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An Optimal Control Approach for Enhancing Transients Stability and Resilience in Super Smart Grids

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Abstract: Super smart grids (SSGs) are a wide area transmission network that mainly uses renewable energy resources (RERs), contributing to the reduction of greenhouse gas (GHGs) emissions and supporting the power infrastructure of multiple countries. The SSGs comprise two-way communication between the loads and sources of different countries, and these loads can be mostly served with numerous types of RERs tied with the grids. The RERs will play a pivotal role in the development of future grids and the generation of electricity. However, the main challenge to tackle in these RERs is that they are intermittent in nature. Due to intermittency in these RERs, transient stability issues have become one of the critical research challenges in SSGs. These stability issues are escalated and become more difficult to handle if a network is vulnerable to an arising of different kinds of faults. To address these problems, multiple approaches to enhance transient stability already exist in the current literature. After reviewing the literature, flexible alternating current transmission systems (FACTS) devices proved more promising in improving transient stability. Among FACTSdevices, UPFC is a versatile FACTS device, which provides complete stability to power system networks in the form of series and shunt compensations. Considering this scenario, a hypothetical network for SSGs is designed in this research work based on the interconnection between two countries, i.e., Denmark and Norway, to address the transient stability issues in SSGs. The complete probabilistic model of the system is also designed to enhance the stability of the system. The results clearly showed that the insertion of UPFC is an effective technique to enhance the transient stability and resilience of the power system networks as compared to other purposed techniques in the literature. The main contribution of this paper is that extensive simulation studies employing accurate RERs models are used to analyze and investigate various problems arising due to the integration of many clusters of RERs in SSGs.

Keywords: super smart grids; transient stability; power quality enhancement; unified power flow controller (UPFC); static compensation (STATCOM); transient stability enhancement

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1. Introduction

The thought of a super grid is not new. The term itself was accustomed to describing the rising unification of Britain's grid within the 1960s. Europe has been uniting its power infrastructure since the 1950s, and the largest combined grid is the synchronized grid of continental Europe, transmitting with twenty-four countries. The conceptual plan for linking renewable energy resources (RERs) with each other is shown in Figure 1. There are studies and current discussions relating to the creation of a synchronized grid spanning thirteen time zones that may result from uniting the Union of Co-ordination of Transmission Electricity (UCTE) grid with the integrated power system interconnecting Russia, Ukraine, and different countries of the Soviet Union. The work done on the transmission network for designing such SSGs until now is shown in Figure 2.

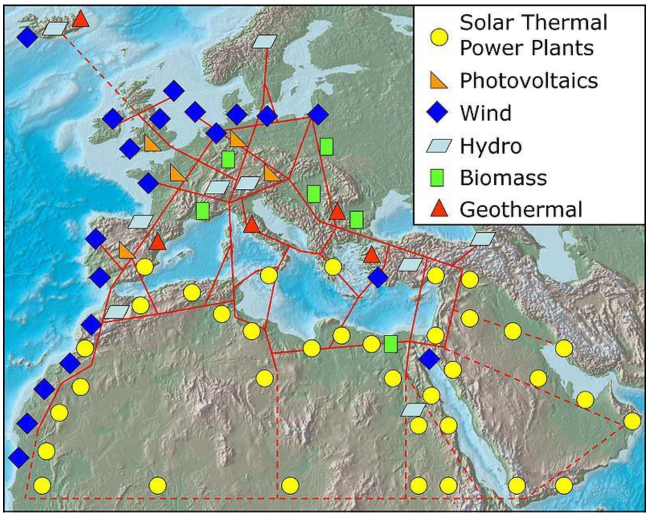

Figure 1. European Super Smart Grid conceptual plan [1].

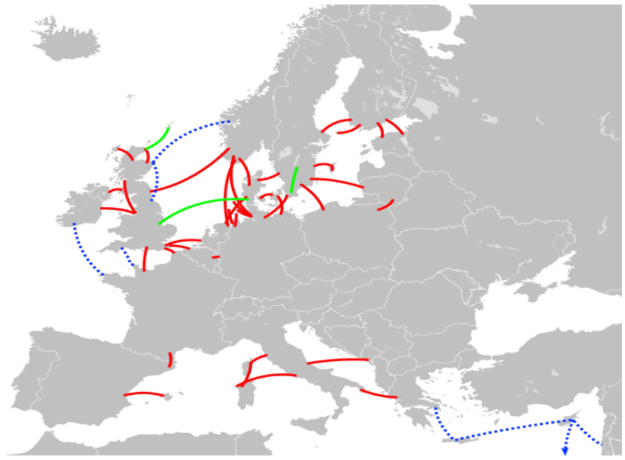

Figure 2. Existing, proposed, and under construction links between countries shown in red, blue, and green lines, respectively [2].

Such complex systems are undergoing scalability issues because of network complexity and overcrowding of transmission, and therefore, they would like fast, analytical coordination and management systems. Advocates of schemes comparable to the SSG claim that such a serious technological upgrade is critical to ensure the sensible operation and secure advantages of such continental mega grids. Talking about infrastructure, any country's economic development is dependent on its electric power infrastructure [1]. The power infrastructure is of two types:

1. Centralized infrastructure
2. Decentralized infrastructure

In the planning of a centralized (conventional) infrastructure, no planning on micro-grids development or renewable energy resources (RERs) insertion is performed. Now, in order to increase the infrastructure in terms of the power of the countries, the centralized grids, which are conventional ones, are transformed into smart grids. A smart grid (SG) is a grid that includes advanced sensing, communication, security, and control technologies that can deliver a more reliable, efficient, sustainable, and cost-effective supply of electricity [2]. SGs rely on clusters of RERs to produce cheaper electricity and to satisfy future load requirements. The renewable integrated power grids (RIPGS) are formed by the linkage of these clusters with each other. They are effective in terms of energy production, as the most important aspect of power system design and operation is the transient-stability correction. After a large disruption, transient stability refers to the system's capacity to return to a stable state. In other words, following a disturbance, the system should be steady, and the swings should be dampened as quickly as feasible [3]. The main issue is that the power quality is disturbed due to the intermittency of the RERs. To meet power demand in both the AC and DC microgrids, a fault-tolerant controller for an isolated hybrid AC/DC microgrid is presented in [4]. In order to determine the hybrid AC/DC micro-ideal grid's power flow, a cost function and a few operational parameters are minimized. In addition, a model predictive control approach built to withstand and handle more severe defects is shown in [5]. There were two fault-tolerant secondary control systems described for SGs. The research done in [6] takes into account both compensation to lessen the impacts of secondary control faults as well as flaws in the dynamics of the SG. A central SMO-based fault-tolerant controller makes up the first approach. The second method employs a fault-tolerant controller based on SMO for each DG, which would estimate faults impacting just that DG and only those faults would be compensated [7,8]. Due to these power disturbances, which are caused by multiple types of faults or abrupt changes in load, transient instability in the SSG can occur. If this instability is not dealt with in a timely manner, it can cause power failure, and these faults can be transported to the other networks. This fault transportation can cause cascading failures, and as a result, a complete blackout of the interconnected systems will occur. To overcome this issue, probabilistic modeling of the SSG is performed, and UPFC is inserted near the faulty buses to mitigate the transients of the system.

Moreover, to manage the futuristic demands in power system networks, smart grids would be transformed into SSGs, in which different countries' clusters are interconnected to manage their demand conditions. In spite of these advantages in terms of fulfillment of demand conditions, certain critical stability issues will also arise due to the interconnection of various countries' clusters with one another. If these stability issues cannot be resolved within a short period, it will lead to cascading failures, leading to a complete blackout of the power system network. In this case, UPFC provides a more promising way to provide stability to this complex network of SSGs infrastructure in a very short span of time as compared to other FACTS devices. In short, the following are the key contributions of this paper:

1. Providing transients stability and resilience in a complex network of SSGs within a short span of time of around 0.1s using a UPFC;
2. Multiple faults analysis can also be performed in SSGs power infrastructure to show the superiority of UPFC for achieving stability in a very short span of time as compared to other FACTS devices;
3. Although SSG projects and ideas have received positive reviews, their development is still a challenging task. Therefore, extensive simulation studies employing accurate RERs models could be used in this research to analyze and investigate various stability problems arising from the integration of many clusters of RERs in SSGs. Moreover, how network operators will resolve these instability issues using a UPFC will also be a significant part of this research work.

The research paper is organized as follows: Section 2 describes the comprehensive review of transient stability analysis methods. Techniques for enhancing transient stability are discussed in Section 3. In Section 4, Algorithms for transient stability enhancement are reviewed. Methodical modeling of the control system is performed in Section 5 by the proposed stochastic modeling of UPFC, whereas the cluster infrastructure is explained in Section 6. The results of the simulations are graphed and explained in Section 7. Healthy conditions in the SSG networking model are explained in Section 7.1. In Section 7.2 multiple intervals, line-ground faults are considered, and their impact on the system is studied, whereas the UPFC impact on the fault to enhance the transient stability is discussed with graphical representations in Section 7.3. Moreover, the multiple-interval double line-to-line faults are studied inSection 7.4, and multiple L-L-L-N faults are studied in Section 7.6, whereas the transients caused by these faults died down and are graphed in

Sections 7.5 and 7.7. In Section 8, conclusions and future work recommendations on the research work are made.

2. Transient Stability Analysis Methods

Transient stability analysis is very important for ensuring the stable and up-to-date system of an SG. In order to get to know the methods of transient stability analysis, three categories are used. These are artificial intelligence (AI) based on data-driven systems, direct methods, and simulation methods in the time domain. A comparison showing the disadvantages and advantages of the methods adopted in transient stability is defined in Table 1.

Table 1. Methods in transient stability analysis.

Method	Function	Advantage	Drawback
Data-driven	The stability status of the system is analyzed by the transient stability assessment model	Fast speed for the calculation is used and a strong learning ability	Poor adaptability and representation to the topological changes
Direct method	Energy function implementation to judge and enhance the transient stability	The speed of calculation is high and enough margin for the stability	Difficulty in energy function and the result calculation is conservative.
Time-domain simulation-based	The system's dynamic processes are defined by algebraic and differential equations	Scalability is good and accurate results	The accuracy of the system can be affected by the results of the calculation

The main theme of the simulation in the time domain is the solution of differential-algebraic equations by the implementation of a numerical integration algorithm. It is also observed that this method is mainly used in the power sector industries. Further, the use of the unsymmetrical multifunctional technique to address the DAEs that arise during power system dynamic simulations is observed in [9]. The energy functions are made by Lyapunov theory in order to assess the stability of transient, and the method used in it is the direct method. Moreover, a Koopman model is also designed to analyze the transient stability by the direct method in [10]. The leverage of this algorithm over the time domain-based system is that after a fault, it does not need any complex simulation in the time domain, and also, a degree of stability can be provided by it. The extended equal area criterion (EEAC) method is used to utilize the transient stability of multiple machine systems in [11]. Moreover, the dynamic state estimators (DSE) and phasor measurement units (PMUs) are used in the assessment of transient stability to collect the data in the real-time domain, and the simulation model was presented in [12,13].

A data-driven TSA technique, unlike the time-domain simulation and direct methods outlined before, is model-free and handles TSA as a pattern identification issue. An AI-based evaluation model is constructed to depict the input power system operating characteristics and the system's stability with respect to the transient state. This technique provides several advantages such as the benefits of great learning capacity and quick evaluation speed, which have a positive impact on the performance in the subject of transient stability for evaluating power systems. A method for solving the first-swing stability problem utilizing UPFC, as well as a thorough analysis, has been performed in [14]. The benefits of this control method include, first and foremost, the use of the local system variable, and second is that it will provide greater stable performances with respect to other methods that are currently in use. A systematic approach relying on a proportional-integral controller with advanced control and tracking along with the behavior of a steady-state and a linear quadratic tracker to control the entire flow of load and voltage fluctuations while at the same time eliminating harmonics is explained in [15]. A Simulink model in MATLAB is also discussed. In it, the authors evaluate the UPFC concepts that were established, and it is concluded that UPFC-relying systems with controllers can effectively manage load flow and voltage sags/flickers. Moreover, in [16], the characterization of UPFC energy functions in lieu of Lyapunov energy functions was also examined in order to assess the influence of UPFCs on the enhancement of transient stability, taking into account the three-phase line-to-ground failures in power systems over a single period occurrence. In [17], SITPFs having no FACTS device controllers are assessed for their stability. To clarify the impact of SITPFs on the operation of wind power plants and transmission lines, it was proposed to use the power infrastructure and after that the FACTS controllers. FACTS controllers receive a high rating for improved transient stability.

3. Techniques for Enhancing Transient Stability

Multiple techniques for transient stability enhancement are discussed in the literature [18–26].

There are two alternative strategies to increase the power quality disruptions caused by transient stability difficulties. The first technique is to employ FACTS devices, such as UPFCs, to develop a power angle connection among generators with wind turbines on the generating side. This will limit rotor speed and position changes caused by multiple interval three phase faults (MITPFs) or single interval three phase faults (SITPFs) and hence decrease the power quality difficulties on the receiving side of power grids. Installing a UPFC over the receiving section of the SG or near the fault occurrence area to stabilize the system, even in situations with SITPFs or MITPFs, is the second way to handle these transient stability difficulties for reducing power quality disruptions [27]. Stability in the transient oscillations is caused by faults, and they are a key source of concern in the power system. In contrast to popular assumption, temporary stability concerns caused by the occurrence of faults in an SSG can be a significant form of energy quality issues despite the prevalent empirical belief that the two problems of power system stability and power quality are unrelated. Furthermore, factors such as fault conditions affect the transient stability of a power system containing wind turbines [28]. In the case of a SITPF, on the receiving side of the SG, for example, there is less variation in the speed and position of the rotor of a wind turbine, resulting in fewer issues in power quality. However, in the case of a MITPF, significant power quality issues due to an important fluctuation in wind turbine rotor speed occur on the receiving side of RIPG stations. The demand response schematic is shown in [23]. As a system closed-loop control for modeling via a probabilistic model in a power system, transient stability is enhanced. The power system will be continually monitored via a closed loop in the form of a smart node and UPFC, and appropriate corrective action will be performed for the balancing of load flow and stability of the transients. There are two cases. One is SITPF, in which the smart node improves the power grid for load flow balancing, and the second is the case of MITPF. In MITPF, a UPFC is incorporated into the transmission network and is used to fully improve the power system for balancing load flow in order to mitigate the transients [24]. Multi-agent systems, incorporation of FACT devices, UPFC, and others are included and discussed in detail here.

3.1. Multi-Agent-Based Technique

An intelligent multi-agent-based technique for increasing transient stability is proposed in [29] by dynamically analyzing a system's critical clearance time (CCT) for generator load variations and varied amounts of wind power penetration at various fault regions. One of the most serious hazards to contemporary power systems is transient instability, which may be prevented by appropriately coordinating a system's protective relays with their associated CCTs. These are important indicators of transient stability since they look at whether the system can maintain balanced and regular functioning after a three-phase fault [30]. Many other techniques are used, such as the agent-based methods defined in [31–37]. In [31], the turbine valve is controlled by new strategy points to improve the transient of the system. Likewise, the technique after the occurrence of fault to control the turbine is depicted in [32]. Authors in [33] defined the usage of an algorithm that was multi-agent based for the control of a wind turbine to ensure transient stability. However, in [34], a multi-agent system technique is devised to decentralize coordinated control in order to improve system stability.

A technique for dynamic evaluation of critical clearing time in case of sudden genset variation and the combination of the renewable energy resources with the Genset by the multi-agent system is discussed in [35]. Its framework consists of local agents (LA) and global agents (GA), which use an algorithm in order to properly provide coordination with the protection systems along with their corresponding critical clearing time (CCT). The agents work continuously to update the information in the system with the continuous stream of CCT information to promote the online capability and scalability of real-time agent-based protection device coordination to improve transient stability, with the CCT computed for the current generator load conditions and wind energy penetration levels during a fault. The GAs can measure and monitor a system's current status based on the physical parameters of its network and then dynamically analyze the CCT as disturbances occur, while the LAs start negotiating and communicating with one another using the agent's communication language to coordinate the system's protection system by tripping and auto-reclosing its CBs with their corresponding CCT information to improve the system's transient stability. A generic design for SG protection and security solution based on MAS is shown in Figure 3.

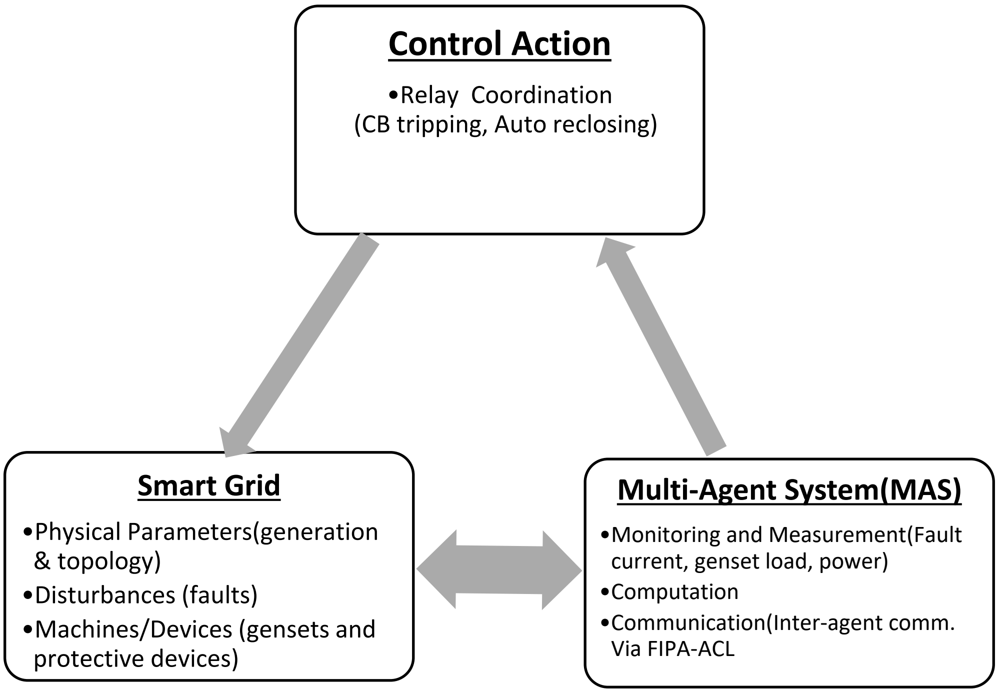

Figure 3. Generic design for SSG protection and security solution relying on MAS [35].

When disturbances such as three-phase faults or unexpected load shifts occur in an SG, the equivalent agents collabo1rate to determine the best real-time protection device coordination to improve the transient stability of the system [36,37]. Figure 4 depicts the interactions between a MAS and an SG for optimal protective device coordination.

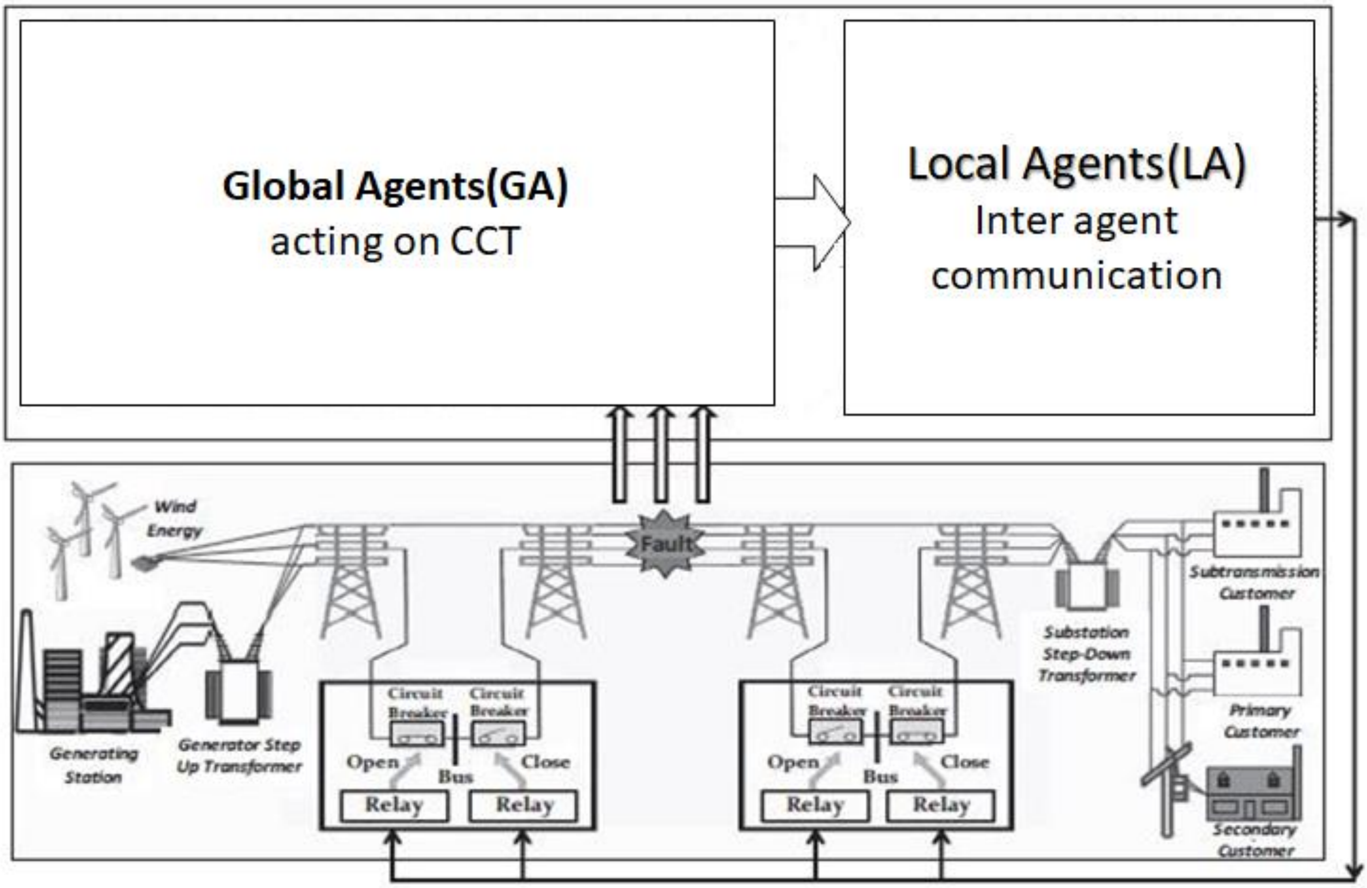

Figure 4. Flowchart of SSG interaction with the multi-agent system in case of fault [25].

Individual intelligent agents in the MAS collaborate and interact with one another to examine a disturbance and take appropriate action, providing a powerful model for real-time collaboration of protection devices to open and close their breakers using the respective CCT information to improve the transient stability of a system.

3.2. Incorporation of FACTS Devices

FACTS devices are utilized in a power system network to boost the transmission line's capacity for the transfer of power and to improve thermal limitations, voltage stability, transient stability, and voltage regulation. These devices are an effective median of transient stability in the system. The transients are a cause of instability in the system, and if the system is unstable, then it can cause disturbances in the power grids. The power grids are of utmost importance in any country. The potential in the FACTS devices for the stability of the system is also studied in [38–45].

Prior to FACTS, these issues were resolved using mechanical switches to connect capacitors, reactors, or synchronous generators prior to the development of power electronics switches. However, there are numerous issues with using mechanical switches. It responds quite slowly, and mechanical switches are susceptible to wear and strain. In order to make the transmission line more stable and controllable, these methods are not trustworthy. Power electronics-based FACTS controllers were created following the development of high-voltage applications-capable power electronics switches such as the thyristor.

The FACTS devices types are:

1. Static compensators (STATCOMs);
2. Unified power flow controllers (UPFCs);
3. Static synchronous series compensators (SSSCs);
4. Thyristor controlled shunt reactor (TCSR).

These FACTS devices are discussed and studied regarding how they can be incorporated into the RIPG to address reliability issues in power systems [46–50]. Among these, UPFC is one of the universal types of FACTS devices that can minimize the effects of power quality disturbances in an SG [51]. Figure 5 shows the active power comparison of a faulty bus using a distributed nonlinear robust controller approach with UPFC used to perform both shunt and series compensation. Here, three-phase line-to-line faults are incorporated in the SG, and a fault on the bus being supplied power through the solar resource is inserted. It should be worth noting that it approached the stability time in 0.16 s [52,53].

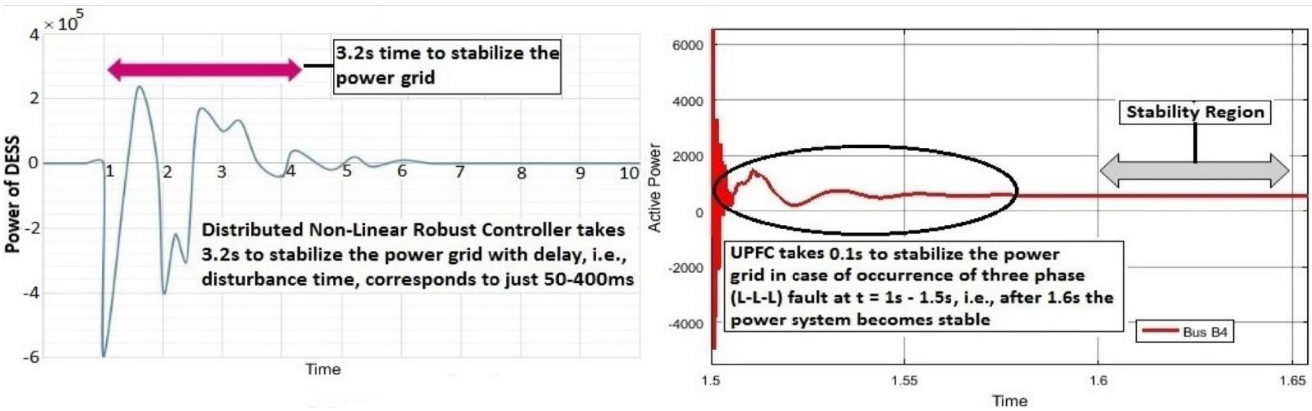

Figure 5. UPFC showing stability within a time interval of 0.16 s [53].

3.2.1. Insertion of UPFC

A detailed simulation of the 30-bus system with the UPFC incorporated is discussed in [54]. Insertion of UPFC in the transmission line is also discussed in [55,56]. Figure 6 shows the UPFC connection with an infinite bus along with a transmission line. This shows the principle function of UPFC in which two transformers are connected along with the parallel and series branches, two inverters for shunt, and series compensation controlled by the given references.

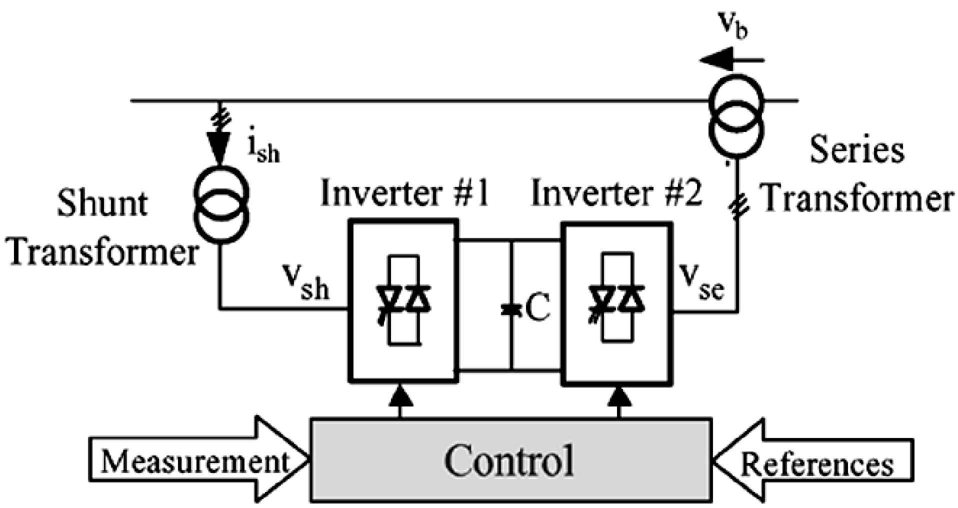

Figure 6. The basic configuration of UPFC showing principle function [57].

Reactive power can be absorbed or generated by inverter 2, whereas the function of inverter 1 is that it supplies real power that is required by other inverters with the help of a DC link. The UPFC basis structure and its working are discussed in detail in [57]. The phase angle and magnitude of voltage produced by the inverter are used to regulate the flow of power in the transmission line, resulting in an increase in transient stability.

The UPFC can operate in a variety of ways, as stated in [58]. The shunt inverter is specifically working in such a way that allows controllable current to be injected into the power line. Regarding the voltage of the line, there are two components of this current: the actual or direct component, which can be either out of phase or in phase along with the voltage of the line, and the quadrature or reactive component, which is in quadrature [59]. The need to balance the real power of the series inverter naturally controls the direct component. Instead, the quadrature component can be individually tuned to any required level of reference (capacitive or inductive) within an inverter's capacity to either engage or create reactive power through the line as appropriate. To understand the series inverter, a block diagram of it is shown in Figure 7. Regarding the shunt inverter, the two ways to control the shunt inverter are described in [60–62].

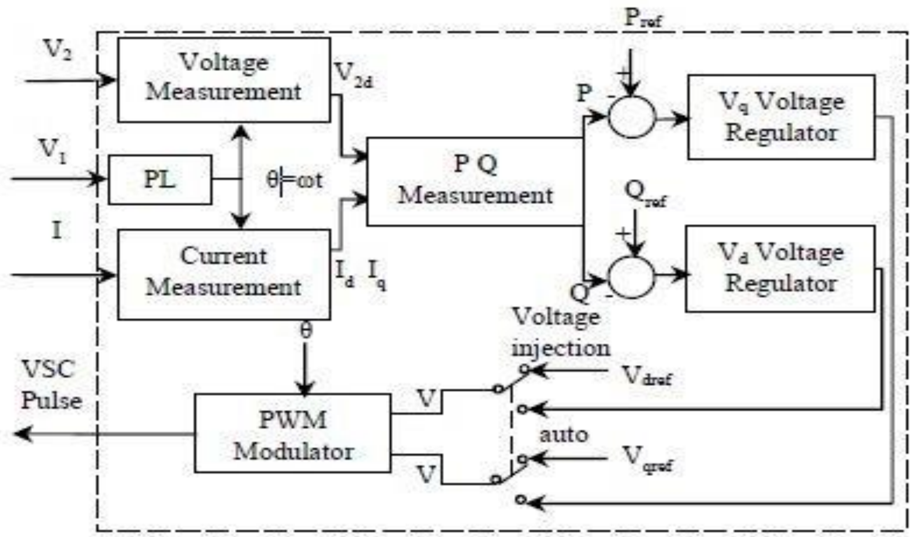

Figure 7. UPFC series converter control system simplified block diagram.

3.2.2. Utilization of the STATCOMS

Series compensation devices such as shunt compensation devices and thyristor-controlled series compensator (TCSC) such as the static synchronous compensator (STATCOM) increase the stability due to the transient's margin in power infrastructure, allowing them to run near their limitations [63,64]. Large power systems, on the other hand, may require more than one compensator to attain the desired performance. Understanding the impact of FACTS devices requires a thorough examination of the system's transient stability situation. The standard technique for this is the transient energy function (TEF) approach [65].

Transient stability and voltage regulation are also achieved by coordinating STATCOM and generator stimulation [66]. The transient stability boost produced by a wide-area controlled SVC is performed in [67] and was confirmed by hardware in the loop validation. The transient stability of power systems with induction generators and synchronous generators is improved when STATCOM is used in conjunction with an energy storage system [68]. UPFC in comparison to the STATCOMS improves initial swing transient stability significantly as discussed in [69,70]. A power system including photovoltaics and wind farms increases its transient stability by using SSSC, TCSC, and STATCOM in conjunction. In order to understand the specs functionality of the FACTS device, which relates to the establishment of product specifications, digital simulations, such as transient stability and dynamic performance, are utilized. IEEE 1031: 2011 [71] presents a method for preparing a transmission SVC specification using ordinary thyristor knowledge, which may be utilized in STATCOM and other instruments in part.

3.2.3. Utilization of the TCSC

The TCSC can be installed in a power system transmission network with an appropriate control structure to increase the system's transient stability [72–80].

A simplified 14-bus power system with four generation stations interconnected to a power system using a two-axis model and multiple loads characterized as power loads is shown in Figure 8. Two FACTS devices, thyristor controlled series compensation (TCSC) and UPFC, were deployed to improve the management of bus voltage and power flow via the transmission network. It is a hybrid model of both UPFC and TCSC installation. Simulations for the network in question as well as the two failures are conducted using the SIMPOW software. It can run the modal analysis and power flow, generate the ABCD matrix, and simulate the system's temporal behavior following faults. This study will provide a detailed description of different types of disruptions that might occur while employing UPFC. The simulation findings reveal that after a major disruption, UPFC's regular working state could no longer be maintained.

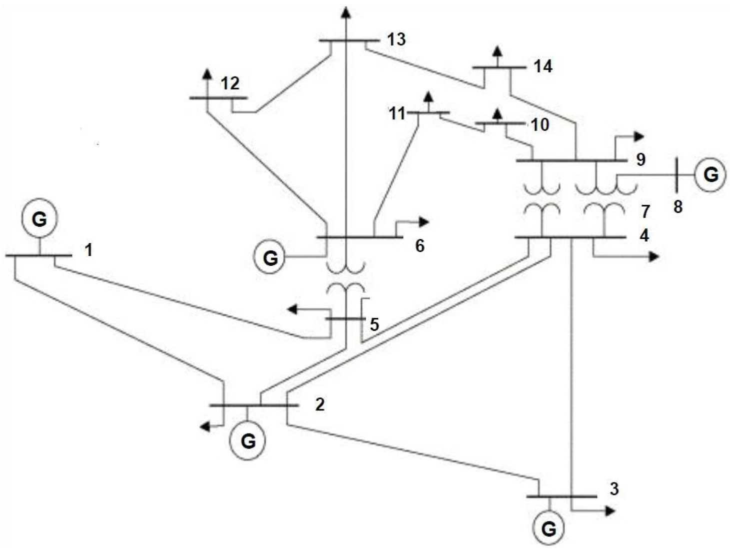

Figure 8. IEEE 14 BUS system single line diagram using TCSC.

An evaluation of the effect of applying STATCOM and TCSC separately on transient stability conditions with the effect of applying both at the same time was conducted. The optimum probable sites for FACTS devices are discovered in [72] to differ dependent on the position of the issue and the devices' operational conditions. These places can be identified using TS and the FACTS scheme can have an unfavorable influence on the stability of system stability in some instances. An escalation in FACTS device compensation does not guarantee a higher stability margin [73]. As a result, assessing the system's stability is necessary for better and safer system functioning.

TCSC technique works by injection of a transmission line current in quadrature with the voltage in series, making it behave as a capacitor of variable series. The injected voltage in the series phase angle is fixed to be in quadrature with the transmission line current as a result of this. The real flow of power may be adjusted by adjusting the magnitude of the voltage injected in series that is in quadrature with the current of the transmission line [74]. The phase angle of the voltage injected in series is adjusted to manage the reactive power flow/transmission line side voltage. This was accomplished by introducing a series of injected voltage component that was in phase with the line current of the transmission line [75]. Hence, the phase angle and magnitude of the series voltage being injected are calculated by accumulating the quadrature and components of the in-phase.

The simulation in [76] also reveals that versatile UPFC can successfully manage the system's power flow and voltage. A promising research area to incorporate all of the desired control objectives in a single UPFC device is the development of an overall control strategy for analyzing the faults. This study provided a detailed description of different types of disruptions that might occur while employing UPFC. The simulation findings reveal that after a major disruption, UPFC's regular working state could no longer be maintained. The simulation also revealed that the UPFC can successfully manage the system's voltage and power flow. A promising research area is the development of an overall control strategy and fault analysis to incorporate all of the desired control objectives in a single UPFC device. For improving the power quality of the system, utilizing power electronics equipment such as FACTS is one of the most crucial things. The reason for this is that FACTS devices are built on a power electronic idea, and they also include additional static controllers that may quickly enhance characteristics such as controllability and power transmission. Furthermore, they can regulate one or more transmission systems of AC network parameters, as defined by IEEE principles and specifications. It has the capacity to regulate numerous parameters autonomously, and therefore, it may be described as a combination of STATCOM and SSSC (static synchronous series compensator). In [77], the authors proposed and analyzed a novel and unique controller for the UPFC's series and shunt converters. The operational system of UPFC presented in the journal clearly shows that it is capable of controlling the flow of the paper. Furthermore, in [78], the suggested control method of UPFC demonstrated that system stability may be improved by simultaneously eliminating sags in voltage, harmonics due to currents, and fluctuation of voltage. The paper's simulation findings also show that the provided control system has a quick dynamic response, strength, and efficiency.

4. Algorithms for Transient Stability Enhancement

Multiple algorithms for transient stability enhancement are discussed in the literature. It includes a genetic algorithm (GA), particle swarm, current limiting algorithms, and adaptive input-output feedback linearization control (AIFLC) to enhance the transient stability caused by the existence of three-phase line-to-ground faults. PS algorithm for an individual interval three-phase faults is used, and the stability is enhanced using a UPFC in [79]. Instability due to transients of power systems was discussed in detail by adopting various control strategies as discussed in [80,81]. The stability evaluation for the presence of SITPFs in the transmission system without FACTS controllers and with FACTS controllers was presented to explain the influence of SITPFs on wind turbine effectiveness. The FACTS controller transient rating for improvement of transient stability concerns is highlighted in [80]. Another perspective is to evaluate various types of oscillations caused by the appearance of a three-phase line-to-ground fault in a single period and compensate for them by utilizing a UPFC, as described. Similarly, using a simple genetic algorithm (GA) to tune the outputs of a UPFC controller to overcome transient stability difficulties in the presence of SITPFs is presented in [81]. In addition, the dampening of oscillations of lower levels in multi-machine power generation systems by utilization of UPFC was presented in [82] using an adaptive input-output feedback linearization control (AIFLC) technique with a SITPF. A six-cycle SITPF was used to study the identical issue of dampening oscillations of lower frequency by utilizing a particle swarm optimization relying on the controller of UPFC by controlling its output feedback of it. By adding tiny delays caused by SITPFs, multiple strategies were applied to SGs for mitigating problems of power quality by utilization of FACTS devices. Probabilistic modeling can enhance accuracy and reduces future power system instabilities caused by SITPFs or MITPFs. Furthermore, the suggested technique enables the researcher to select the best setting for a UPFC in a synchronized network and better control mode of multiple generation resources when a MITPF occurs.

5. Mathematical Modelling

Stochastic modeling for the UPFC is proposed relying on a periodicity of fault occurrence to cater to the transient's stability issues. A closed-loop control system block diagram for the SSG modeling is also shown below in Figure 9. The block diagram represents how the generation and load profile are subject to variation due to the occurrence of faults. The RERS are intermittent in nature, due to which the faults occur. The UPFC transmission network is used to control the backlogged demand. This backlogged demand is the required demand along with the UPFC inserted to save the system from transients in cases of multiple-interval faults. The UPFC will serve as a power flow control device, and the RER is subjected to overloading due to the faults. The power system depends on the generation and demandsupply.

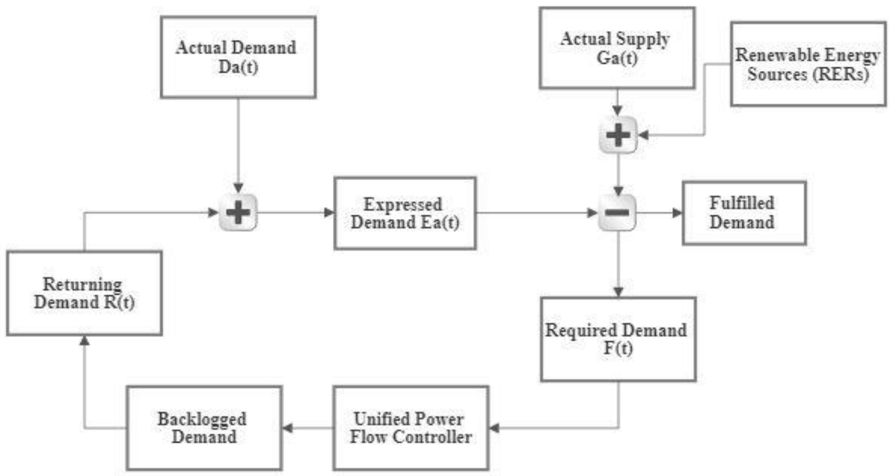

Figure 9. Block diagram of closed-loop control system for UPFC modeling.

The forecasted generation $G^f(t)$ is the generation that is forecasted on observing the forecasted demand $D^f(t)$ along with r_0 reserve supply, which in this case is the UPFC being used for power flow control and transient stability.

$$G^f(t) = D^f(t) + r_0 \tag{1}$$

There must be a delay in the system being incorporated along with the λ_i, the interval time for the demand to be fulfilled.

$$A_d = \lambda_i \tag{2}$$

A consideration of the delay up to n_1 times is considered.

$$A_d = \frac{1}{n_1} \sum_{i_1=1}^{n_1} (\lambda_{i_1}) \tag{3}$$

Now, consider that there will be a difference in the actual demand of the system $D^a\ (t)$ and forecasted one. The difference is represented by the variation in the system $V_D(t)$. Then, a delay is implemented in (4) for fulfilling the requirement, resulting in (5).

$$D^a(t) = D^f(t) + V_D(t) \tag{4}$$

Then, a delay is implemented in (4) for fulfilling the requirement, resulting in (5).

$$D^a(t) = \left\{ \left[D^f(t) \times \frac{1}{n_1} \sum_{i_1=1}^{n_1} (\lambda_{i_1}) \right] + V_D(t) \right\} \tag{5}$$

Now, considering that the demand is not fulfilled in one step, then a close loop is incorporated into the system, resulting in (6).

$$D^a(t) = \sum_{i=1}^{n} \left\{ \left[D_i^f(t) \times \frac{1}{n_1} \sum_{i=1}^{n_1} (\lambda_{ij}) \right] + V_{D_i}(t) \right\} \tag{6}$$

Here, $V_D(t)$ is the randomness in the system that is found by the probabilistic model of autocorrelation.

$$V_D(t) = E\left[D^a(t)D^f(t)\right] \tag{7}$$

Case 1:

We now consider that if the actual demand of the loads is equal to the forecasted demand of the loads, then the system randomness will approach zero.

If $D^a(t) \rightarrow D^f(t)$, the variation in the demand would be $V_D(t) \rightarrow 0$, resulting in (8).

$$G^f(t) = D^f(t) \tag{8}$$

Considering the same situation for the generation side, the actual generation is:

$$G^a(t) = G(t-1) + G^f(t) + V_G(t) \tag{9}$$

For catering generation response pattern in real time, the actual supply G^a (t) is considered to be synchronized with the previous supply G $(t-1)$ and G^f (t) along with the addition of some randomness RG (t).

$$G^a(t) = \sum_{i=1}^{n} \left\{ \left[G_i(t-1) \times \frac{1}{n_1} \sum_{i=1}^{n_1} (\lambda_{ij}) \right] + \left[G_i^f(t) \times \frac{1}{n_1} \sum_{i=1}^{n_1} (\lambda_{ij}) \right] + V_{G_i}(t) \right\} \tag{10}$$

Case 2:

We now consider that if the actual generation of the sources is equal to the forecasted generation of the sources, then the system randomness will approach zero. If $G^a(t) \rightarrow G^f(t)$, the random deviation $V_G(t) \rightarrow 0$, resulting in (11).

$$G^f(t) = D^f(t) \tag{11}$$

For that, the control parameter G $(t-1)$ would be adjusted in such a way that the (11) occurs. Here, $V_G(t)$ is the randomness in the generation of RERS that is found by the probabilistic model of autocorrelation. Thus,

$$V_G(t) = E\left[G^a(t)G^f(t)\right] \tag{12}$$

The required demand F (t) represents the active power deficit resulting from the emergence of TPF. It can be written as:

$$F(t) = E^a(t) - G^a(t) \tag{13}$$

To obtain the best flow of the load between response and demand, E^a (t) stands for the expressed demand, which must always be met at a specific time interval. The required demand F (t) will occur when:

$$E^a(t) > G^a(t) \tag{14}$$

As there would be a delay in required demand, i.e., $F(t)$ shown in (13), inserting the Ad delay in (13), we obtain

$$F(t) = \left[(E_i^a(t) - G_i^a(t)) \times \frac{1}{n_1} \sum_{i_1=1}^{n_1} (\lambda_{i_1}) \right] \tag{15}$$

Considering that the demand is not fulfilled in one run, then a generalized form of (15) will be:

$$F(t) = \sum_{i=1}^{n} \left\{ \left[(E_i^a(t) - G_i^a(t)) \times \frac{1}{n_1} \sum_{i_1=1}^{n_1} (\lambda_{i_1}) \right] \right\} \tag{16}$$

Now, we considered there must be a closed-loop delay in the system, which is also to be incorporated into the system required demand. That demand with a loop delay is named backlogged demand for our ease and is:

$$B(t) = \sum_{c_1=1}^{n_1} \left(\frac{1}{\lambda_{c_1}} \right) \times (E^a(t) - G^a(t)) \tag{17}$$

The required reserve *r* (*t*) is the reserve that is required in case of a fault in the SSG to compensate for the overloading issue. This reserve is actually UPFC, which will act as a power flow controlling device here, and it is the result of actual minus the express demand. It is expressed as:

$$r(t) = G^a(t) - E^a(t) \tag{18}$$

Incorporating a delay in (18) and the generalized form of (18) would be:

$$r(t) = \sum_{i=1}^{n} \left\{ \left[(G_i^a(t) - E_i^a(t)) \times \frac{1}{n_1} \sum_{i_1=1}^{n_1} (\lambda_{i_1}) \right] \right\} \tag{19}$$

Taking into account Equation (18), different cases are considered.

Case 3:

When $G^a(t) > E^a(t)$,

then the SSGs generation is more than the required demand. Therefore, the UPFC would be in a steady position. In addition, no power flow control is required.

Case 4:

Now, consideration of the required and an actual reserve is completed and compared. Therefore, if

$$r_o < r(t) \tag{20}$$

then the actual generation is to be increased by a UPFC. In this way, by doing this, the *F*(*t*) will be reduced and required, and actual reserves will be as close to one another as possible. One can carry out this action by adhering to the ramp-up constraint path.

Case 5:

However, if

$$r_o > r(t) \tag{21}$$

then the actual generation is to be decreased by a UPFC to make the required and actual reserves as close to one another as possible. You can carry out this action by adhering to the ramp-down constraint path, whereas the constraints are:

$$r_o \leq G(t) - G(t-1) \leq r(t) \tag{22}$$

Inserting the value of $G(t) - G(t-1)$ from (9), we obtain:

$$r_o \leq G^f(t) + V_G(t) \leq r(t) \tag{23}$$

To maintain constant stability of the backlogged demand, or B (t), in each and every situation, $V_G(t)$ via a UPFC is reduced. To do this, we must synchronize the parameter r_o with *r* (*t*) by controlling it in accordance with the ramping up and down requirements from (20) and (21). Therefore, by reducing the randomness in generation $V_G(t)$, (23) can be written as:

$$r_o \leq G^f(t) \leq r(t) \tag{24}$$

An achievement of synchronization can be attained by (1). Therefore, the (24) can be rewritten as:

$$r_o \leq D^f(t) \leq r(t) \tag{25}$$

In this case, integrated UPFC in a network will offer transient stability and perform load flow balancing between various clusters of numerous renewable energy resources. The versatile UPFC will also function as a power buffer to counteract RERs instability. Therefore, the transients in RERs can be mitigated, and the chances of instability in the system can be minimized.

6. Designing of Clusters

We took into consideration that the two European nations of Denmark and Norway would form two clusters of interconnected SGs to test our proposed methodology. The total distance between these two countries is around 500 KM. Therefore, it is assumed that the HVAC transmission network would be more feasible in the SSG interconnection rather than the HVDC network taking into account the breakeven distance as described below in Figure 10.

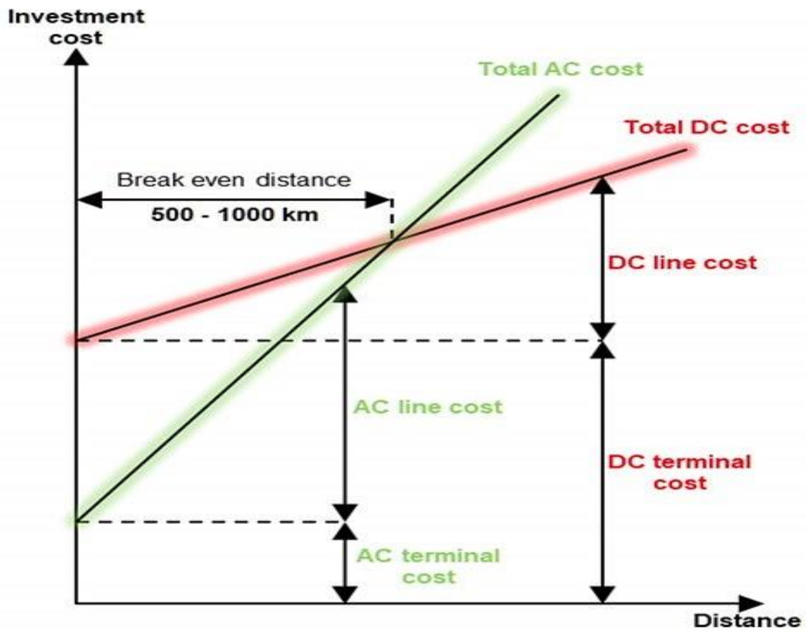

Figure 10. Graphical representation of breakeven distance and compassion of cost and distance of HVDC and HVAC transmission network.

Two clusters each showing an infrastructure of Denmark and Norway SG are designed on Simulink MATLAB. Multiple renewable energy resources are incorporated into the system. The UPFC and three-phase multiple faults are injected into the system. The VPQ measurement blocks are used to obtain the results from the different buses. The VPQ measurement subsystem is formed and is shown in Figure 11. Figure 12 shows the infrastructure of the SSG having a 21-bus IEEE system with the interconnection of two countries.

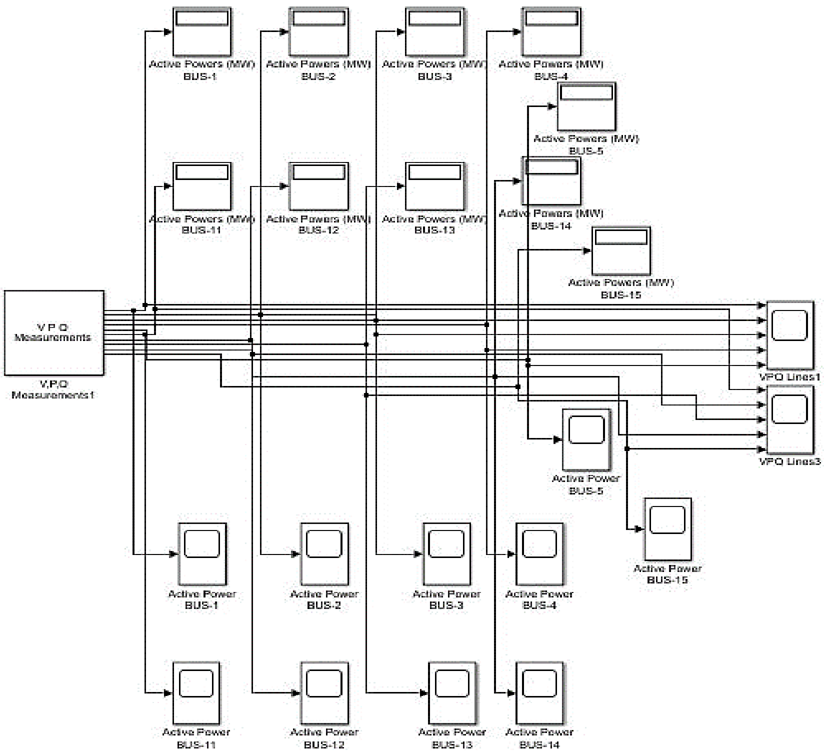

Figure 11. VPQ measurement block subsystem.

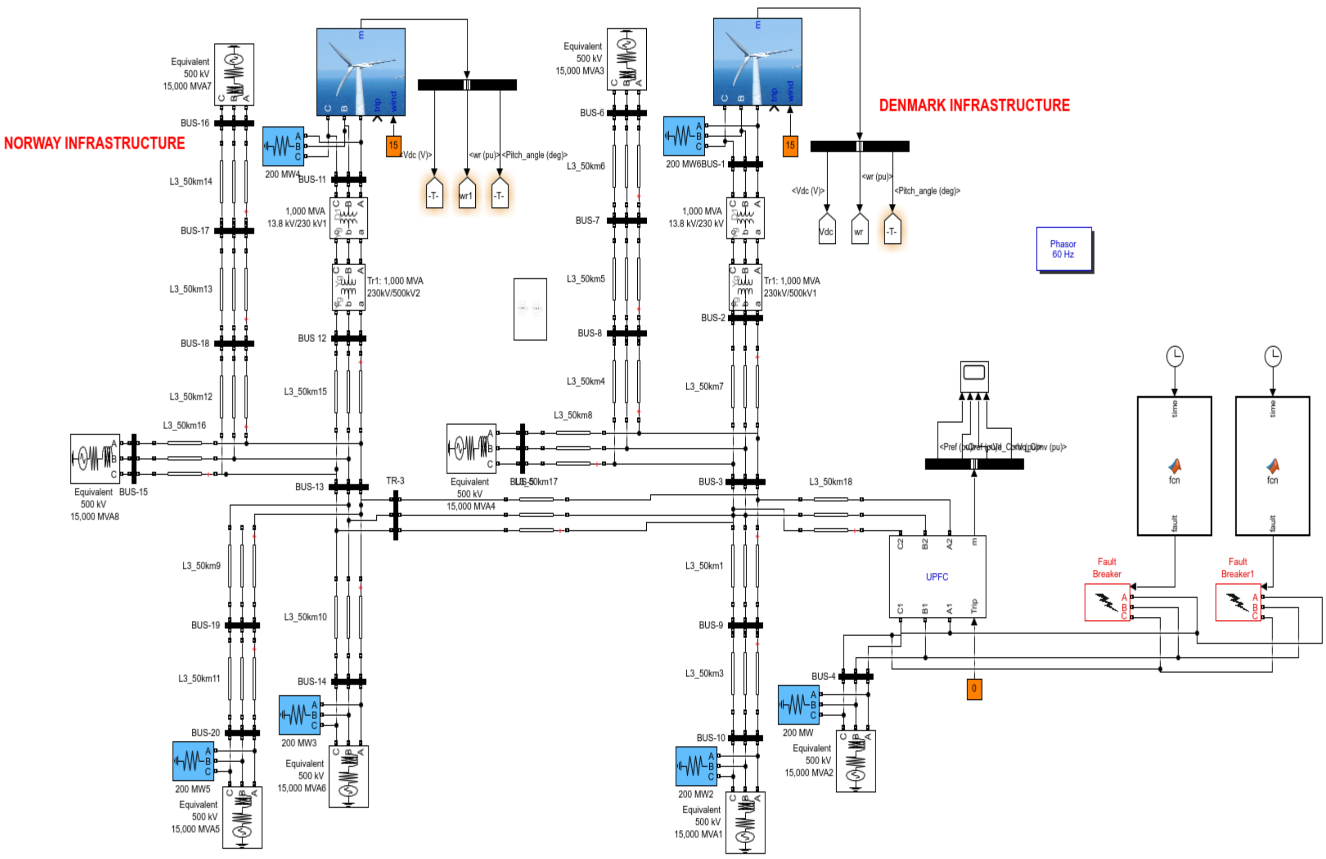

Figure 12. SIMULINK model of 21-BUS SSG.

First, we designed the loads, and the parameters for loads are described in Figure 13, whereas the model of the wind farms as RER sources along with the parameters is shown in Figure 14. In addition, the generation sources such as biomass and micro-hydro are designed, and their parameters are defined in Figure 15, respectively. Then, the transmission network model was designed. Then, the vulnerability of the SSG was evaluated in terms of transition instability that develops as a result of multiple faults. Also taken into consideration are the overloaded circumstances brought on by some power sources tripping and the transients that develop as a result of several three-phase faults. Let us say that transient instability makes an SSG susceptible. The main result of the suggested methodology is a transient stability increase provided by a UPFC. This will lessen the likelihood of cascading failures and SSG blackouts. Secondly, the multiple three-phase faults are inserted in the SSG, which are more severe than the SGs faults due to the complexity and transmission network issues. Mathematically, modeling of two clusters of SGs and their interconnection with each other is performed on MATLAB. The case-based scenarios are discussed in the model. The effect of power flow before and after the faults was analyzed along with the UPFC insertion and without the UPFC. Multiple faults were considered, and the variation in the results was also discussed, which elaborates the UPFC importance in SSGs.

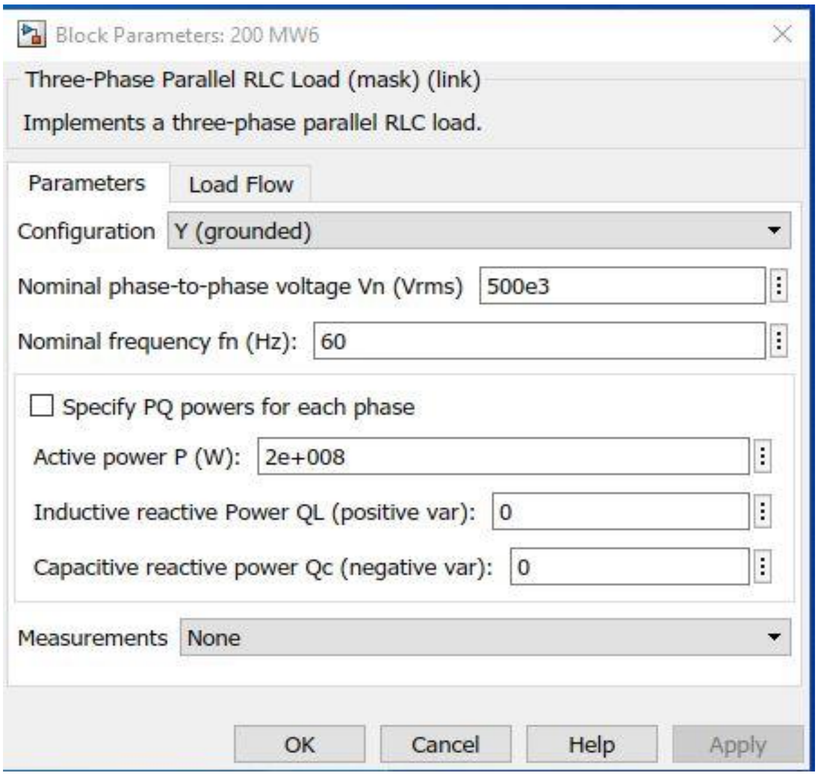

Figure 13. Parameters setting of 200 Load Block.

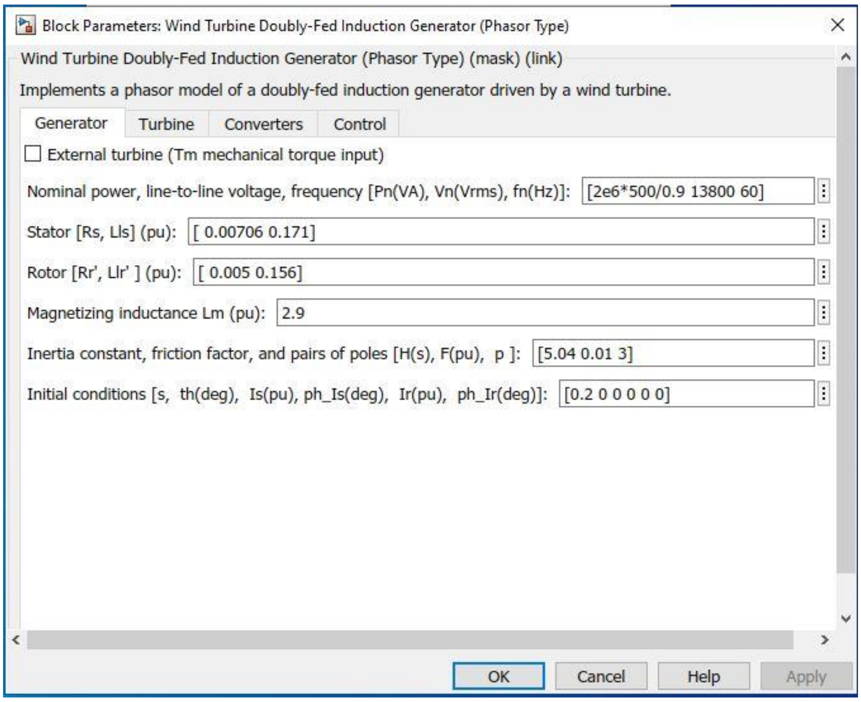

Figure 14. Parameters setting of 1000 MW Wind Farm Block.

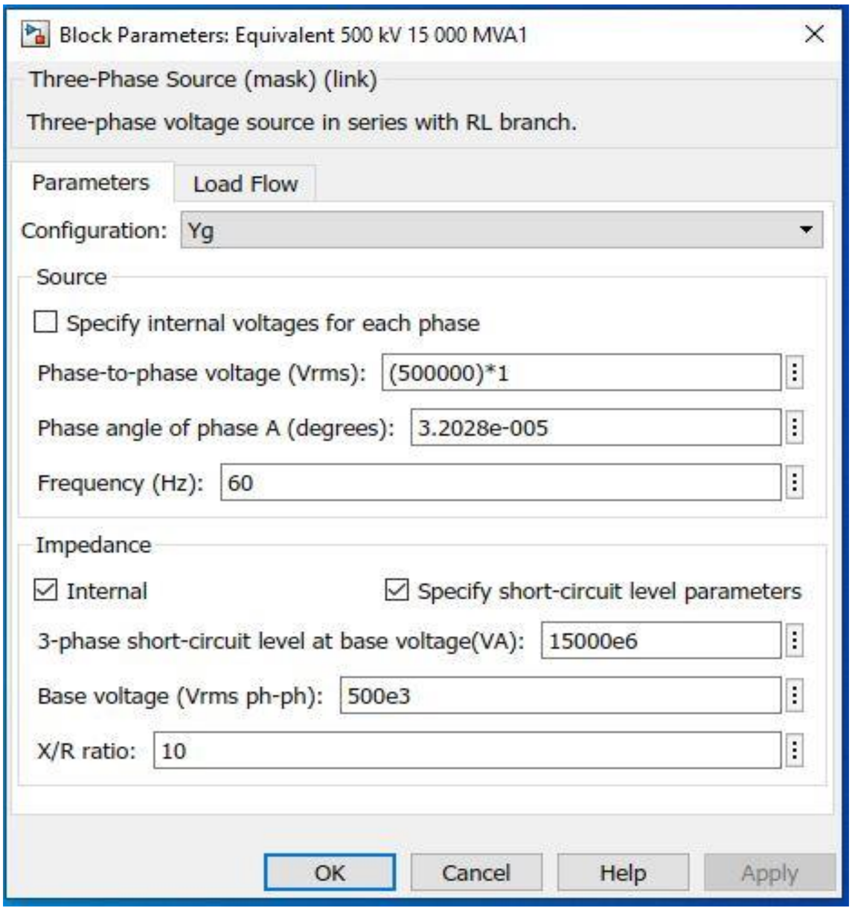

Figure 15. Parameters setting of 15,000 MVA Biomass generation Block.

7. Simulations and Results

Several simulations were run using MATLAB as the simulation tool to validate and assess the analysis. The consequence of more serious three-phase faults, or MITPFs, is explored in this research, which is built on a more generic system model than the past literature for transient stability analysis, as detailed in Section 2. The issue under investigation is novel and distinct from all others. We considered case-based scenarios in the simulation and gathered the results considering each case using a simulation time of T = 18 s.

7.1. Case 1. System in Normal State and No-Fault Is Introduced

In the first case, we considered that the SSG is operating in a normal state and that no fault is inserted in the system. The power output in the normal case approaches 1000 MW on Bus 1 and so on. It takes time to ramp up because the wind turbine used in the Denmark and Norway infrastructure model is ramping up from 0 to 10 s, as explained in Figures 16 and 17, respectively.

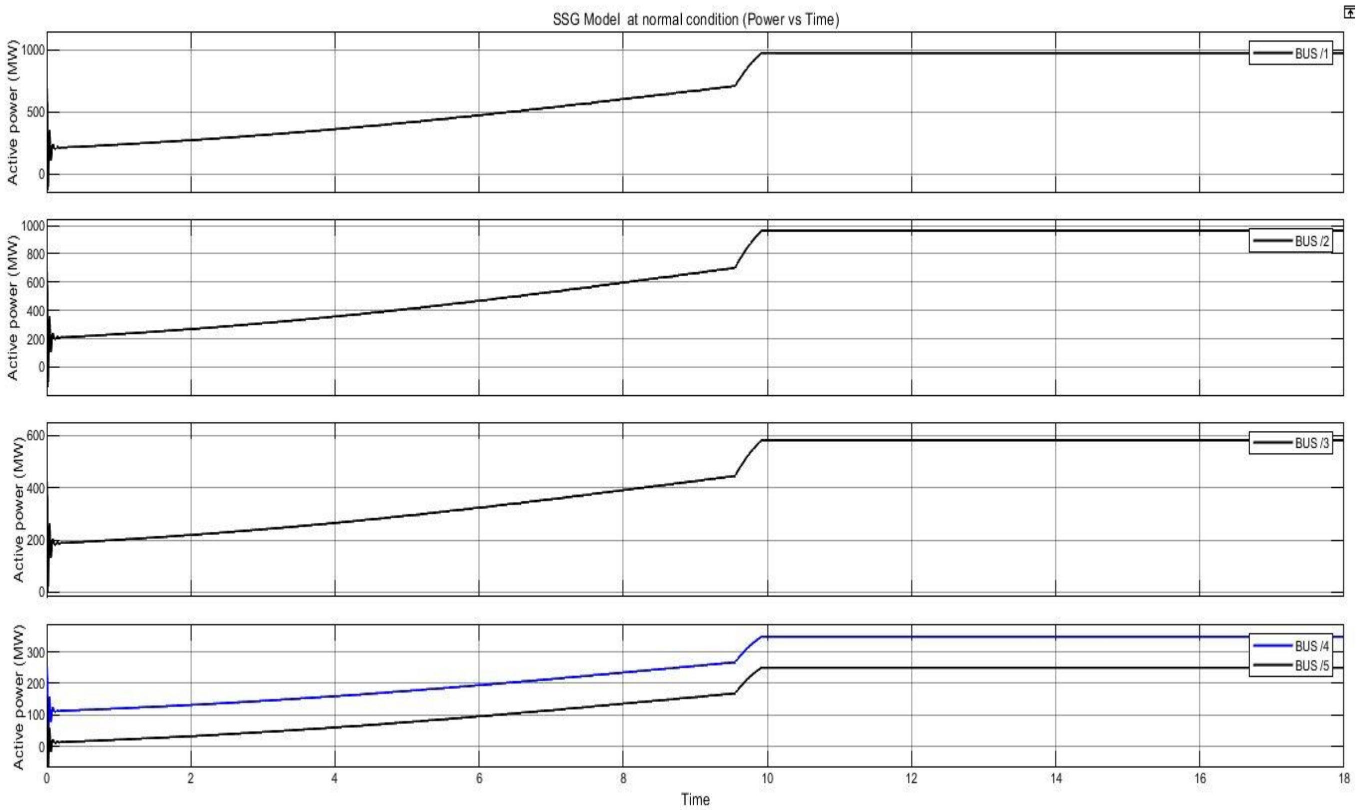

Figure 16. System in normal state, and no fault is introduced (Bus 1 to Bus 5).

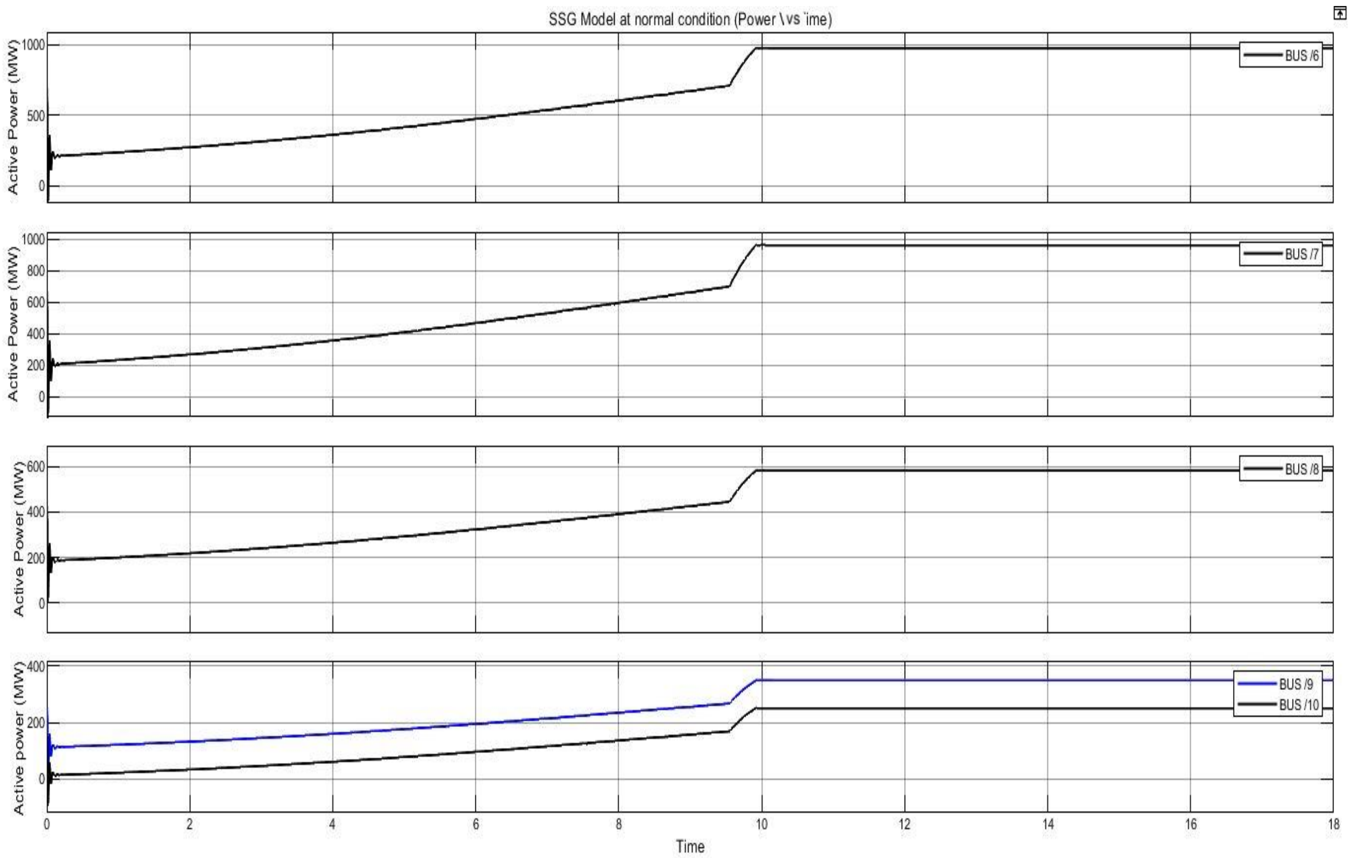

Figure 17. System in normal state, and no fault is introduced (Bus 6 to Bus 10).

7.2. Case 2. System in Instability State, and Multiple L-GFaults Are Introduced

In the second case, we considered that the SSG is operating in a faulty condition and that multiple L-G faults are inserted in the system. The faults are inserted by an external control parameter, and it is programmed as:

```
function fault = fcn(time)
%#codegen
fault = 0;
if (time >= 12 && time <= 12.3)
fault = 1;
end
```

Two faults are inserted, and each one is controlled externally and can be varied by observing the effect in the system. The power output in the faulty case approaches 1000 MW on Bus 1 and so on. However, after the faults at a time of 12 to 12.3 s and 16 to 16.5 s, transients occur. These transients take around 1.5 s in case of the 0.3s fault and 1.9 s in the case of the 0.5 s fault time to be steady to the normal position of the system. There are fluctuations in the system due to the ramp-up time because the wind turbine used in the Denmark and Norway infrastructure model is ramping up from 0 to 10 s, as explained in Figures 16 and 17. It can be observed that even though the faults are inserted on Bus 3 and Bus 1, the effects of the faults can also be seen on Bus 6 to 10. This clearly explains that after the fault the whole system results in transients. However, the bus that is close to the fault will experience a severity more than that of the farthest bus, as can be seen in Figures 18–20.

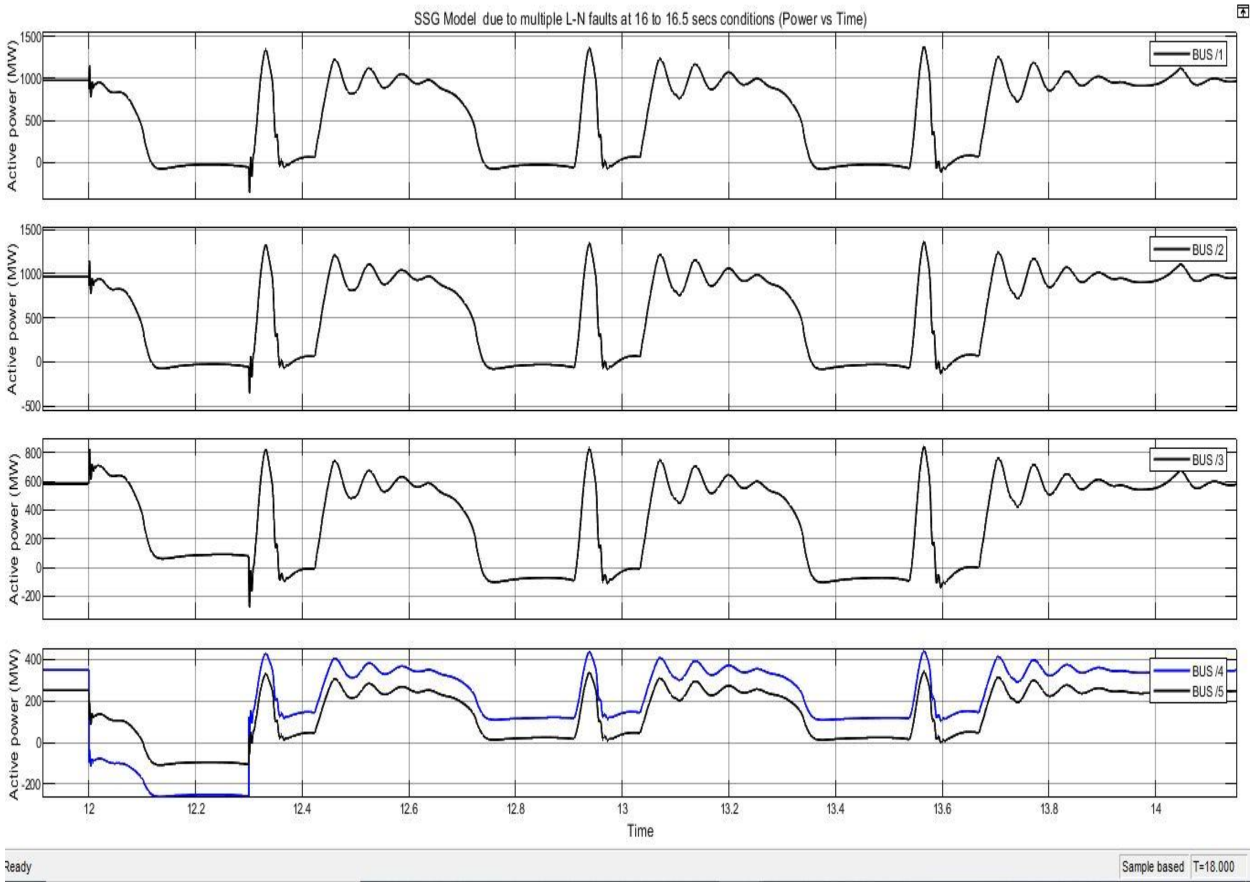

Figure 18. Multiple line-to-ground faults are inserted in the system from 12 to 12.3 s (Bus 1 to Bus 5).

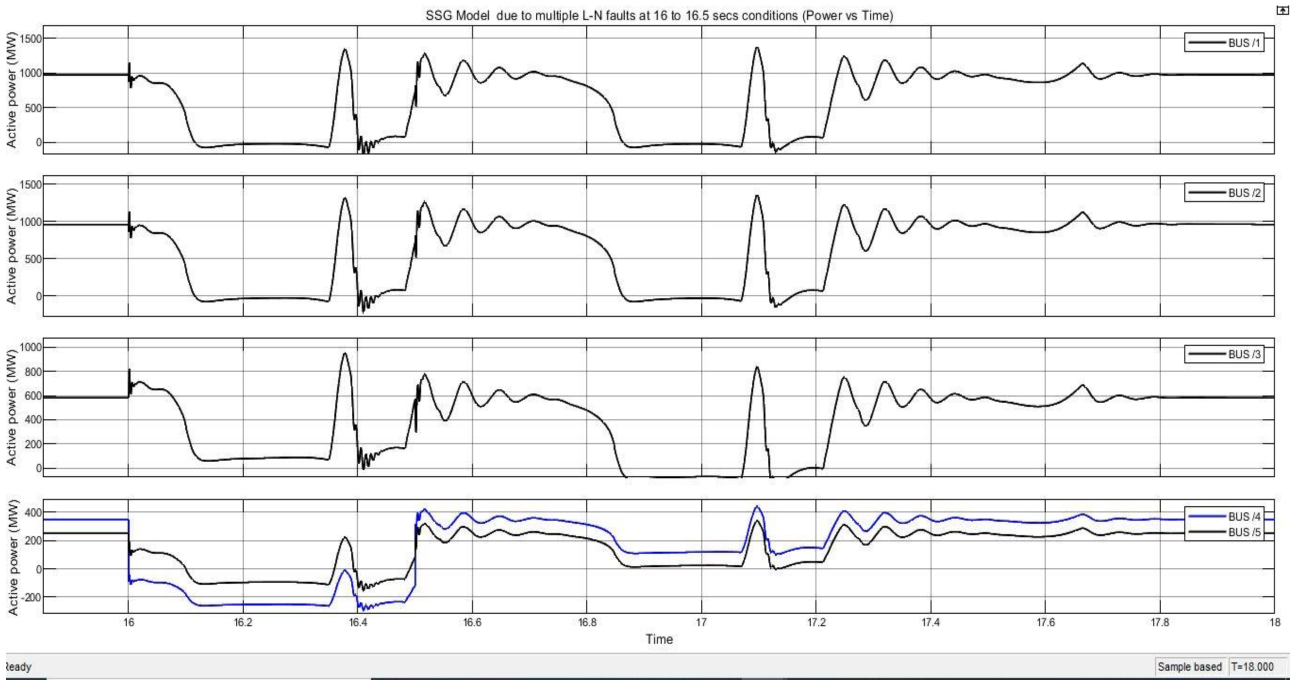

Figure 19. Multiple line-to-ground faults are inserted in the system from 16 to 16.5 s (Bus 1 to Bus 5).

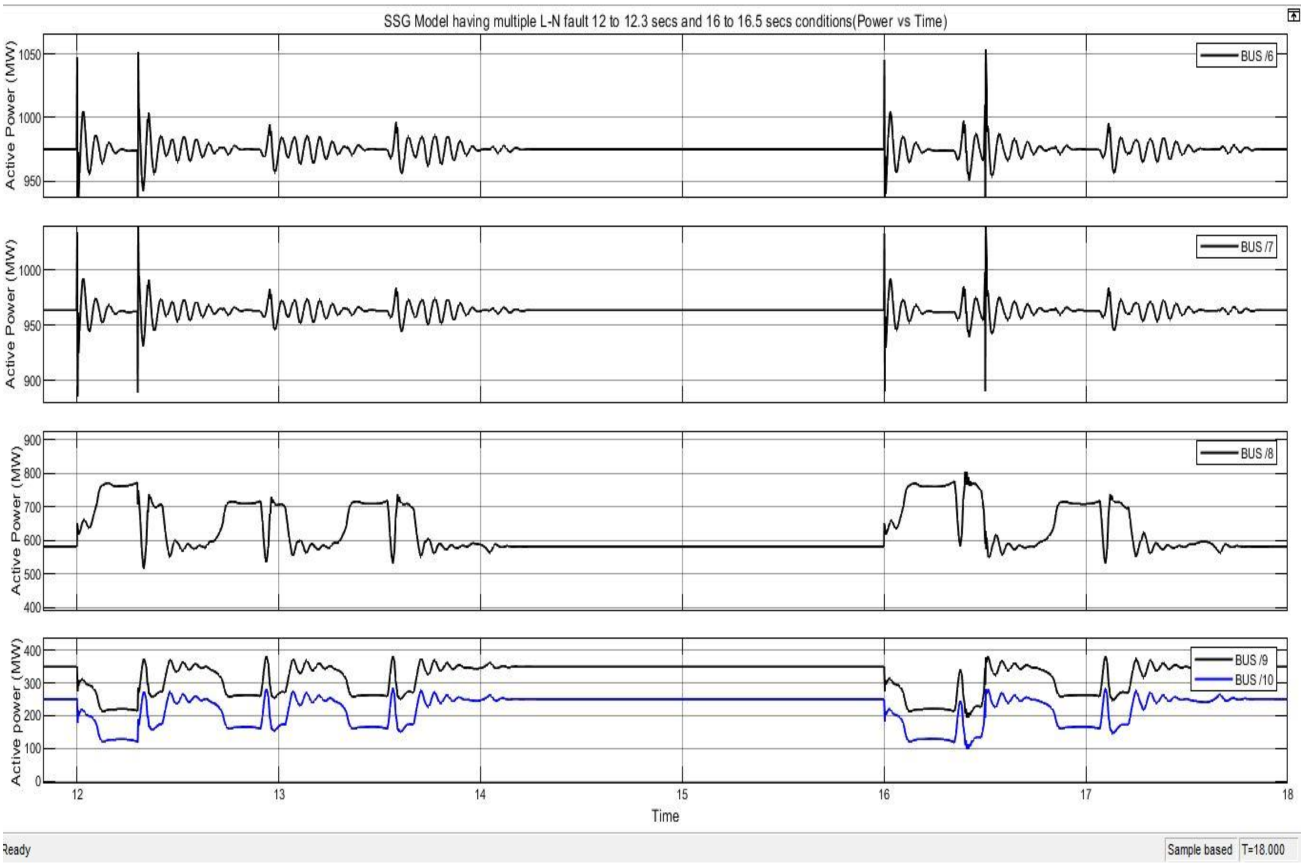

Figure 20. Multiple line-to-ground faults are inserted in the system from 12 to 12.3 s and 16 to 16.5 s (Bus 6 to Bus 10).

7.3. Case 3. By Incorporation of UPFC, and Multiple L-GFaults Are Also Inserted

In the third case, we considered that the SSG is operating in a faulty condition and that multiple L-G faults are inserted in the system.

The power output in the faulty case approaches 1000 MW on Bus 1 and so on. However, after the faults at a time of 12 to 12.3 s and 16 to 16.5 s, transients are mitigated within a time span of only 0.1 s. The transients that took 1.5 s in the case of the 0.3s fault and of 1.9 s in the case of the 0.5 s fault time to be steady now only take 0.1 s to mitigate the transients of the system. There are fluctuations in the system because it takes ramp-up time because the wind turbine used in the Denmark and Norway infrastructure model is ramping up from 0 to 10 s. The output of UPFC in case of faults shows that the power flow control and the transients are eliminated within the interval of 0.1 s, as shown in Figures 21 and 22 for Buses 1 to 5, respectively.

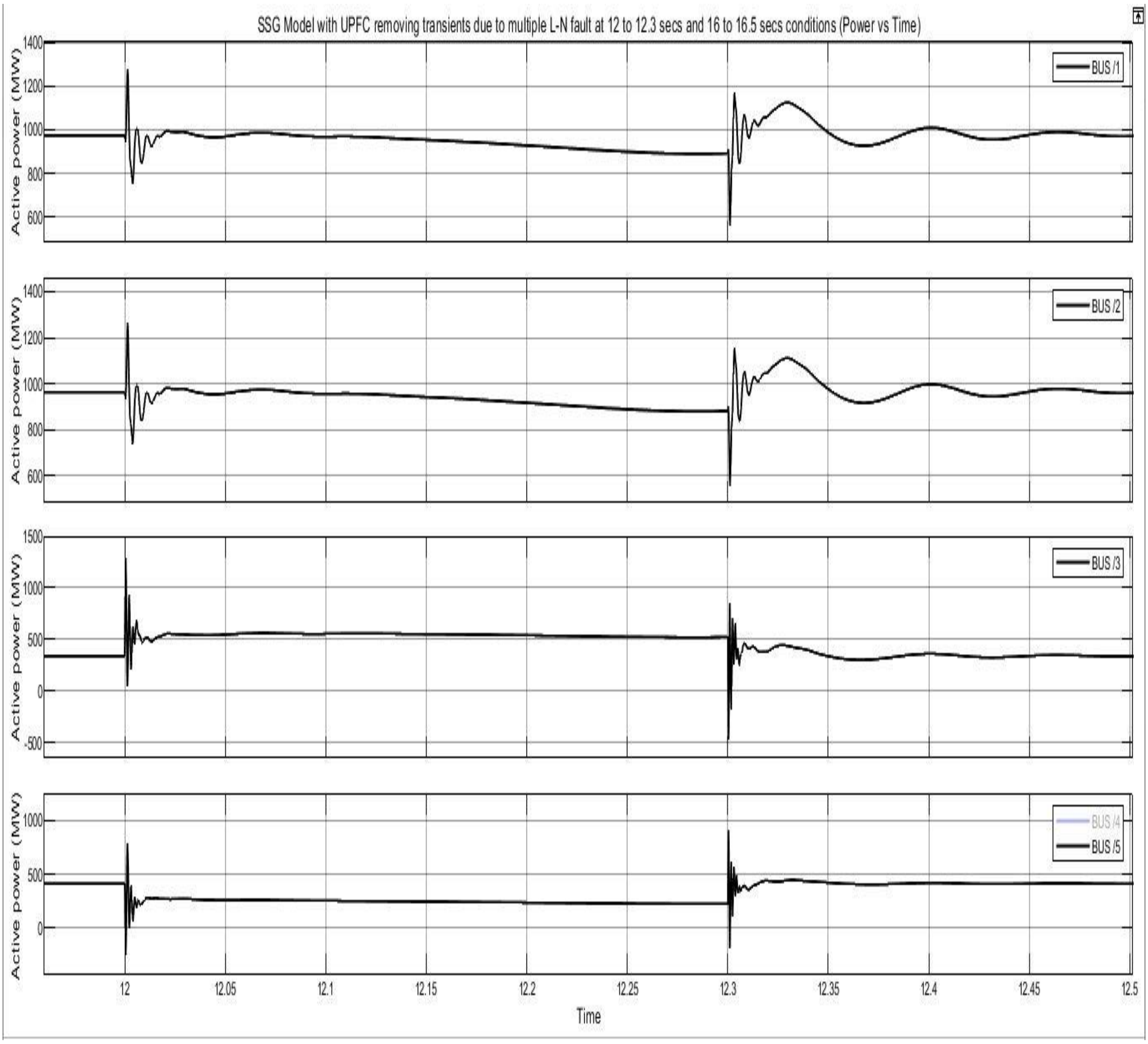

Figure 21. Transient stability being provided by UPFC at multiple L-G faults from 12 to 12.3 s (Bus 1 to Bus 5).

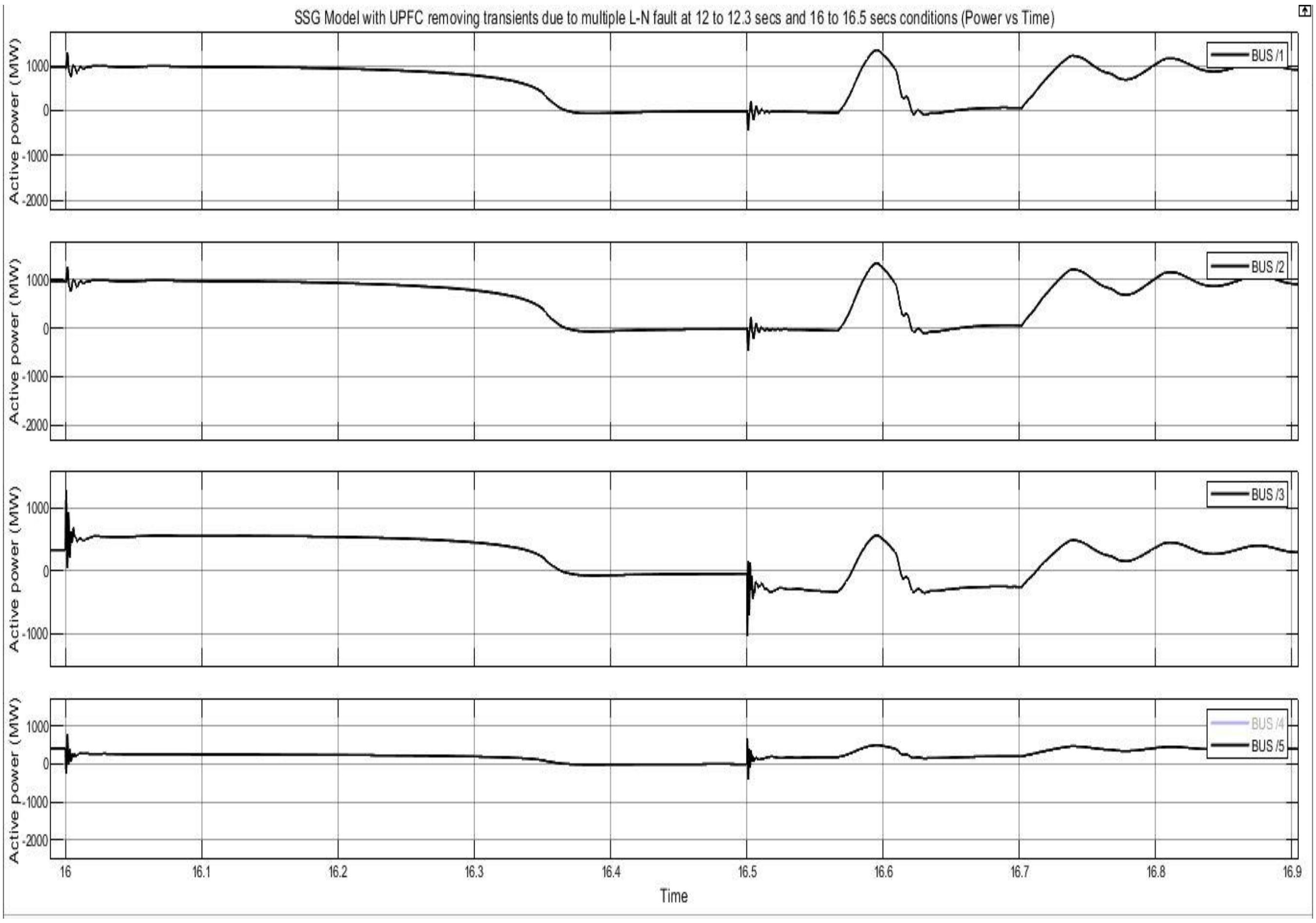

Figure 22. Transient stability being provided by UPFC at multiple L-G faults from 16 to 16.5 s (Bus 1 to Bus 5).

7.4. Case 4. System in Instability State, and Multiple Double L-LFaults Are Introduced

In the fourth case, we considered that the SSG is operating in a faulty condition and that multiple double L-L faults are inserted in the system.

The power output in the faulty case approaches 1000 MW on Bus 1 and so on. However, after the faults at a time of 12 to 12.3 s and 16 to 16.5 s, transients occur. These transients take around 1.5 s in the case of the 0.3s fault and of 1.9 s in the case of the 0.5 s fault time to be steady to the normal position of the system. There are fluctuations in the system because it takes ramp-up time because the wind turbine is being used from 0 to 10 s. It can be observed that even though the faults are inserted on Bus 3 and Bus 1, the effects of the faults can also be seen on Bus 6 to 10. Here, we inserted double line-to-line faults in the system to observe their impacts and to see whether UPFC can cater to these faults properly or not. The faults' effect resulting in transients can be seen in Figures 23 and 24 on Bus 1 to 5 and Figures 25 and 26 for Bus 6 to 10.

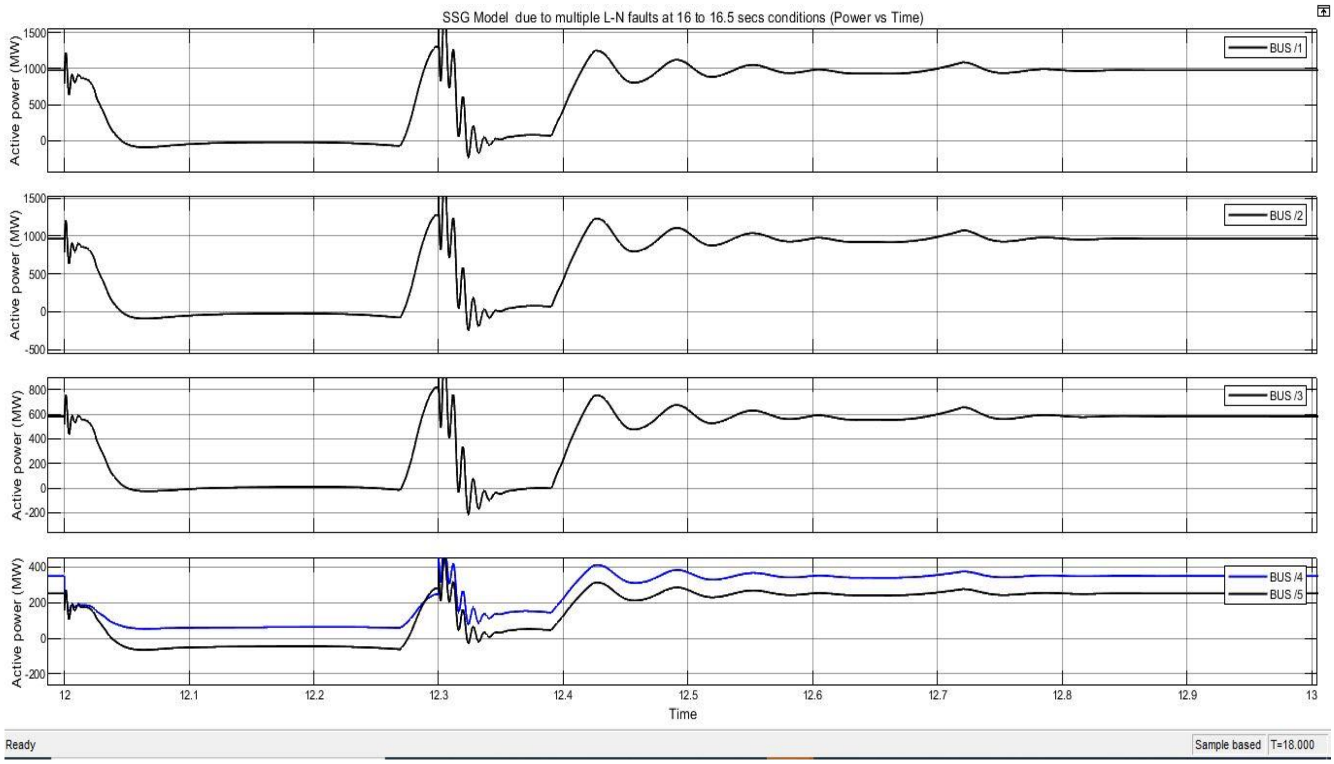

Figure 23. Multiple double line-to-line (L-L) faults are inserted in the system from 12 to 12.3 s (Bus 1 to Bus 5).

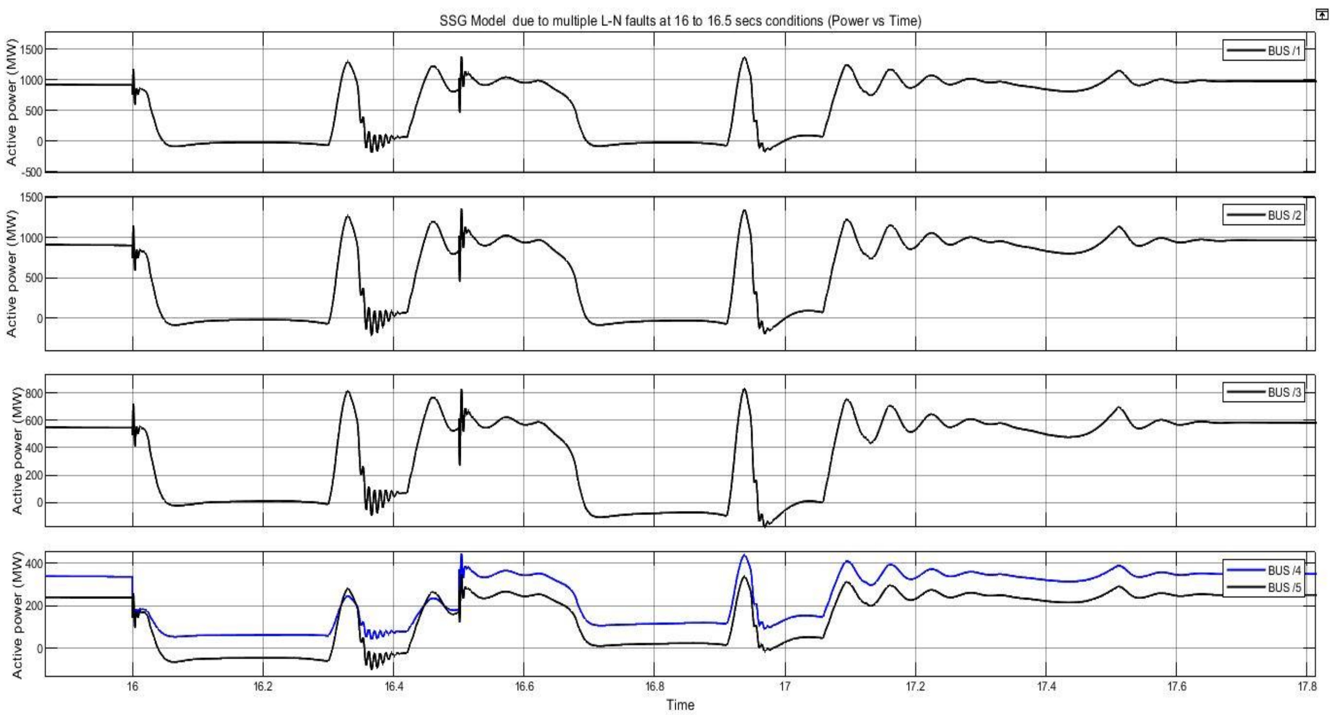

Figure 24. Multiple double line-to-line (L-L) faults are inserted in the system from 16 to 16.5 s (Bus 1 to Bus 5).

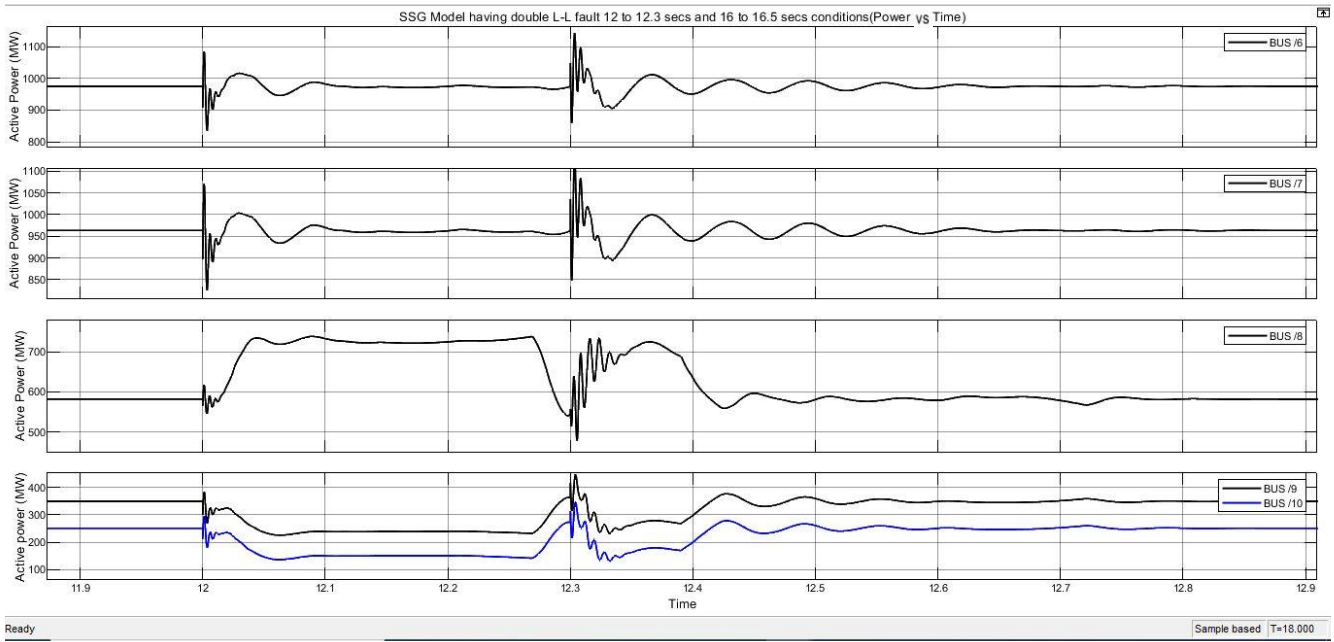

Figure 25. Multiple double line to line (L-L) faults are inserted in the system from 12 to 12.3s (Bus 6 to Bus 10).

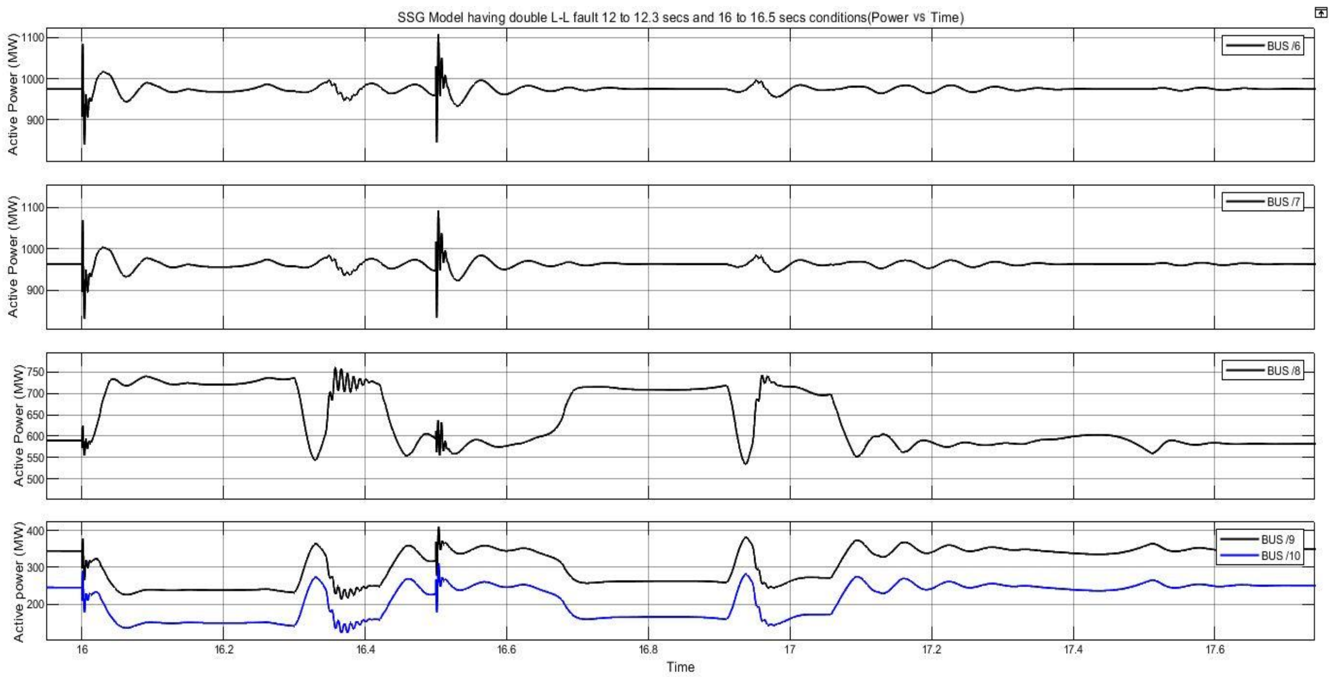

Figure 26. Multiple double line-to-line (L-L) faults are inserted in the system from 16 to 16.5 s (Bus 6 to Bus 10).

7.5. Case 5. By Incorporation of UPFC, and Multiple Double L-L Faults Are Also Injected

In the fifth case, we considered that the SSG is operating in a faulty condition and that multiple double L-L faults are inserted in the system. The power output in the faulty case approaches 1000 MW on Bus 1 and so on. However, after the faults at a time of 12 to 12.3 s and 16 to 16.5 s, transients are mitigated within a time span of only 0.1 s. The transients that took around 1.5 s in the case of the 0.3s fault and of 1.9 s in the case of the 0.5 s fault time to be steady now take only 0.1 s to mitigate the transients of the system. There are fluctuations in the system due to the ramp-up time because the wind turbine used in the

Denmark and Norway infrastructure model is ramping up from 0 to 10 s, as explained in Figures 23–26. Here, the UPFC takes around 0.2 s to achieve stability in the system as shown in Figures 27–30, respectively.

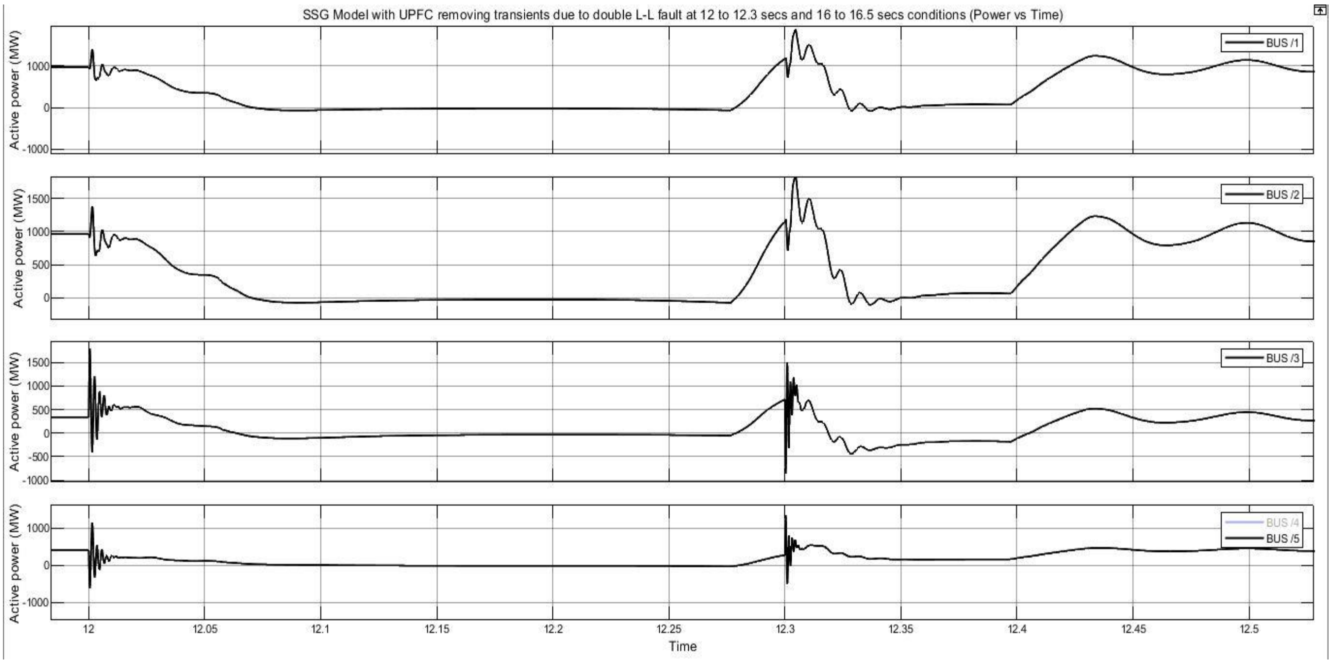

Figure 27. Transient stability being provided by UPFC after multiple double faults L-L introduced 12 to 12.3 s (Bus 1 to Bus 5).

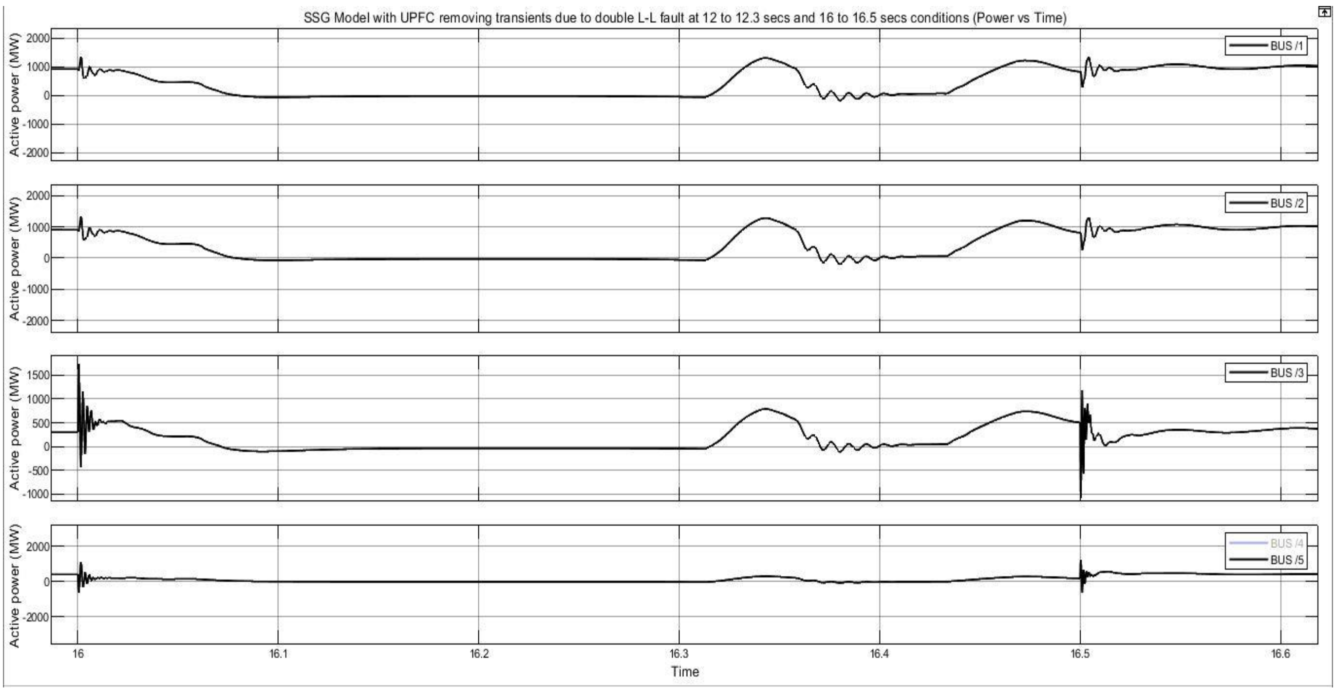

Figure 28. Transient stability being provided by UPFC after multiple double faults L-L introduced 16 to 16.5 s (Bus 1 to Bus 5).

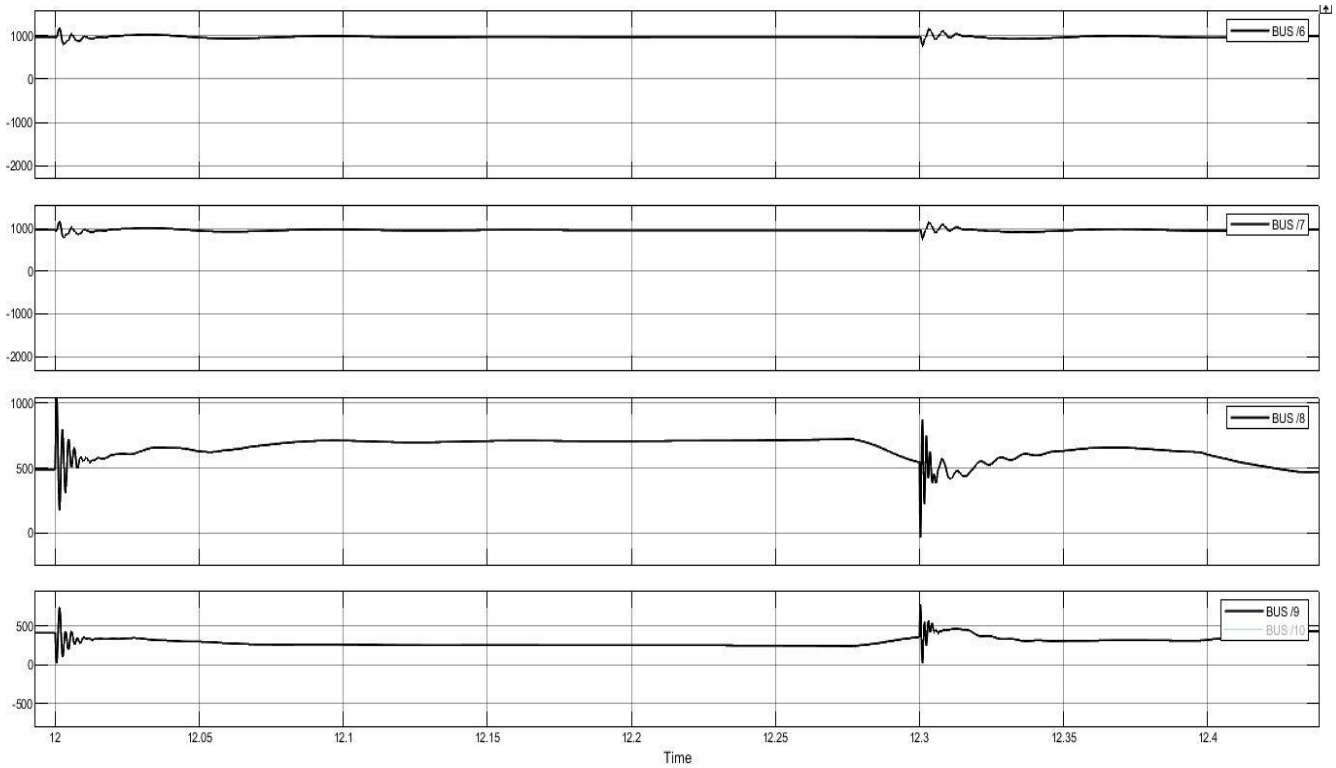

Figure 29. Transient stability being provided by UPFC after multiple double faults L-L introduced 12 to 12.3 s (Bus 6 to Bus 10).

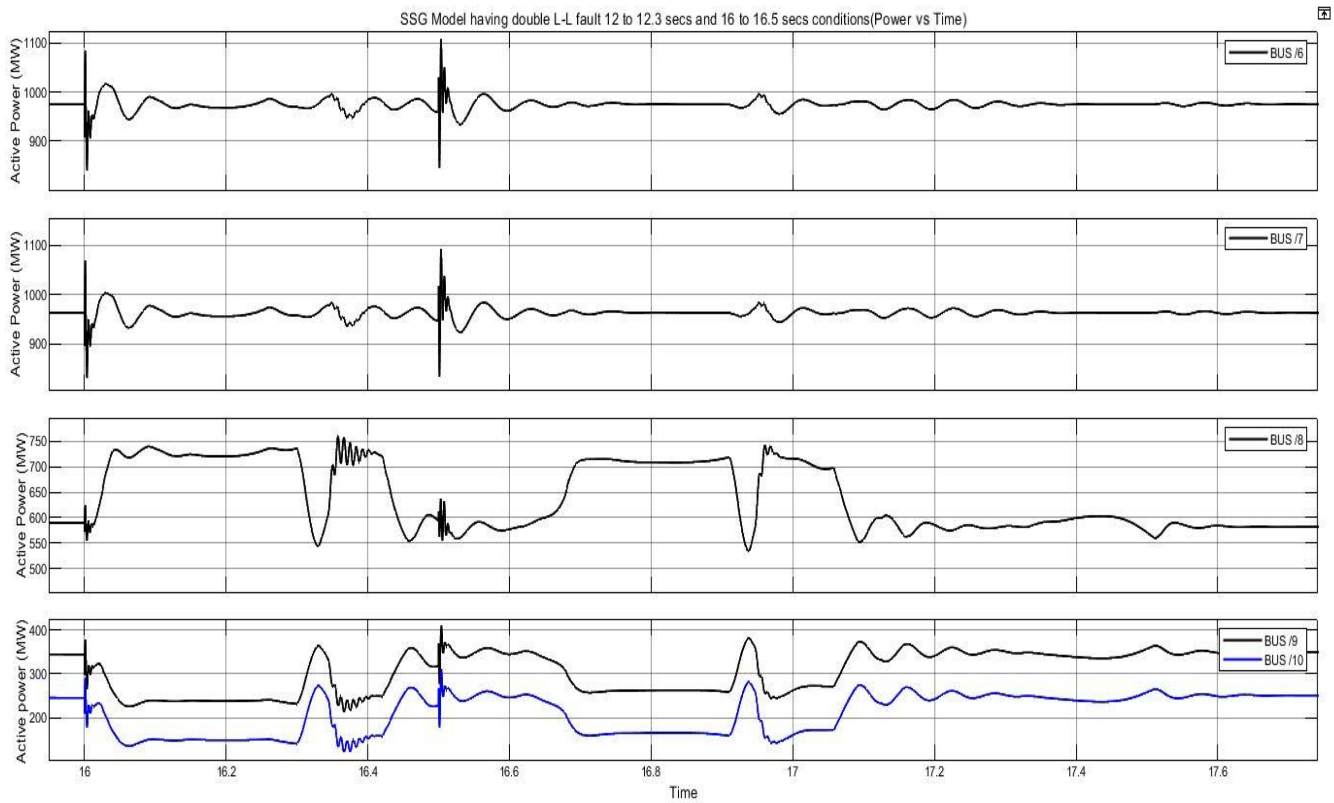

Figure 30. Transient stability being provided by UPFC after multiple double faults L-L introduced 16 to 16.5 s (Bus 6 to Bus 10).

7.6. Case 6. System in Instability State, and Multiple L-L-L-NFaults Are Introduced

In the sixth case, we considered that the SSG is operating in a faulty condition and that multiple L-L-L-N faults are inserted in the system. The power output in the faulty case approaches 1000 MW on Bus 1 and so on. However, after the faults at a time of 12 to 12.3 s and 16 to 16.5 s, transients occur. These transients take around 1.5 s in the case of the 0.3s fault and of 1.9 s in the case of the 0.5 s fault time to be steady to the normal position of the system. There are fluctuations in the system because the ramp-up takes time because the wind turbine is being used from 0 to 10 s. It can be observed that even though the faults are inserted on Bus 3 and Bus 1, the effects of the faults can also be seen on Bus 6 to 10. Here, we inserted multiple line-to-line faults in the system, as can be seen in Figures 31–34, to observe their impacts and to see whether UPFC can cater to these faults properly or not.

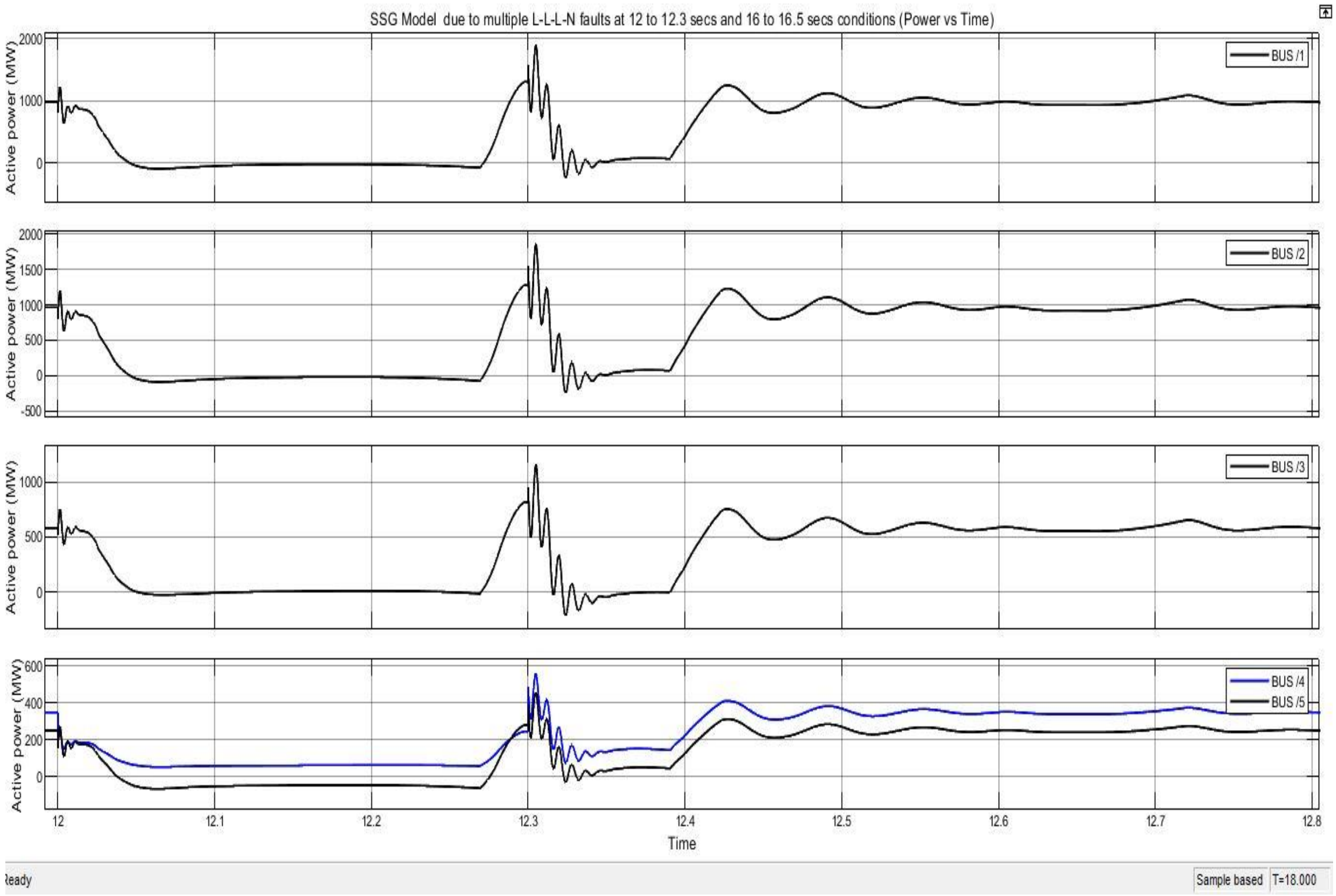

Figure 31. Multiple line-to-line (L-L-L-N) faults are inserted in the system from 12 to 12.3 s (Bus 1 to Bus 5).

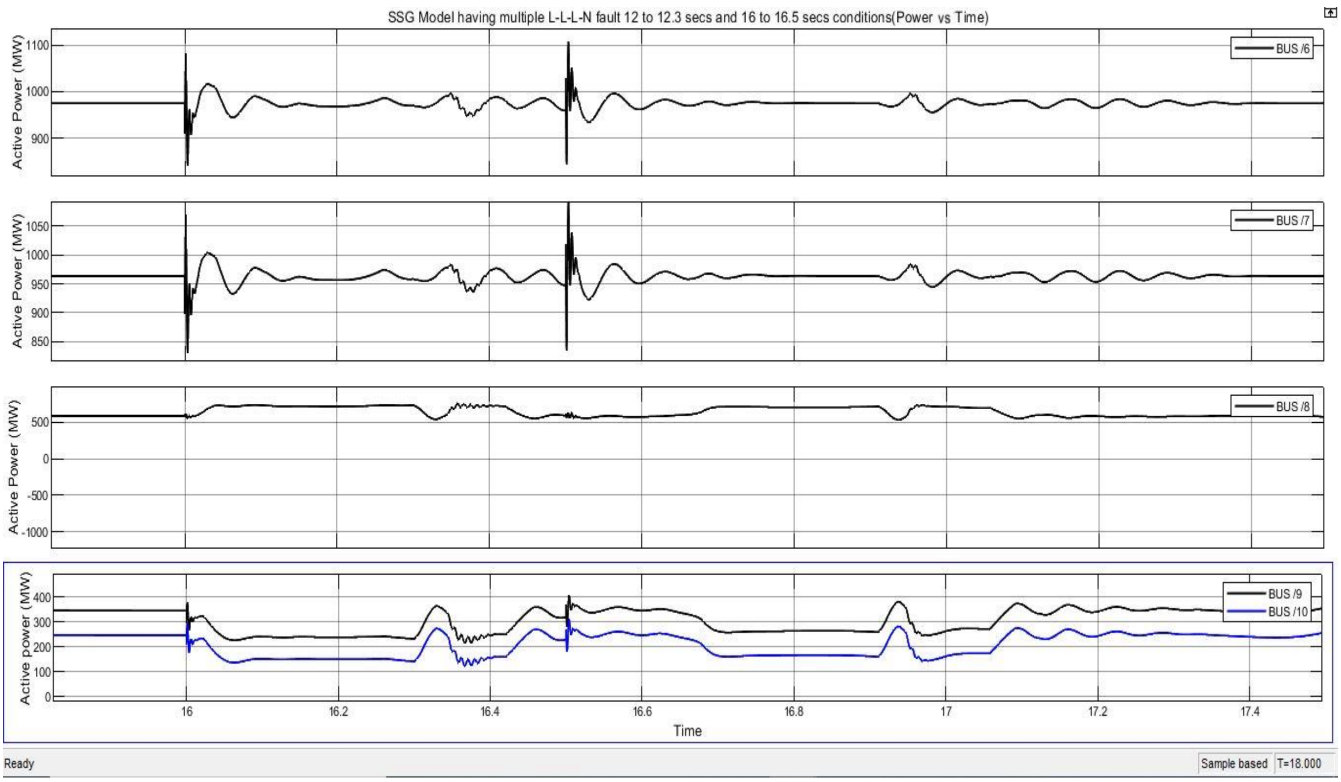

Figure 32. Multiple line-to-line (L-L-L-N) faults are inserted in the system from 16 to 16.5 s (Bus 1 to Bus 5).

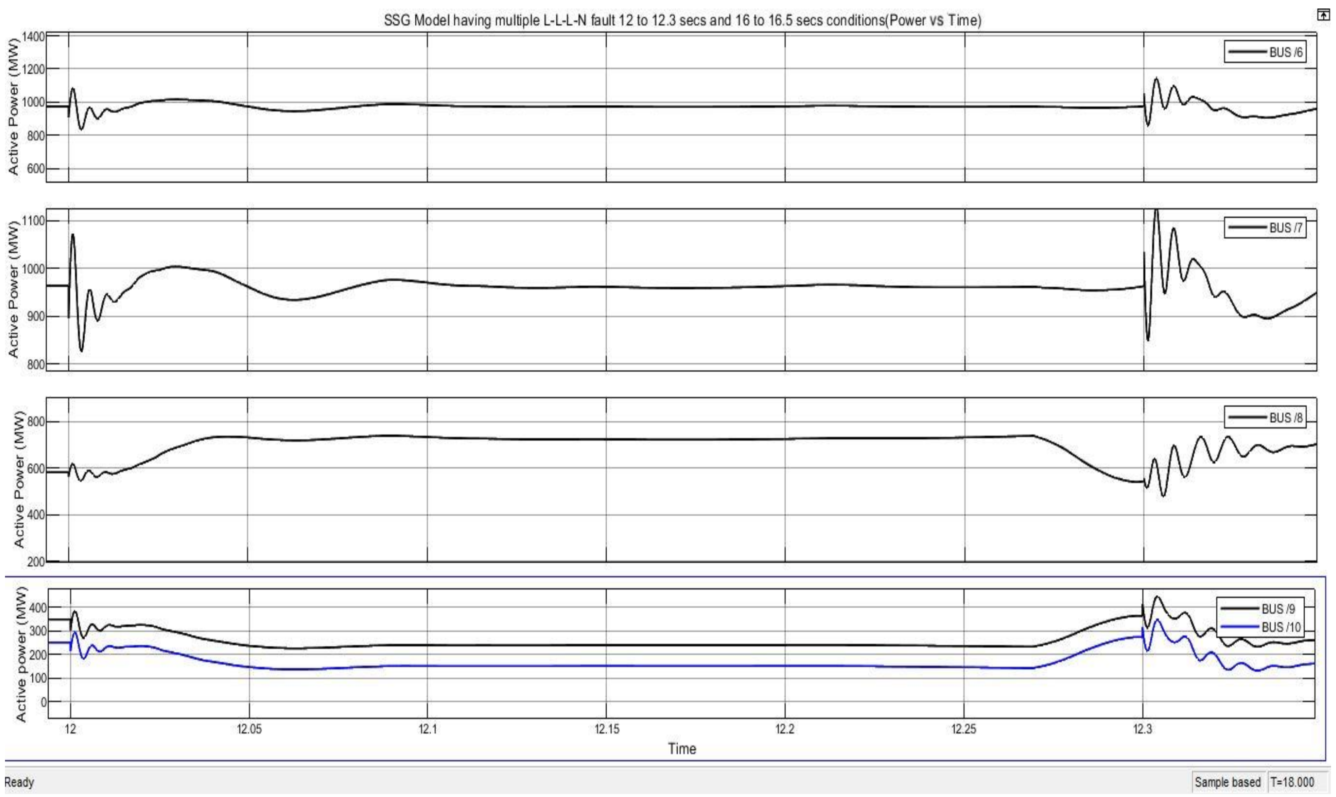

Figure 33. Multiple line-to-line (L-L-L-N) faults are inserted in the system from 12 to 12.3s (Bus 6 to Bus 10).

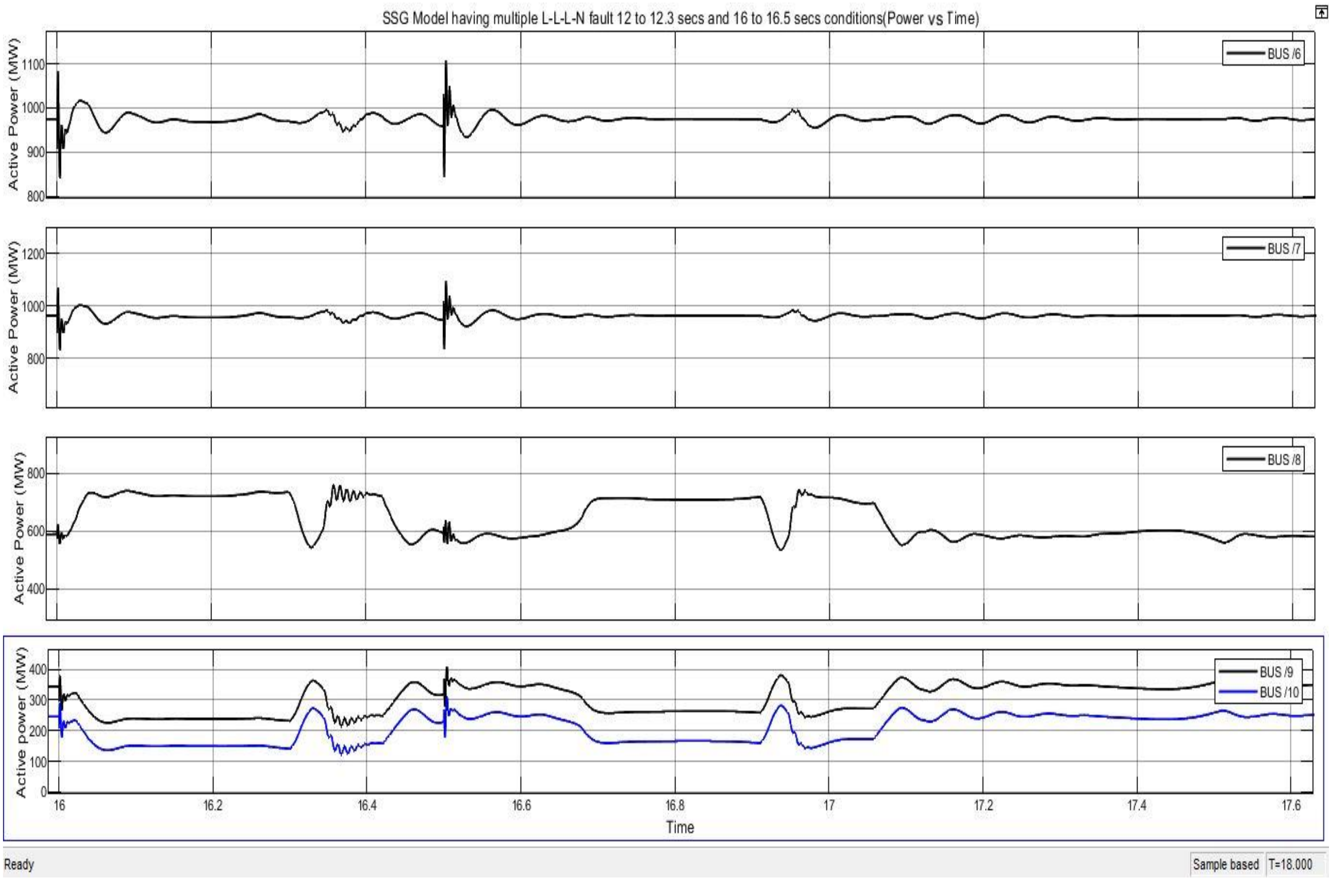

Figure 34. Multiple line-to-line (L-L-L-N) faults are inserted in the system from 16 to 16.5 s (Bus 6 to Bus 10).

7.7. Case 7. By Incorporation of UPFC, and Multiple L-L-L-N Faults Are Also Injected

In the seventh case, we considered that the SSG is operating in a faulty condition and that multiple L-L-L-N faults are inserted in the system. The power output in the faulty case approaches 1000 MW on Bus 1 and so on. However, after the faults at a time of 12 to 12.3 s and 16 to 16.5 s, transients are mitigated within a time span of only 0.1 s. The transients that took a time of around 1.5 s in the case of the 0.3s fault and 1.9 s in the case of the 0.5 s fault time to be steady now take only 0.1 s to mitigate the transients of the system. There are fluctuations in the system because the ramp-up takes time because the wind turbine used in this model is ramping up from 0 to 10 s. as explained in Figure 20. Here, the UPFC takes around 0.23 s to achieve stability in the system, as shown in Figure 26.

The results clearly show that the resilience of the SSG is enhanced and that the transients are catered out timely to save the infrastructure from fault propagation. In the case of L-G faults, the UPFC achieves stability in 0.1 s. In the case of L-L faults, the UPFC achieves stability of around 0.2 s, as depicted in Figures 35–38, respectively. The results shown describe that the UPFC can cater the multiple L-L-L-N faults easily and that the transients die out soon after the fault as compared to the case without UPFC.

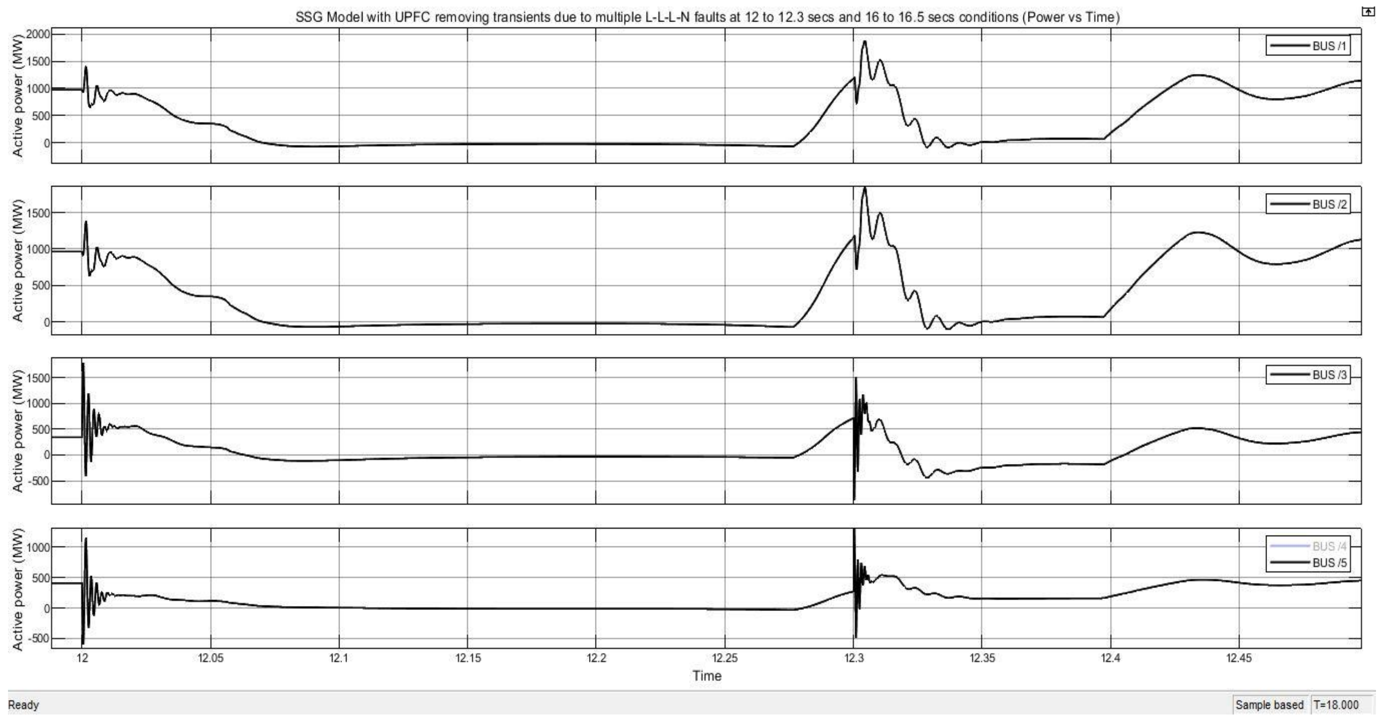

Figure 35. Transient stability being provided by UPFC after multiple L-L-L faults are introduced at 12 to 12.3 s (Bus 1 to Bus 5).

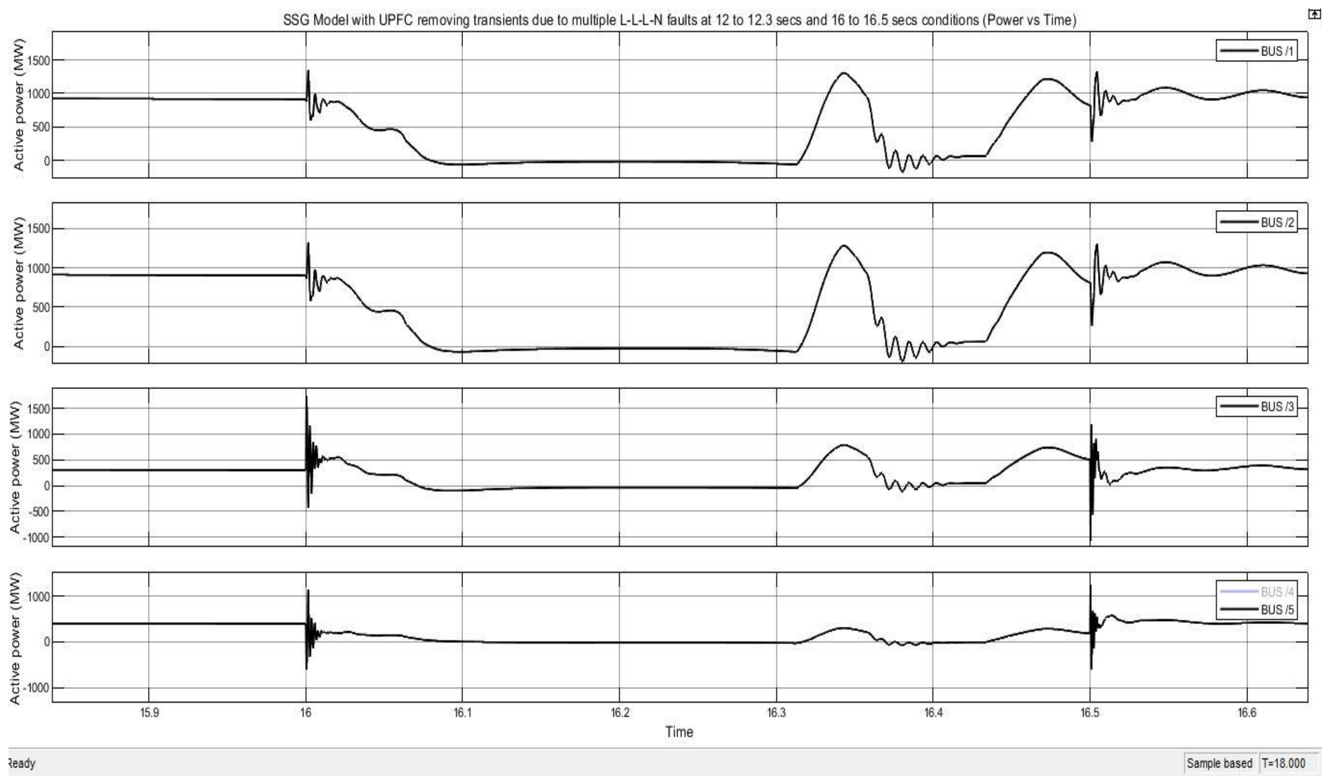

Figure 36. Transient stability being provided by UPFC after multiple L-L-L faults are introduced at 16 to 16.5 s (Bus 1 to Bus 5).

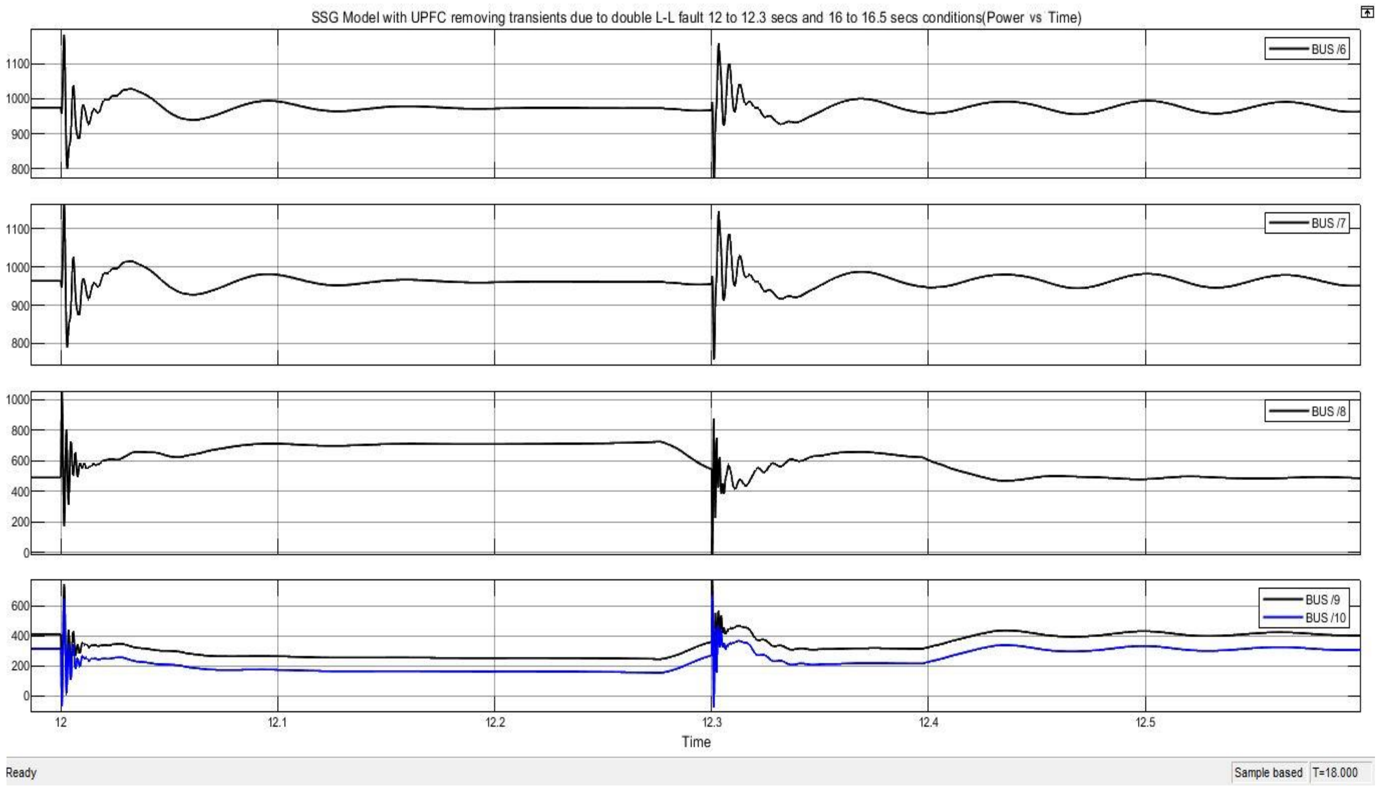

Figure 37. Transient stability being provided by UPFC after multiple L-L-L faults are introduced at 12 to 12.3 s (Bus 6 to Bus 10).

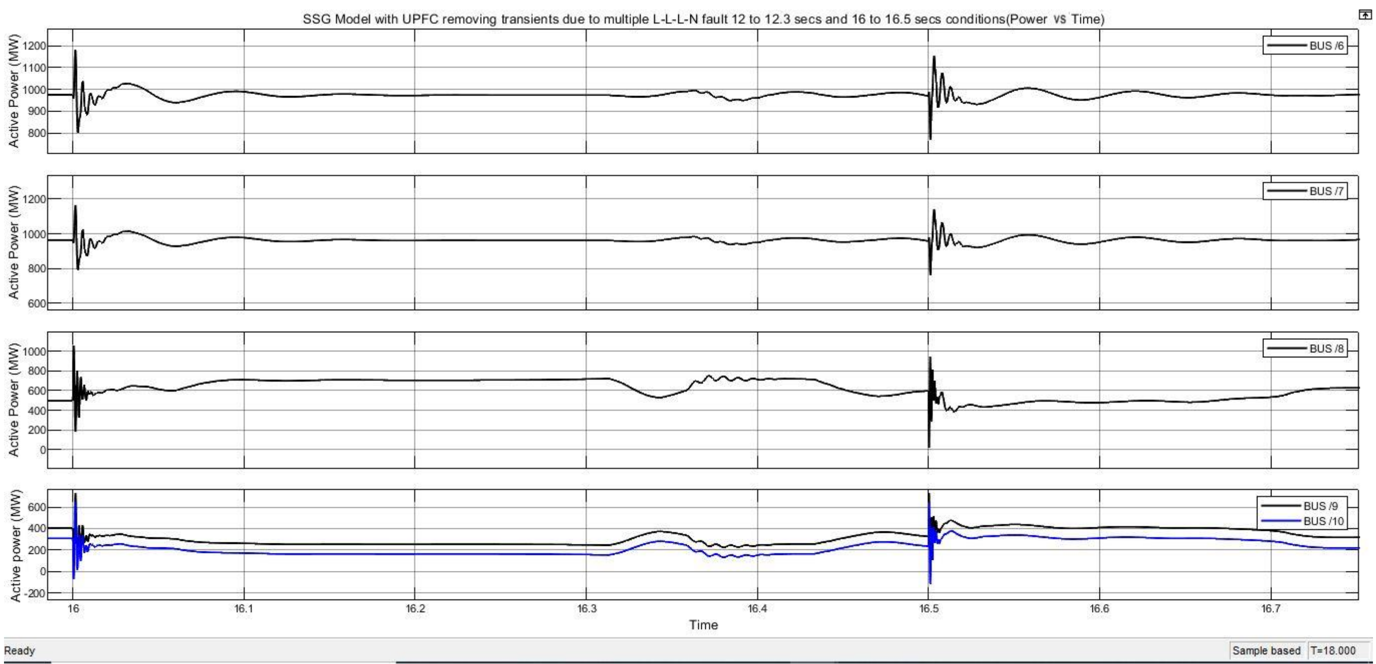

Figure 38. Transient stability being provided by UPFC after multiple L-L-L faults are introduced at 16 to 16.5 s (Bus 6 to Bus 10).

8. Conclusions and Future Research

This research work addressed the transient stability issues in a hypothetical network based on the interconnection between two countries Denmark and Norway. The complete probabilistic model of the system was also designed to enhance the stability of the system.

The results clearly showed that insertion of UPFC is an effective technique to enhance the transient stability and resilience of the power system networks as compared to other prosed techniques in the literature. Although SSGs projects and ideas have received positive reviews, their development is still a challenging task. Therefore, extensive simulation studies employing accurate RERs models could be used to analyze and investigate various problems arising due to the integration of many clusters of RERs in SSGs. UPFC mitigates the issue of transient instability, which occurs in the faults cases. As the work in the case of single-interval three-phase faults has already been done in the case of SGs, and the multiple-interval faults are more severe, an analysis of the multiple-interval faults, including line-to-line(L-L), line-to-ground (L-G), and line-to-line-to-line (L-L-L), was performed, and the system instability was analyzed. UPFC was incorporated near the fault bus, and the results in the power flow were analyzed. UPFC clearly showed that the transient stability of the SSGs is increased and is attained in a time span of around 0.1 s.

Future extensions of this work include:

1. Upgrading the SSGs in terms of their protection and monitoring using various control protocols on a periodic basis to increase the network's reliability;
2. Considering more than two clusters and performing their transmission network analysis on the DIG silent power factory;
3. Utilizing more than one UPFC and their impact on the SSGs and operating the power system network and the study on cascading failures due to N-1 contingencies and its techniques;
4. Additionally, a pre-disturbance systems study will be performed, taking into account the potential for catastrophic events.

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