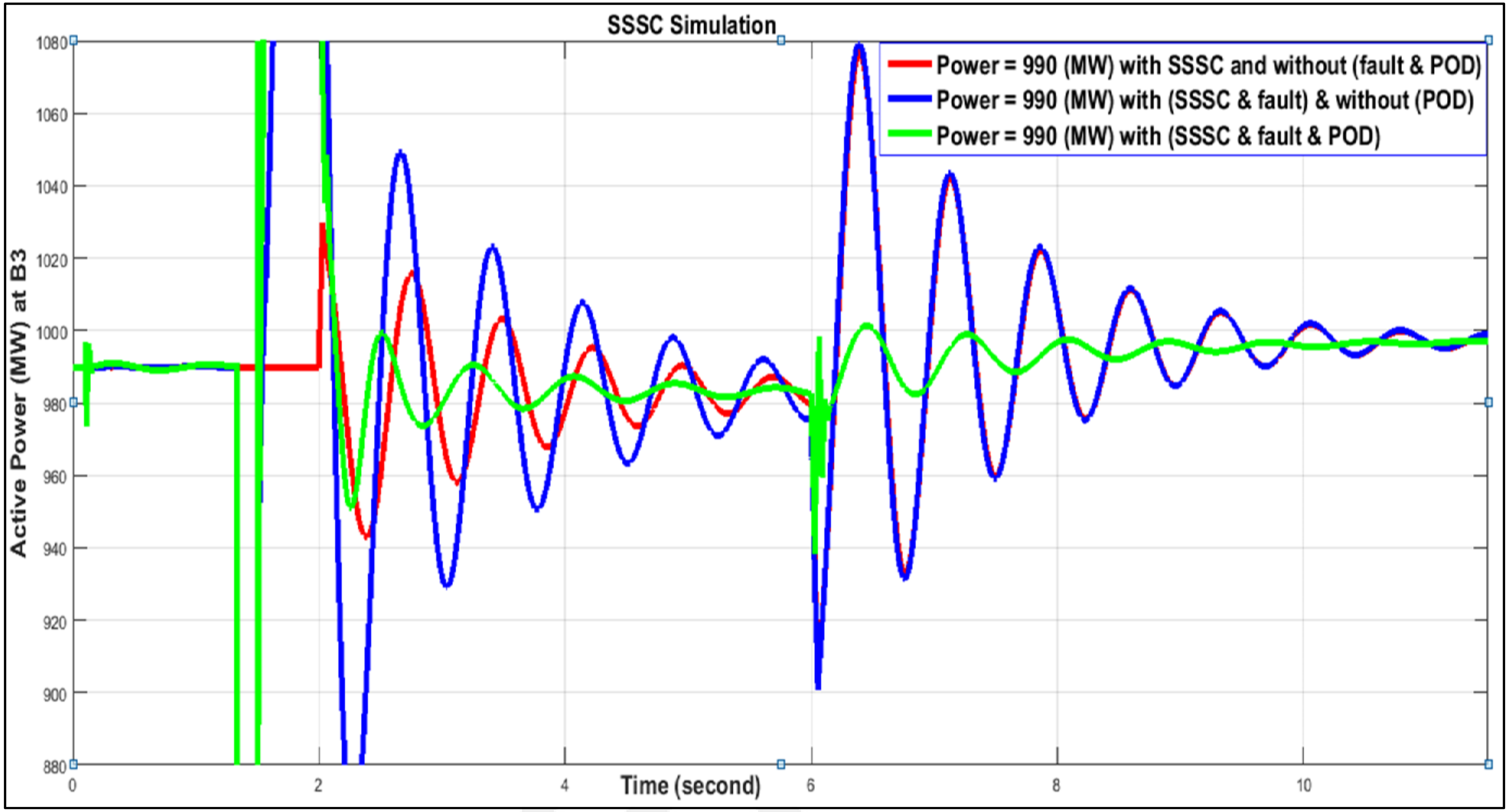


Figure 3.54: Active power at B3, SSSC in the second location with and without fault and POD.

d) B4 measurement: Voltage (p.u) and active power (563) (MW), as shown in Figures (3.55) and (3.56) below in all cases.

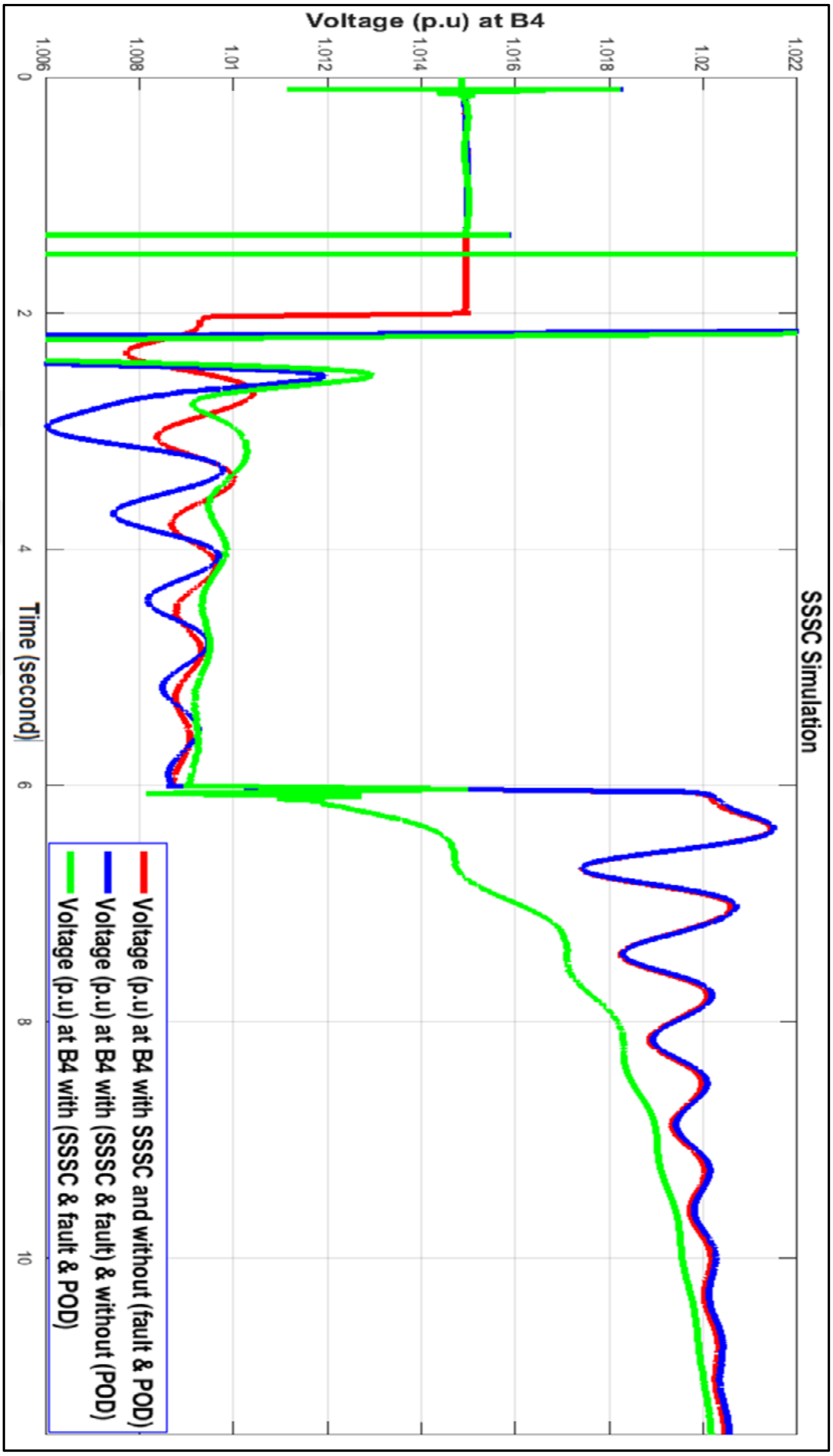


Figure 3.55: Voltage (p.u) at B4, SSSC in the second location with and without fault and POD.

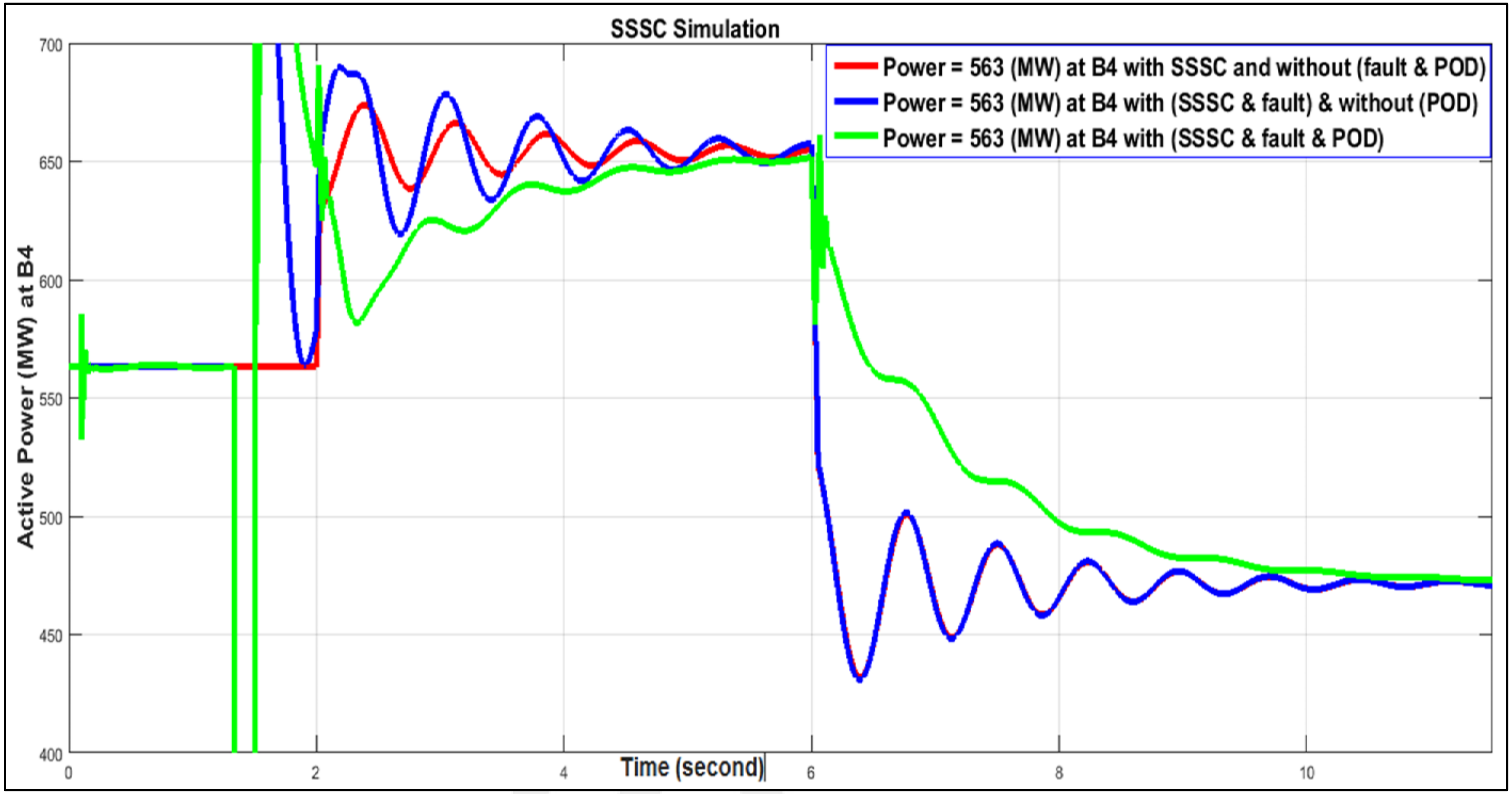


Figure 3.56: Active power at B4, SSSC in the second location with and without fault and POD.

3.4.4 Comparison of the Figures in the First and Second Location

For comparisons between the forms obtained from the results of the simulation, we take a measurement time of 20 seconds so that we can obtain and see the stability and damping of the total system and the voltages on the bus-bars and power transmission lines, as shown by the results of the respective waveforms in Figures (3.57), (3.58), (3.59), (3.60), (3.61), (3.62), (3.63), (3.64) and (3.65).

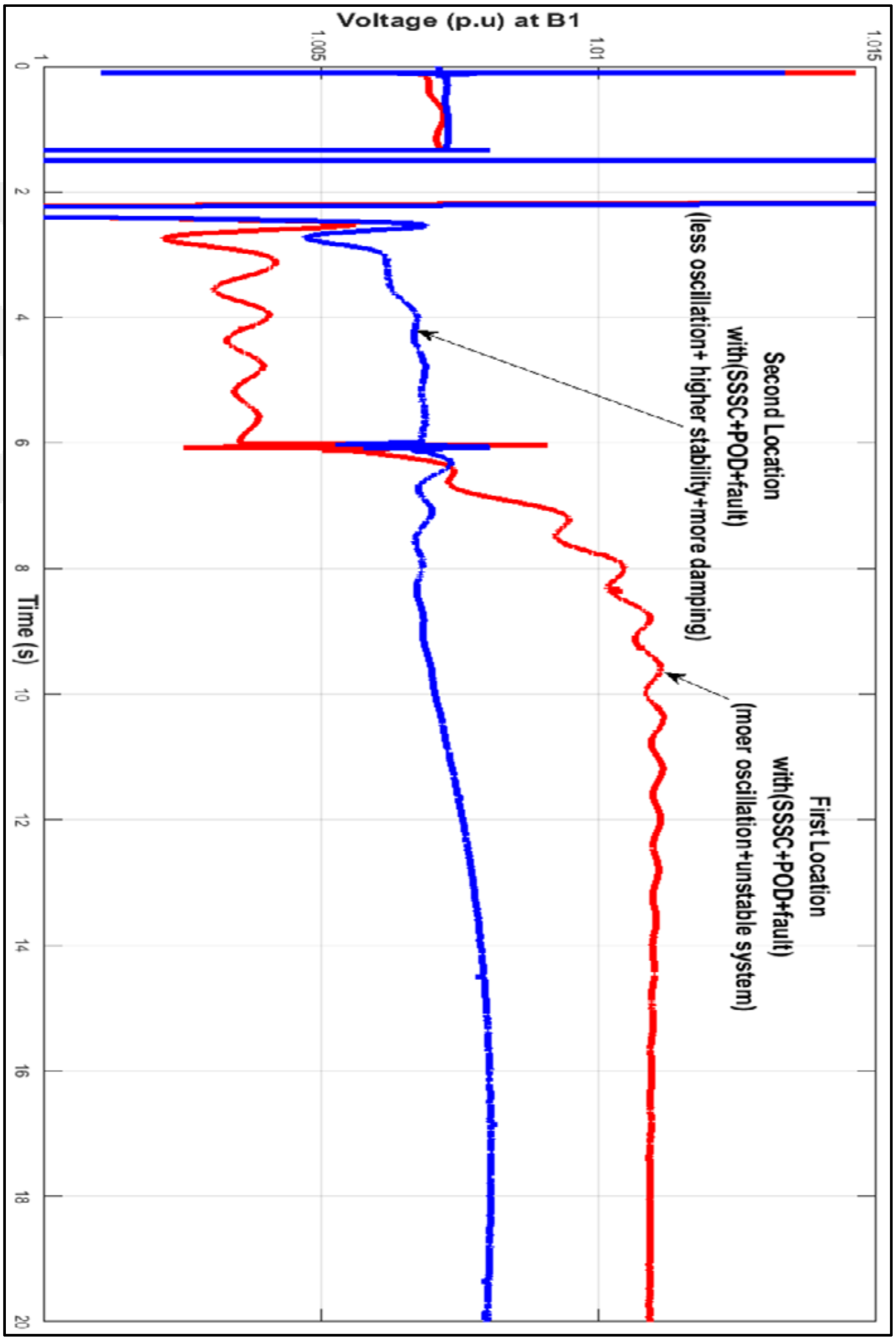


Figure 3.57: Voltage (p.u) at B1, SSSC in the first and second location with fault and POD.

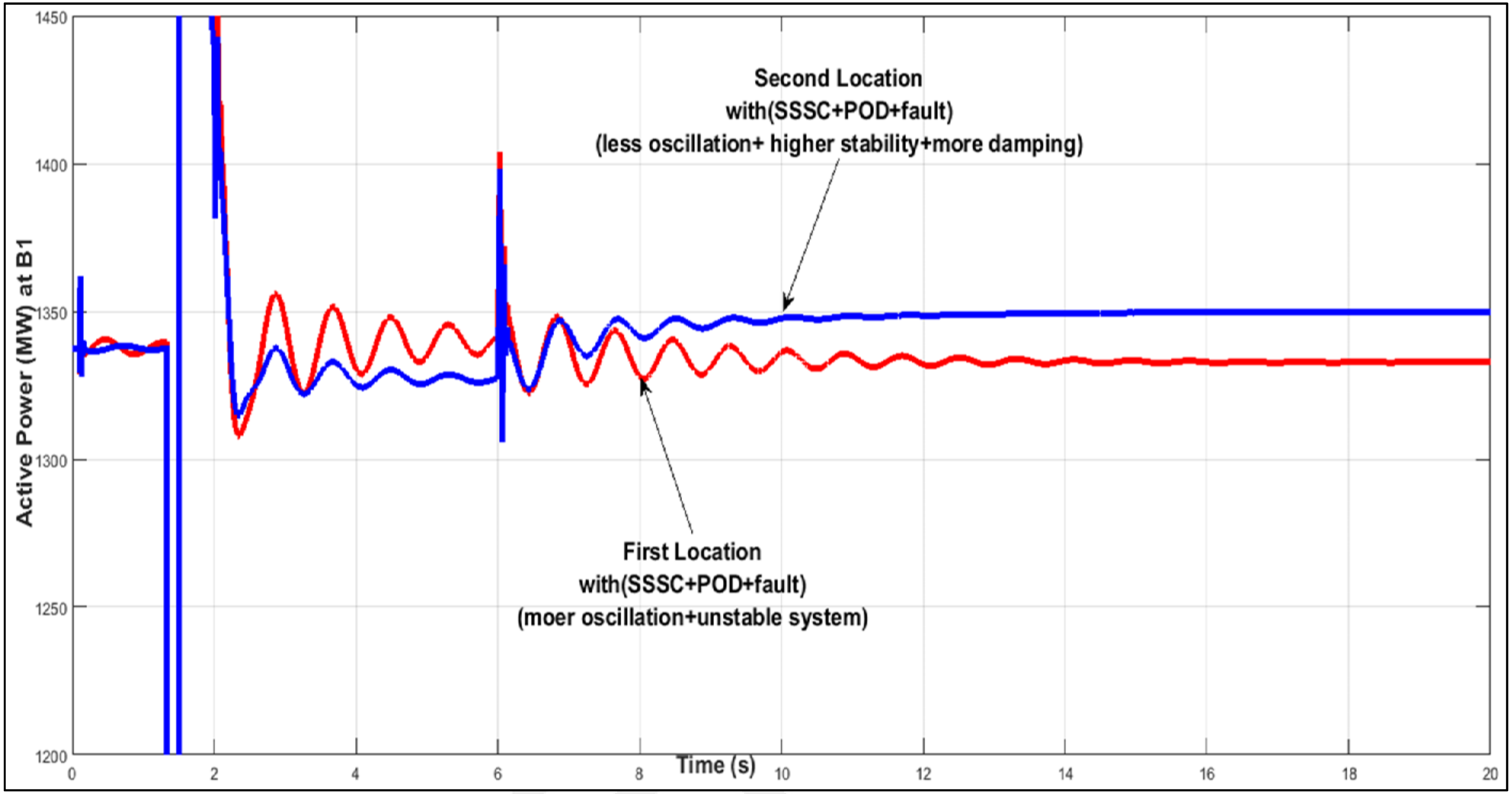


Figure 3.58: Active power at B1, SSSC in the first and second location with fault and POD.

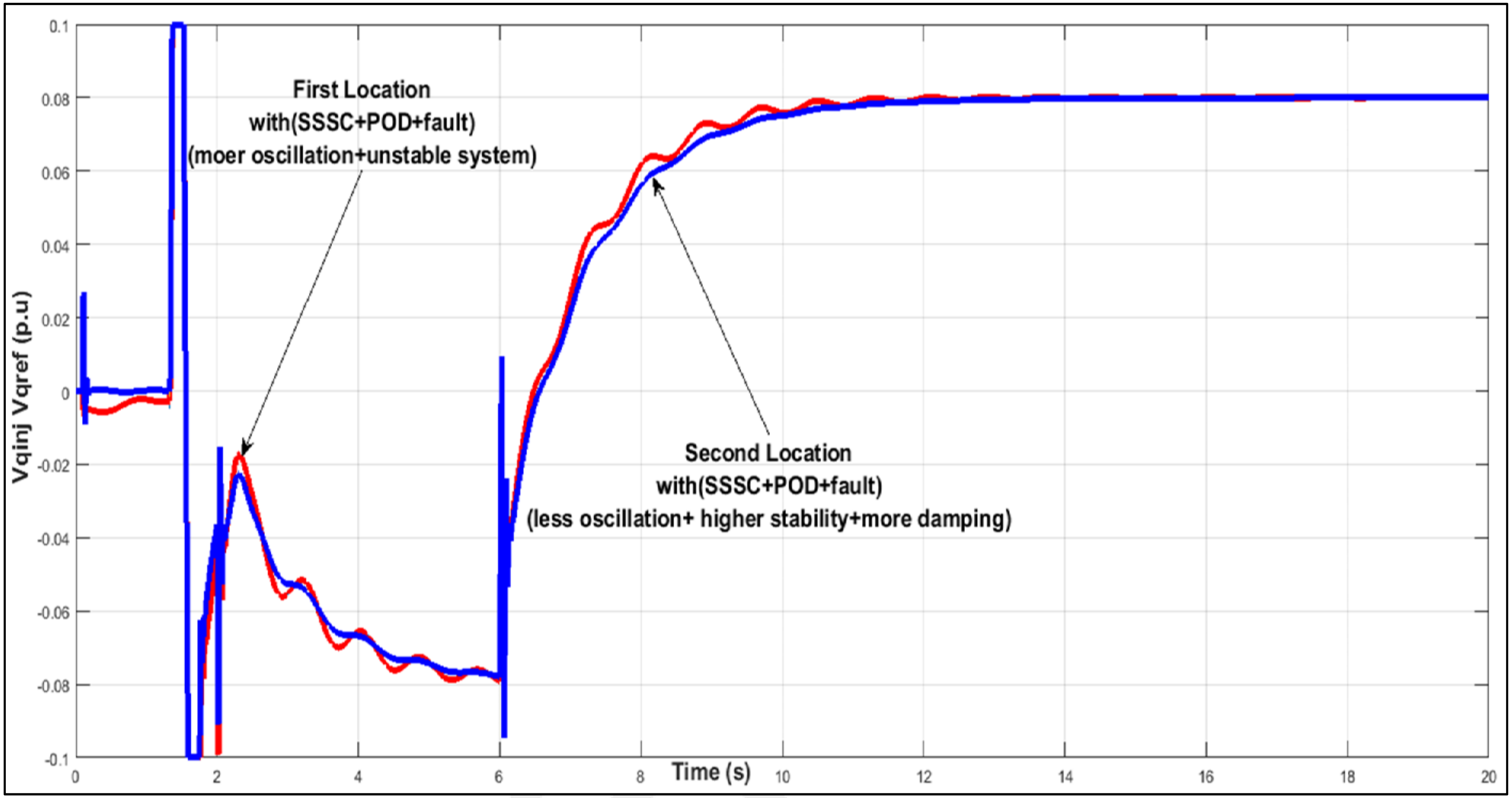


Figure 3.59: Voltage Vqinj Vqref (p.u) at B2, SSSC in the first and second location with fault and POD.

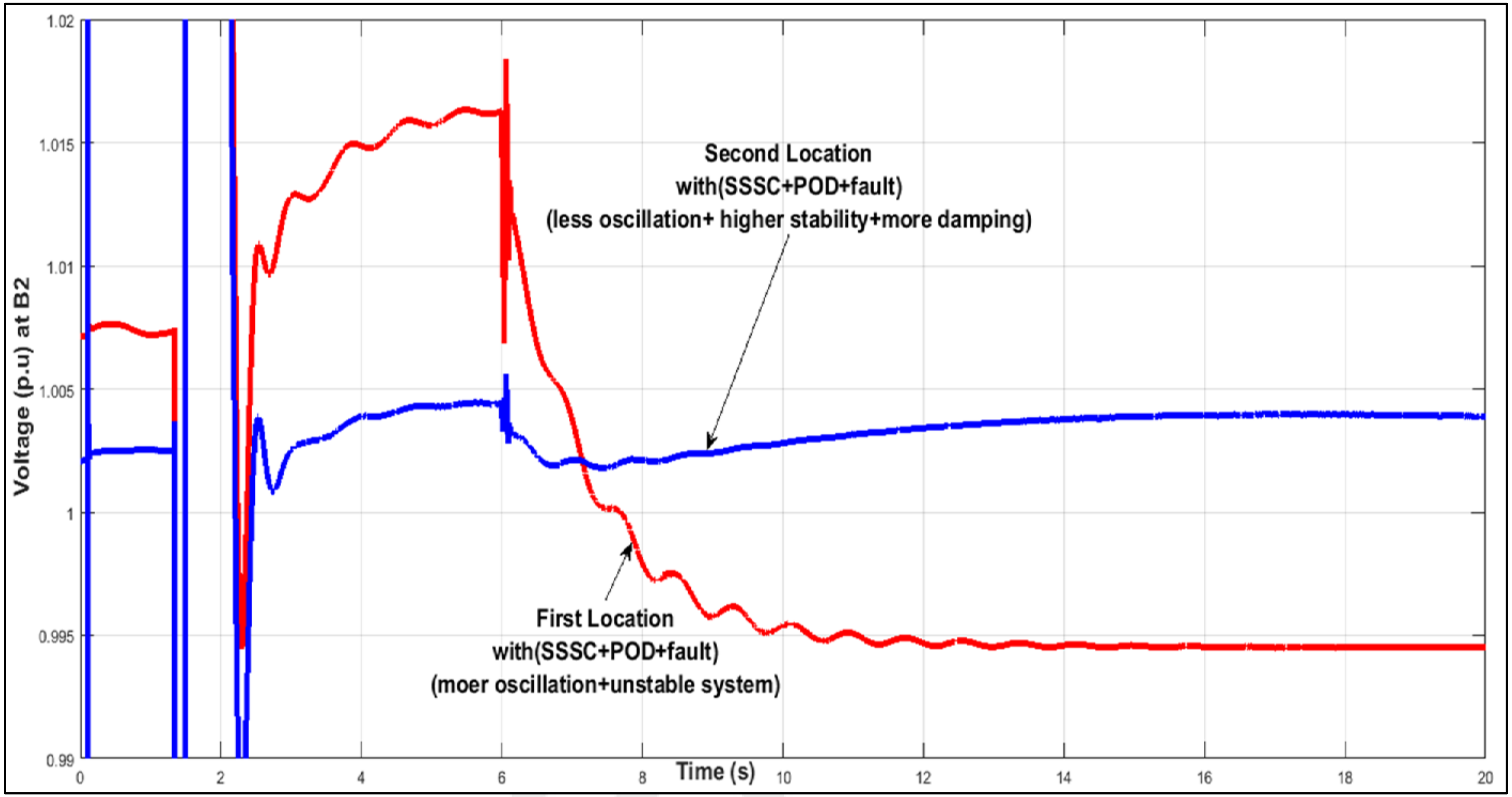


Figure 3.60: Voltage (p.u) at B2, SSSC in the first and second location with fault and POD.

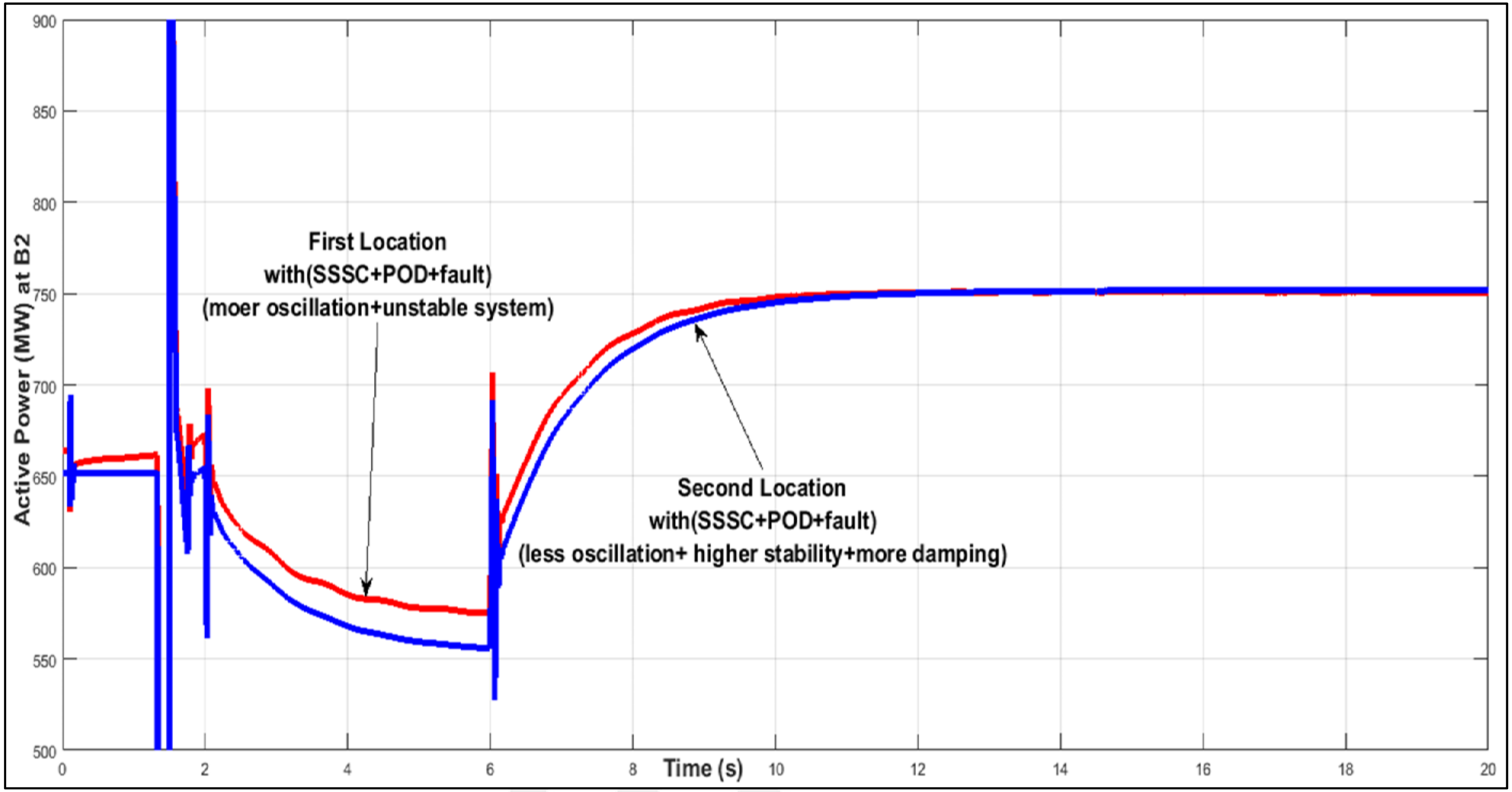


Figure 3.61: Active power at B2, SSSC in the first and second location with fault and POD.

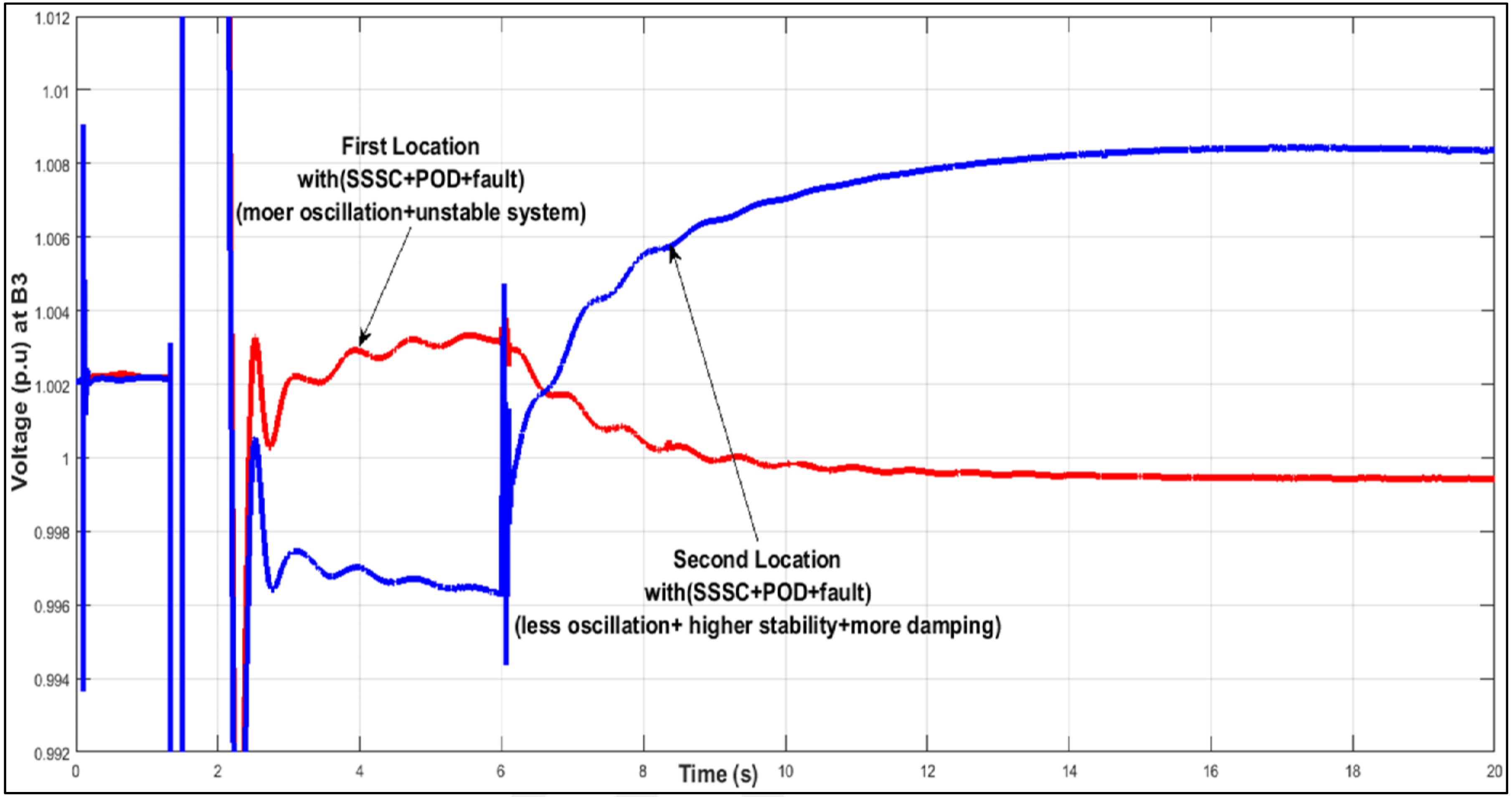


Figure 3.62: Voltage (p.u) at B3, SSSC in the first and second location with fault and POD.

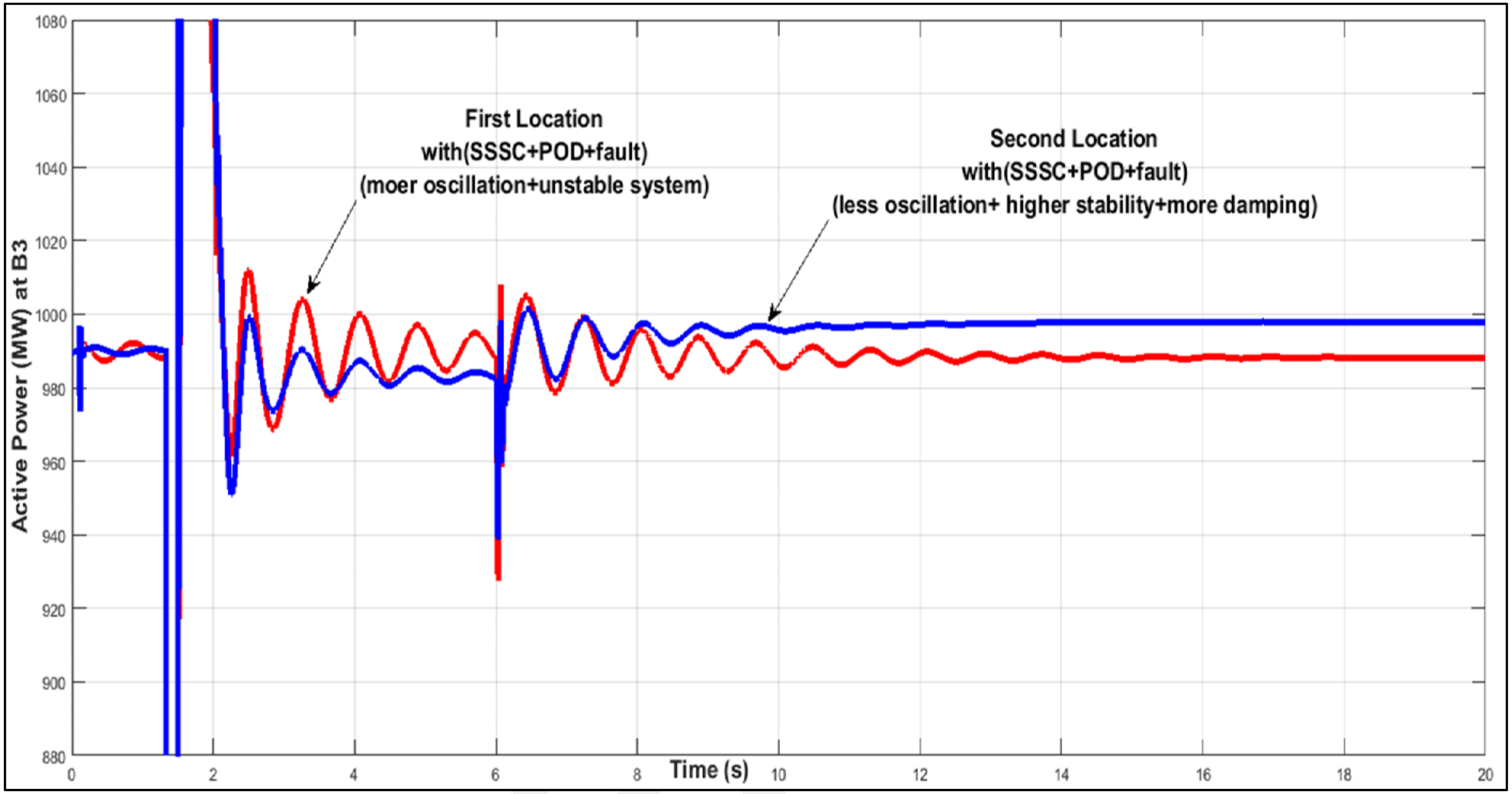


Figure 3.63: Active power at B3, SSSC in the first and second location with fault and POD.

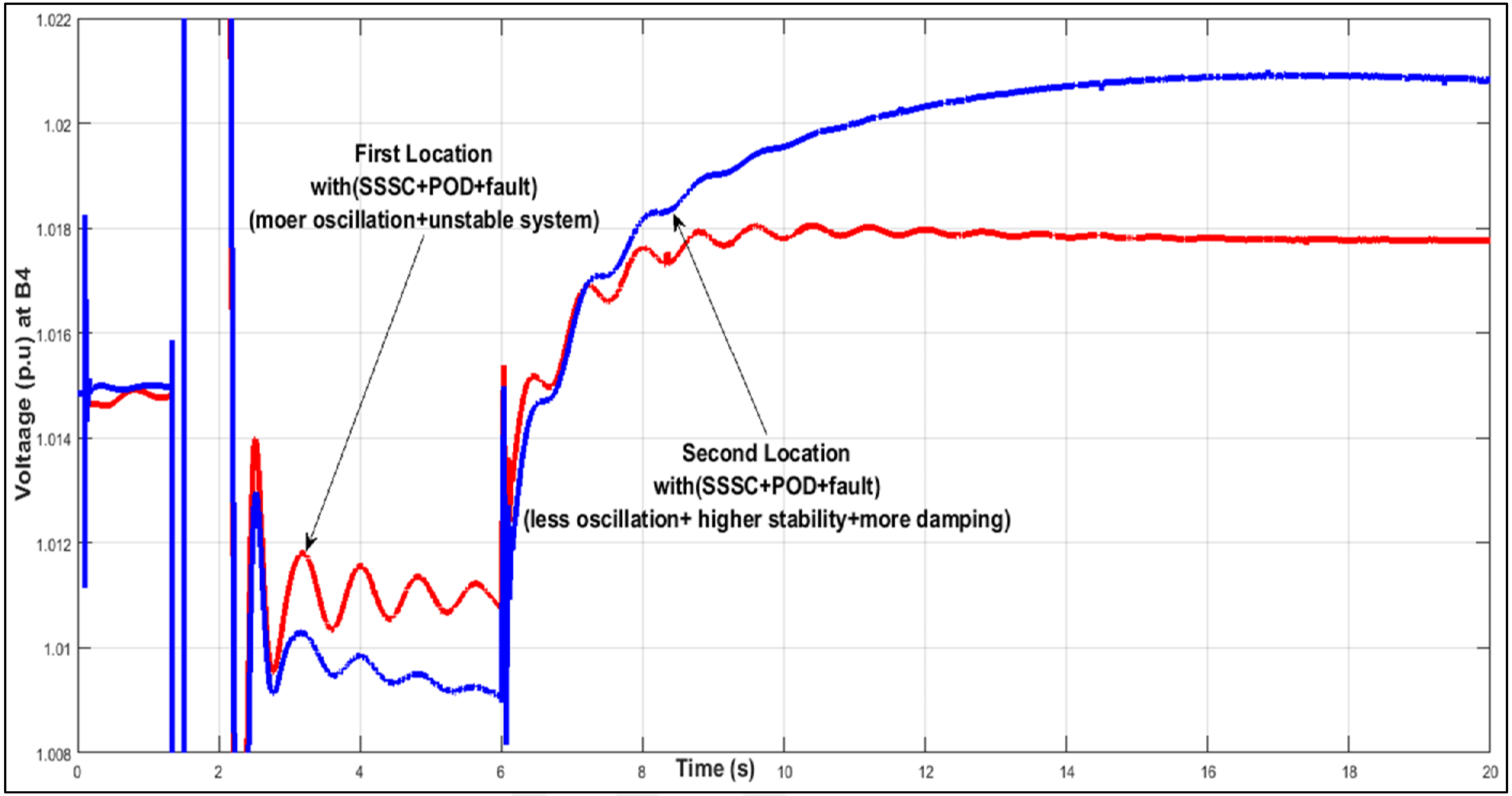


Figure 3.64: Voltage (p.u) at B4, SSSC in the first and second location with fault and POD.

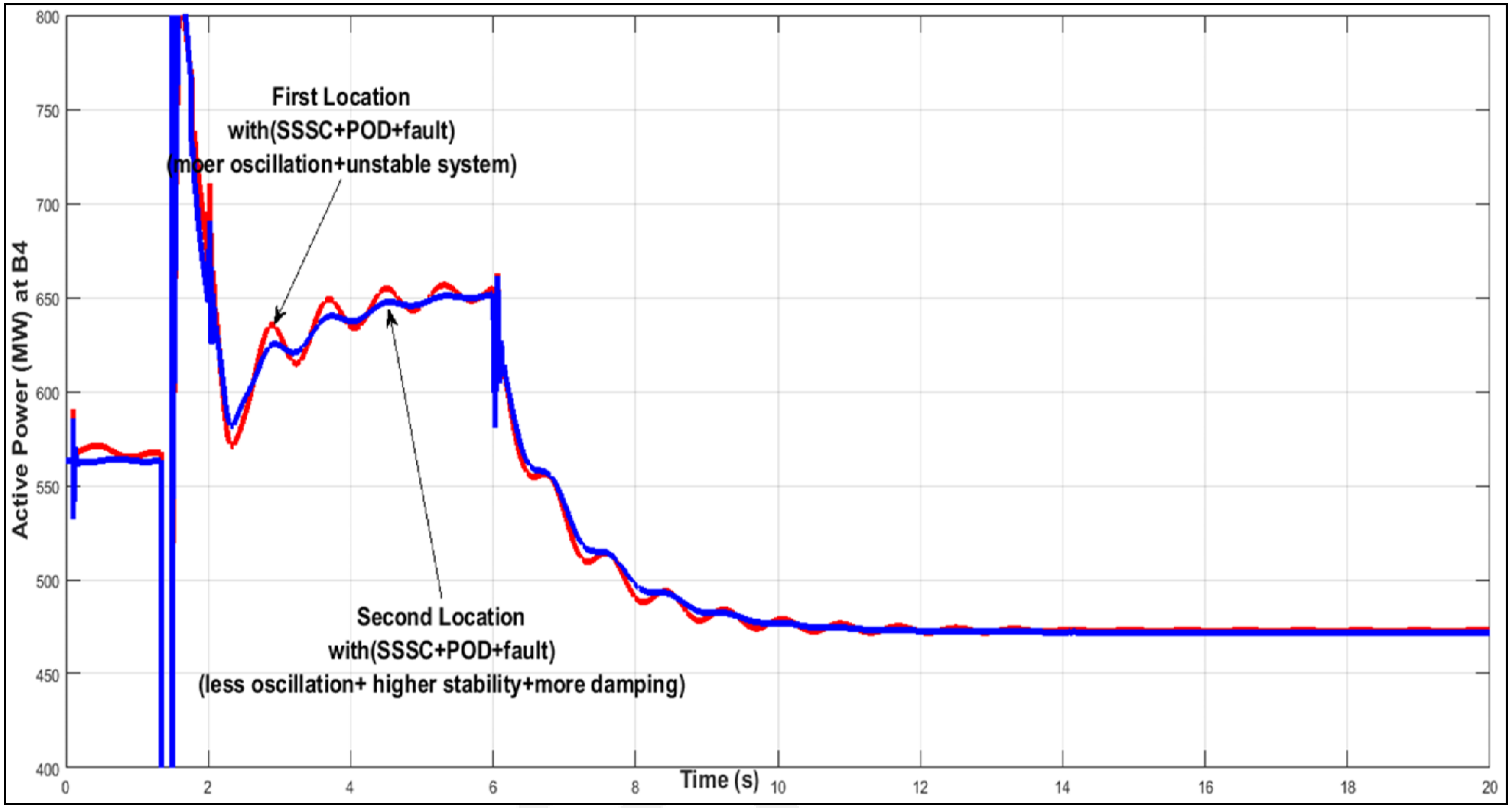


Figure 3.65: Active power at B4, SSSC in the first and second location with fault and POD.

3.5 Results of Simulation

The results of the investigations for this thesis were completed to scout about for activity of the SSSC compensation form in damped oscillations of the power system in multi-machine power systems in two locations (first and second) suggested for simulations and comparisons of results. We can see that an SSSC with a POD controller is a very strong, efficient tool to damp any oscillation of electrical power for active power in an electric power transmission grid in the second location. This means the fast response of controlling the stability, power flow, and reducing the power oscillations in the system with fault conditions are as explained. It is observed in the simulation that whatever the magnitude and phase of the line current would be, the SSSC can inject a rapid treat voltage in series with the line. It is also demonstrated that the power flow at a designated point on the transmission line can be controlled by the SSSC.

From the results and the forms we obtained, we see that the second location is more effective than the first location in terms of the stability of the overall system over a few seconds to reach a steady state case due to its important position as a midpoint of the system and its efficiency in handling the oscillation in the transfer of the active power. Moreover, through the second location and important for being near to bus bar 3, we can improve the voltage on it at two ends and also improve the voltages on the ends of transmission lines 1 and 2, thereby improving the voltages and power transferred on these lines. Therefore, the size of the system has been improved in terms of voltages, power, and the damping of the oscillations due to the conditions of the fault, as shown in Figures (3.57), (3.58), (3.60), (3.61), (3.62), (3.63), (3.64), and (3.65) of the waveforms, respectively. As a summary of the final results in the table shown below in Schedule (3.1), we have:

1- SSSC with a POD controller being a very good, effective tool to damp power oscillations for active power.
2- Fast response when controlling the voltage and power flow.
3- Reducing the power oscillation to achieve a steady state and stability in time.
4- Smoothly reaching nominal line power and voltage in an oscillation-free manner.

5- The strong impact of the SSSC in the injection voltage (Vqinj) in electrical transmission networks and the possibility of tracking the reference voltage (Vqref) in cases of increased and decreased power (inductive or capacitive mode).

6- The capability of providing reactive power compensation to a power system.

7- Current control, transient and dynamic stability, voltage stability, fault current limitation.

8- A strong impact to improve stability (power angle and voltage).

Schedule 3.1: Voltage (p.u), Active power (MW), Stability time (s) in two locations.

Bus bar no.	Locations with (SSSC, POD, Fault)	Voltage (p.u)	Active power (MW)	Stability time (s)	
				Voltage	Active power
1	**First location**	1.0109	1332.88	**12.67**	**14.67**
	Second location	1.008	1349.64	**7.67**	**8.67**
2	**First location**	0.9945	750.785	**12.67**	**8.67**
	Second location	1.0039	751.80	**6.67**	**8.67**
3	**First location**	0.9994	988.14	**10.67**	**14.67**
	Second location	1.0084	997.55	**8.67**	**10.67**
4	**First location**	1.0178	472.85	**12.67**	**12.67**
	Second location	1.0208	471.95	**8.67**	**7.67**

After a three-phase fault is generated, the power oscillation in the grid is dampened with the utilization of the SSSC. The performance of the SSSC has been studied in a two-machine system configuration. Based on these results, SSSC applications may be further scaled to more complex multi-machine configurations in the future in order further to study several types of power oscillation problems in power grids.

3.6 Discussion of Methodology and Validation of Results

This thesis analyses the implementation of an SSSC in a manifold-machine power system operation in the presence of a 3-Ø short circuit fault being expressed. The results explain that the power system oscillations are damped out very quickly with the aid of SSSC-based damping controllers in a few seconds. The survey reveals that SSSC is proficient at improving the power flow through the line by inserting a fast-changing voltage in sequence with the transmission line. The inserted voltage is in quadrature along with the transmission line current, and hence it can supply both inductive and capacitive compensation.

The FACTS controller has emerged as a controller connected in series as the SSSC has made it possible to regulate the flow of power in critical lines. By inductive or capacitive reactance emulation in sequence with the transmission line, the SSSC has a reactive voltage control that can inject a quadrature controllable reactive voltage with the line current. In this work, the procedure of the SSSC model to which it is linked in series with the line is verified. SSSCs have been studied in two power systems of the machine and connected at bus-2. Therefore, from this document, an SSSC can be used effectively to dampen power oscillations in a power transmission system with and without faults. One can also control the power flow at a particular or desired point. The application of the SSSC can be scaled further in the future to complex and multi-machine configurations to mitigate the problem of power oscillations in power systems. Through the results obtained, we can identify the ability to use the SSSC device in electrical power transmission lines. The device has many characteristics, including fast responses to work in terms of voltage injection and tracking voltage references to maintain the stability of power system operations under different conditions to reduce fluctuations of the transfer of effective ability and access to the point of good stability of the system after a few seconds.

The strong impact of the SSSC in the injection voltage (Vqinj) in an electrical transmission network and the possibility of tracking the reference voltage (Vqref) in cases of an increase or decrease of power (inductive or capacitive mode) are advantages as the SSSC device can regularly keep track of the reference voltage (Vqref). Depending on the injection voltage (Vqinj), the power transfer on the line differs according to different values. Moreover, a quick response to an injection of voltage and the possibility of obtaining control of the best real power (active power) at the lowest oscillations will tend to vanish in order avoid power oscillations. This means that the SSSC is ideal for fast responses and effective as a tool for transmission power networks. We concluded the rapid response to damp the oscillations using the POD controller with the SSSC and obtained good results in improving the stability during the time of the fault with a few seconds in the second location.

CHAPTER FOUR

CONCLUSIONS AND FUTURE WORK

4.1 Conclusions

The vast and rapid development of industry and population has created a huge demand for electrical power. Not only is new power generation needed; transmission line capacity also has to be upgraded to match demand commensurately. SSSC is a series FACTS device that is used for transmission line compensation to control transferred power and damp system oscillations during disturbances. The scope of this thesis is to demonstrate the behavior and applications of an SSSC in power systems. All simulation cases have been carried out in the MATLAB/Simulink tool. The cases were performed on a power system model with an SSSC installed in series with the electrical transmission line. The SSSC was employed to damp power transfer during system disturbances. The achieved results are consistent with theoretical predictions of device functioning and capability. In fact, SSSC behavior in different conditions was outstanding in all cases. Finally, fast and dynamic response qualifies the SSSC for further research and improvement to meet desired system disturbance damping and power control.

Real power oscillations in power transmission systems may emerge in corridors amidst generating regions because of poor damping of the correlation, in particular during hulking power transmission. These cases of oscillations can be excited by a number of reasons, such as line faults, switching of lines or a surprising variation of generator output. The existence of active power oscillations acts to limit the power transmission capacity of interconnections between areas or transmission areas [18].

In this thesis, the SSSC has the ability to control the power flow to some extent on the transmission line. Since the purpose of an SSSC is to insert a voltage into the transmission line serially, this voltage is independent of the magnitude of the line current. Here, power oscillations are damped properly using SSSC in a two-machine power system with a (3Ø) L-G fault. From the simulation results produced, the performance of the SSSC is shown clearly in a two-machine power system. The results were produced in a two-machine power system with and without the SSSC. Thus, by installing the SSSC in a power system, the voltage stability was improved and power oscillations were damped properly in comparison with the two-machine system without the SSSC [7].

As an effect of the FACTS initiative, considerable effort has been spent in the last two decades on the evolution of electronic-based power flow regulators. The prospective benefits of these FACTS controllers are now widely famed by power system engineering and transmission and distribution groups. However, there is no stand-alone SSSC in service, but it has a potential to be a strong and very effective controller for power flow control and system oscillations damping [18].

Voltage stability is a prerequisite for the safe operation of an electro-energy system. It is endangered in heavily loaded networks because a reactive power deficiency occurs at local points in the network and node voltages drop uncontrollably.

The analysis of the operations which lead to voltage instability must include all operating means that influence reactive power flows. In order to cope with the dynamics of the processes that lead to loss of voltage stability, a complete dynamic modeling of these operating means is necessary for their investigation. Simulations in the time domain permit very precise predictions when the dynamic modeling is used. In order to investigate the voltage stability of electro-energy systems, the static and dynamic methods are also available and provide the stable equilibrium with the help of power flow equations.

An investigation of the voltage stability is performed on two power generation stations and one main load midpoint, which are completely dynamically modeled for this purpose. Depending on the load, the loss of the voltage stability of the systems occurs. Several cases are considered by means of simulations in the time domain.

Reactive power requirements must be covered at all times. In this work, a consumer middle of almost 2200 MW is displayed by a dynamic load model where the real and reactive power consumed by the load is a function of the system voltage.

Its influence on the voltage stability is investigated in the time domain. The results show the role of the weighting of static to dynamic loads on a consumer bus bar.

The transfer of the results of the dynamic simulation for the detailed consumption modeling used to a general dynamic consumer model with recreational dynamics is presented. The results show that the parameterization of this model depends largely on the underlying assumptions in the detailed modeling. Considering the prerequisites, the comparisons of the results show good agreement. The presented transfer of the detailed modeling to the general dynamic model with recovery dynamics leads to a reduction of the parameters and a larger time step in the dynamic simulation.

A detailed network model of an SSSC is presented. This model can be used to represent all the electrical quantities of the equipment. The comparison with measurements provides the validation of the model. A nonlinear controller design is performed using the resulting non-linear differential equation system. The designed controllers are transferred to the network model. The network model developed in this work can be applied to further magnetic and electrical configurations of the operating medium.

4.2 Future Work

General issues and challenges of the SSSC have been covered in this thesis. However, there are still items identified for future research. The following paragraphs summarize the future work identified.

1. For the series compensators that are based on converters, the transformer is the primary cost item. Hence, it is worth studying the effect of increased numbers of voltage levels present in the waveform of the converter o/p voltage to remove the expensive transformer. The transformer is used primarily to achieve electrical isolation of the converter from the grid. Moreover, in an effort to increase the series compensation level, the transformer provides voltage boosts to the output of the converter. The prospective research subtopic may achieve the necessary level of electrical isolation without employing a transformer in the series connection, thereby completely removing the transformer from the system.

2. Another future research that is logical can be to study the Dynamic Voltage Regulator (DVR). A DVR is essentially an SSSC with energy storage. The addition of energy storage allows the SSSC to provide real power voltage support during a voltage sag condition caused by a fault.
3. Studying the UPFC is also identified as a future area of work for this thesis. The UPFC is a combination of the SSSC and the STATCOM as described previously.
4. This future work can be extended in SSSC modeling by replacing the PI Controller with a number of other controllers to provide voltage stability and especially power in the power systems and a comparative study can be performed.

REFERENCES

[1] Dhoble, Prashant, and Arti Bhandakkar. "Review of active reactive power flow control using static synchronous series compensator (SSSC)." International Journal of Innovative Research and Development ISSN 2278–0211 2.4 (2013): pp146-165.

[2] Bhowmick, Suman. "Flexible AC Transmission Systems (FACTS): Newton Power-Flow Modeling of Voltage-Sourced Converter-Based Controllers". CRC Press, (2016).pp1-283.

[3] De Almeida, A., L. Moreira, and J. Delgado."Power quality problems and new solutions." International conference on renewable energies and power quality. Vol. 3. 2003.pp25-33.

[4] Bollen, Math HJ. "Understanding power quality problems". Vol. 3. New York: IEEE press, (2000).pp1-543.

[5] Khalid, S., and Bharti Dwivedi. "Power quality issues, problems, standards & their effects in industry with corrective means." International Journal of Advances in Engineering & Technology 1.2 (2011): pp1-11.

[6] Smith, J. Charles, G. Hensley, and L. Ray. "IEEE Recommended Practice for Monitoring Electric Power Quality." IEEE Std (1995): pp1159-1995.

[7] Shankar, C. Udhaya, Rani Thottungal, and S. Mythili. "Stability Improvement and Power Oscillation Damping Using Static Synchronous Series Compensator (SSSC)." (Vol. 2, Issue 1, January 2015).pp341-349.

[8] Zhang, Xiao-Ping, Christian Rehtanz, and Bikash Pal." Flexible AC transmission systems: modelling and control". Springer Science & Business Media, 2012.pp1-568.

[9] Acha, Enrique, et al. "FACTS: modelling and simulation in power networks". John Wiley & Sons, 2004.pp1-403.

[10] Sen, Kalyan K., and Mey Ling Sen. "Introduction to FACTS controllers: theory, modeling, and applications". Vol. 54. John Wiley & Sons, 2009.pp1-523.

[11] Padiyar, K. R. "FACTS controllers in power transmission and distribution". New Age International, 2007.pp1-532.

[12] Glanzmann, Gabriela. "FACTS: flexible alternating current transmission systems." (2005).pp1-31.

[13] Masood, Arsalan, and Anzar Mahmood Qadeer-ul-Hassan. "Flexible AC Transmission System Controllers: A Review." pp: 393-402.

[14] Jowder, Fawzi A. Rahman AL. "Embedded SSSC in series capacitor compensation and in voltage source converter station." (2004).pp1-148.

[15] Terek, Cristina Iulia. "A New Static Synchronous Series Compensator for Real Power Control on AC Transmission Lines". National Library of Canada= Bibliothèque nationale du Canada, (2000).pp1-96.

[16] Norouzi, Amir H., and A. M. Sharaf. "Two control schemes to enhance the dynamic performance of the STATCOM and SSSC." IEEE Transactions on Power delivery 20.1 (2005): pp435-442.

[17] Dodiya, Piyush. "Improvement of Power System Transient Stability using Static Synchronous Series Compensator (SSSC)." (Volume 3, Issue 01, July 2016) India.pp170-176.

[18] Unal, Irfan, D. Rai, and S. O. Faried. "Damping power system oscillations using an SSSC-based hybrid series capacitive compensation scheme." PowerTech, 2011 IEEE Trondheim. IEEE, 2011.pp1-122.

[19] Pradhan, Anil C., and P. W. Lehn. "Frequency-domain analysis of the static synchronous series compensator." IEEE transactions on power delivery.(Volume: 21, Issue: 1, Jan. 2006) pp440-449.

[20] Kumkratug, Prechanon, and Panthep Laohachai. "Direct Method for Transient Stability Assessment of a Power System with a SSSC." JCP 2.8 (2007): pp77-82.

[21] Ustun, Taha Selim, and Saad Mekhilef. "Effects of a static synchronous series compensator (SSSC) based on a soft switching 48-pulse PWM inverter on the

power demand from the grid." Journal of Power Electronics 10.1 (2010): pp85-90.

[22] Masood, Tariq. "Improvement of Voltage and Power Flow Control in the GCC Power Grid by using Coordinated FACTS Devices". Diss. University of Bath, (September, 2012). pp22-212.

[23] Hingorani, Narain G., and Laszlo Gyugyi. "Understanding facts". IEEE press, 2000.pp1-432.

[24] Song, Yong-Hua, and Allan Johns. "Flexible ac transmission systems (FACTS)". No. 30. IET, 1999.pp1-576.

[25] Hanson, D. J., et al. "STATCOM: a new era of reactive compensation." Power Engineering Journal 16.3 (2002): pp151-160.

[26] Ghaisari, J., and A. Bakhshai. "An advanced robust MIMO SSSC control technique for power oscillation damping improvement." IRANIAN JOURNAL OF SCIENCE AND TECHNOLOGY .Vol. 30, No. B6,(2006): pp667-679.

[27] Yadav, Kiran, and Kuldeep Kumar Swarnkar. "Mitigation of Power Oscillation and Voltage Fluctuation to Improve Power System Stability using SSSC." Volume 4, Special Issue.(2015).pp121-125.

[28] Habibur, Md, and Harun Fayzur Rahman. "Modelling & Performance Comparison Of Different Types Of SSSC-Based Controllers." International Journal of Engineering Research and Technology. Vol. 1. No. 7(September-2012). IJERT, 2012.pp1-6.

[29] Sadiković, Rusejla. "Use of FACTS devices for power flow control and damping of oscillations in power systems". Doctroal Dissertation. (2006).pp1-139.

[30] Geethalakshmi, B., T. Hajmunnisa, and P. Dananjayan. "A Fuzzy Logic Controller for Enhancing the Transient Stability of 48-Pulse Inverter Based SSSC." Elektrika vol.10.no.2 (2008): pp53-58.

[31] Maninder Rohal, Ravi. "Analysis of Power System Oscillation Damping & Voltage Stability Improvement Using SSSC in A Multimachine System." International Journal of Engineering Research and Technology. Vol. 3. No. 7 (July-2014). IJERT, 2014.pp643-649.

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