Comparison of Transient Stability Enhancement in Power System with Distributed Static Series Compensator Using PI and Fuzzy Logic Controllers

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Abstract

Recent development of power electronics has introduced the use of flexible alternative current transmission system (FACTS) controllers in power systems. High costs and reliability concerns have restricted their use in these applications. The concept of distributed FACTS (D-FACTS) is introduced as a way to remove these barriers. Long distance AC transmission system is often subjected to stability problems which limit the transmission capability A new device, the distributed static series compensator (DSSC), manufactured at low cost with desired power flow control by effectively changing the line reactance This paper aims to enhance the transient stability of the power system with the use of Distributed Static Series Compensator(DSSC).Prototype of two-machine power system has been considered for time domain simulations. Experimental results from a prototype module are presented which approve the DSSC ability for increasing transient stability margin of the power system.

Index Terms— *Flexible AC transmission systems (FACTS), Distributed FACTS (D-FACTS),series compensation, distributed static series compensator (DSSC), transient stability enhancement*

1. Introduction

FACTS devices are based on application of power electronics and high voltage high power converters, which are in series or parallel configurations or a combination of both. These well-known devices effectively increase power handling capacity of the line and improve transient stability as well as damping performance.

Recently a new concept, designated as distributed FACTS (D-FACTS), has been introduced as a possible way to achieve more merits beside those raised by lumped FACTS devices [1]. Distributed Static Series Compensator (DSSC), as a new DFACTS device, is composed of a low-power single-phase inverter which attaches directly to the transmission line conductor [1].

With the aim of improving the transient stability, a supplementary controller has been designed and suitably combined to the main control loop of DSSCs. Simulation results exhibit the efficient influence of DSSCs in the transient stability augmentation and justifies its controller performance.

2. DSSC basic concept

DSSC concept has been originated based on FACTS devices, which is in fact a model of a SSSC but in a smaller size, at a lower price, and with a higher capability. The distributed fashion of the DSSC contributes more safety and improved controllability of power system.

Fig. 1 displays an imaginary schematic of DSSC exploited in a power line so as to control the power flow by changing the line impedance. Each DSSC module is rated at about 10 KVA and is clamped around the line. The individually controlling of each module provides an opportunity to increase or decrease the impedance of the line or to leave it unaltered. With a large number of modules performing together, it will be feasible to yield substantial influence on the overall power flow in the line [4].

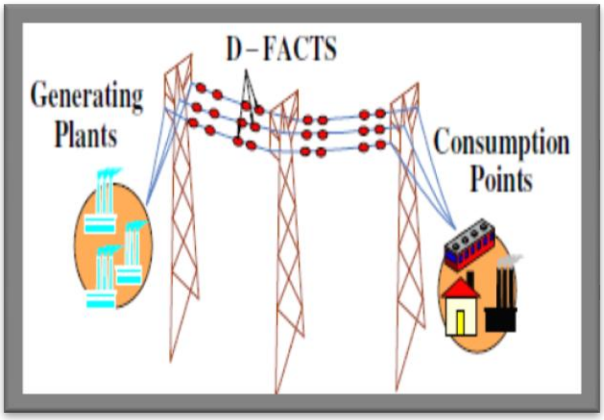
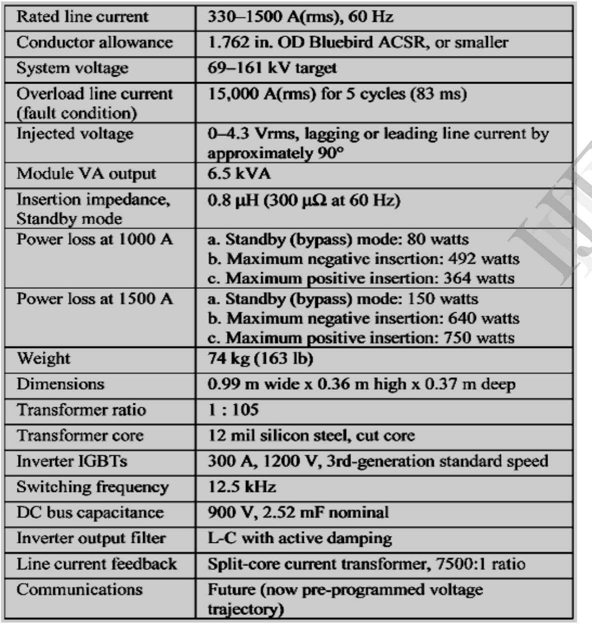


Fig.1: D-Facts deployed on power line

3. Distributed static series compensator (DSSC)

Table.1: Prototype DSSC module specifications



Rated line current	330–1500 A(rms), 60 Hz
Conductor allowance	1.762 in. OD Bluebird ACSR, or smaller
System voltage	69–161 kV target
Overload line current (fault condition)	15,000 A(rms) for 5 cycles (83 ms)
Injected voltage	0–4.3 Vrms, lagging or leading line current by approximately 90°
Module VA output	6.5 kVA
Insertion impedance, Standby mode	0.8 µH (300 µΩ at 60 Hz)
Power loss at 1000 A	a. Standby (bypass) mode: 80 watts b. Maximum negative insertion: 492 watts c. Maximum positive insertion: 364 watts
Power loss at 1500 A	a. Standby (bypass) mode: 150 watts b. Maximum negative insertion: 640 watts c. Maximum positive insertion: 750 watts
Weight	74 kg (163 lb)
Dimensions	0.99 m wide x 0.36 m high x 0.37 m deep
Transformer ratio	1 : 105
Transformer core	12 mil silicon steel, cut core
Inverter IGBTs	300 A, 1200 V, 3rd-generation standard speed
Switching frequency	12.5 kHz
DC bus capacitance	900 V, 2.52 mF nominal
Inverter output filter	L-C with active damping
Line current feedback	Split-core current transformer, 7500:1 ratio
Communications	Future (now pre-programmed voltage trajectory)

The STT is a critical component of the DSSC. It makes the use of the transmission conductor as a secondary winding and is designed with high turn ratio which reduces the current handled by the inverter; hence it will be possible to use commercial IGBTs to realize lower cost [5]. The transformer core is made up of two parts that can be physically clamped around the transmission line to constitute a complete magnetic circuit [6].

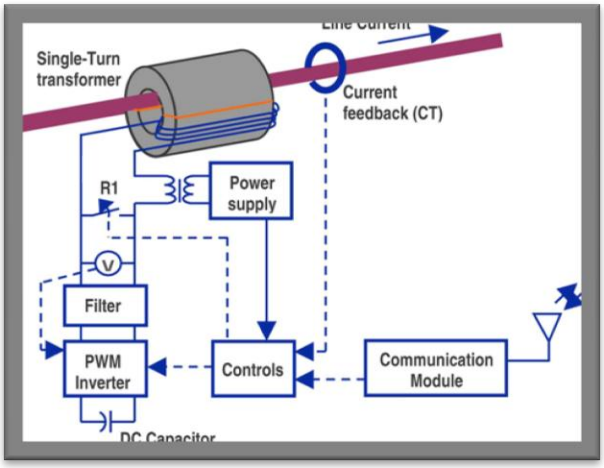


Fig. 2: Circuit schematic of a DSSC module

4.DSSC impact on power flow

For controlling power flow on transmission lines, the series elements clearly have the highest potential and impact. The real and reactive power flow, along a transmission line connecting two voltage buses is governed by the two voltage magnitudes and and the voltage phase angle difference

$$\delta = (\delta_1 - \delta_2),\ \text{as}$$

$$P_{12} = \frac{V_1 V_2 \sin\delta}{X_L}$$

$$Q_{12} = \frac{V_1^2 - V_1 V_2 \cos\delta}{X_L}$$

Where X∟ is the impedance of the line, assumed to be purely inductive. A series compensator is typically used to increase or decrease the effective reactive impedance of the line, thus allowing control of real power flow between the two buses. The impedance changes can be affected by series injection of a passive capacitive or inductive element in the line. Alternatively, a static inverter can be used to realize a controllable active loss-less element such as a negative or positive inductor or a synchronous fundamental voltage that is orthogonal to the line current [8].In the latter case, the power flow depends on the injected qudrature voltage Vq as

$$P_{12}=\frac{V_1\ V_2}{X_L}\sin\delta \pm \frac{V_1\ V_q}{X_L}\cos\left(\frac{\delta}{2}\right)\left[\frac{\sin\left(\frac{\delta}{2}\right)}{\sqrt{\left(\frac{V_1+V_2}{2\ V_2}\right)^2-\frac{V_1}{V_2}\cos^2\left(\frac{\delta}{2}\right)}}\right]$$

where:

V_1 and V_2 = the bus voltage magnitudes;
V_q = the series injected voltage magnitude;
δ = the voltage phase difference; and
X_L = the impedance of the line, assumed to be purely inductive.

The DSSC can simply increase the transmittable power as well as decrease it by reversing the polarity of the injected ac voltage [9]. This is worth noting DSSC salient ability for power flow control in the overall system. The variation of the transmitted power verses load angle with different quadrate voltage injections, for equal bus voltage magnitudes is depicted in Fig. 3.

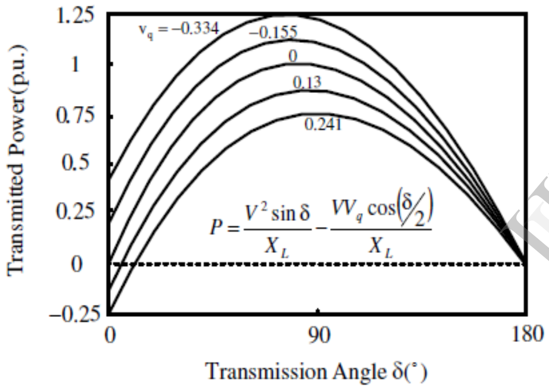


Fig. 3: Variation of transmitted power by Vq injection

5. DSSC control strategy module

Fig.4 exhibits the DSSC control system and SPWM generator. Power circuit includes the inverter, filter circuit, breaker, and transformer. The controller main objective is to hold the charge constant on the dc capacitor and also to inject a voltage that is in quadrature with the line current. A small phase displacement namely, error, beyond the required 90° between the injected voltage and the line current is needed to fix the dc capacitor voltage. The signal obtained by comparing Vdc with Vdc(ref) is passed through a proportional integral (PI) controller which generates the required phase angle displacement or error. The Phase-Locked Loop (PLL) provides the basic synchronization signal, which is the phase angle of the line current [10].

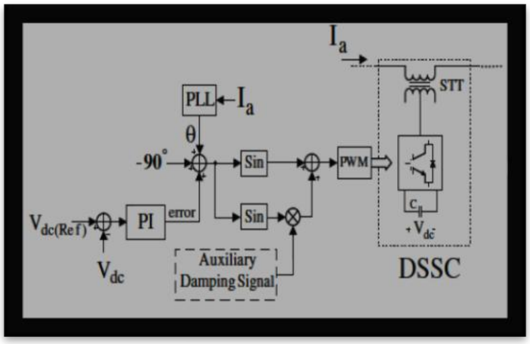


Fig. 4: DSSC control system and SPWM generator

5.1.Single phase inverter structure

DSSC single phase inverter consists of four IGBT devices in a full bridge configuration. The dc link is realized with a fixed capacitor. Also an output LC filter (Lf and Cf) is expected in the output of the inverter to alleviate the harmonic pollution of the injected voltage.

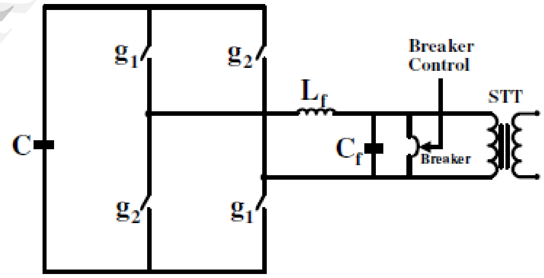


Fig. 5: H-Bridge Inverter

Sinusoidal pulse width modulation (SPWM) technique is well known to offer simplicity and good response for inverter switching strategy. On account of this reason, SPWM is the case which is speculated here.

5.2.DSSC control system

The fundamental task of the DSSC is to control the power flow in a transmission line. This goal can be obtained either by direct control in which both the angular position and the magnitude of the output voltage are controlled, or by indirect control in which only the angular position of the output voltage is to be controlled and the magnitude remains proportional to the dc terminal voltage [11]. The inverters which are directly controlled impose more difficulty and higher cost to be implemented compared to indirectly controlled inverters, also their function is typically correlated with some penalty in terms of increased losses, greater circuit complexity and increased harmonic components in the output. As a consequence, the control scheme used for the DSSC model investigated in this paper is based on indirect control technique [10].

5.2.1. Supplementary POD controller

To be more precise, the DSSC by itself does not provide the essential damping of oscillations as its primary duty is to control the line power flow. With the purpose of achieving better damping over a wide range of operation, a power oscillation damping (POD) controller is added to the main control loop of DSSCs. Fig. 6 shows the POD controller structure.

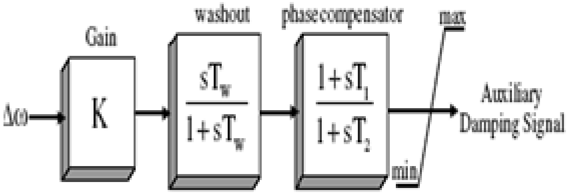


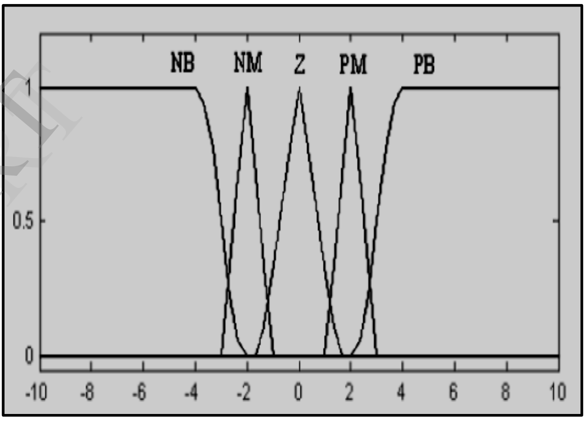
Fig. 6: POD Controller Structure

This figure displays that the damping controller is composed of a gain block, a washout filter, and a lead-lag compensator. The damping controller is designed so as to provide an extra electrical torque in phase with the speed deviation in order to enhance the damping of oscillations [1]. The gain setting of the damping controller is adopted so as to achieve the desired damping ratio of the electromechanical fluctuations. The purpose of the washout circuit is to block the auxiliary controller from responding to the steady-state power conditions. The parameters of the lead-lag compensator are adjusted so that the phase shift between the speed deviation and the resulting electrical torque at the desired frequency is compensated. In the following, an additional electrical damping torque output is acquired in phase with the speed deviation. Here, the parameters of the controller are determined through the simulation studies by a trial-error method with the aim of achieving the best damping. The selection of an appropriate input signal is a fundamental issue in the design of an effective and robust auxiliary damping controller. The output of the auxiliary damping controller is used to modulate the reference setting of DSSC in order to provide the excellent damping [11].

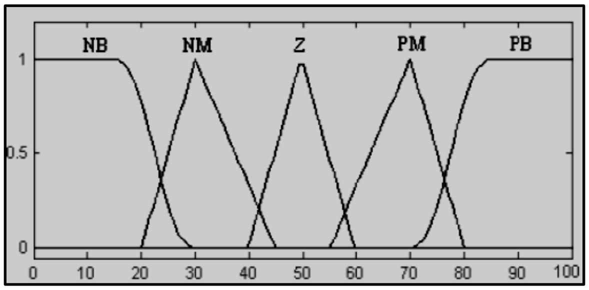
For the work at hand, as illustrated earlier in Fig. 5, the output of the POD controller is utilized to regulate the magnitude of the series injected voltage during electromechanical transients to yield the proper damping of oscillations.

5.2.2. Fuzzy logic controller

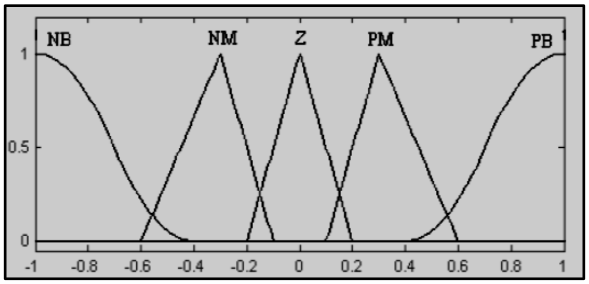
To increase the transient stability of the system, a supplementary fuzzy logic controller based on the Mamdani type fuzzy logic controller was added to the main control loop of DSSCs. Fig. 8 shows how FLC has been added to the main control loop of DSSCs. In the figure, K1, K2, and K3 are 1000, 180/pi and 1.2 respectively. In this case, a two-input, one-output fuzzy logic controller was considered. The input signals for the FLC were the rotor angle difference and angular speed difference between the two machines. The membership functions of the input and output signals are shown



$\Delta W12$ Membership function

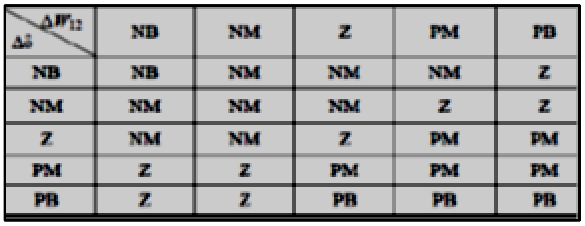


$\Delta\delta$ Membership function



output membership function,

Table. 2: Truth table of fuzzy logic controller



ΔW_{12} / $\Delta\delta$	NB	NM	Z	PM	PB
NB	NB	NM	NM	NM	Z
NM	NM	NM	NM	Z	Z
Z	NM	NM	Z	PM	PM
PM	Z	Z	PM	PM	PM
PB	Z	Z	PB	PB	PB

There are five linguistic variables for each input and output variable, namely, “Positive Big”(PB), “Positive Medium” (PM),”Zero”(Z), ”Negative Medium” (NM), and “Negative Big” (NB). The rule bases used are shown in Table 2 using symbols that are well-known in literature. Generally, FLC generates the required small change amplitude modulation ratio to control the magnitude of the injected voltage based on these rules. The Centroid defuzzification technique was used in this fuzzy controller. DSSC would enhance the transient stability by partial eliminating of the series impedance of the transmission line. The transient stability however, can be more increased by temporarily changing the compensation with supplementary controller combined to the main control loop of DSSCs

6. Simulation model of DSSC

Figure shows the power system considered as the case study in the following simulations. It can be observed that the load center is modeled by a 50 MW resistive load.

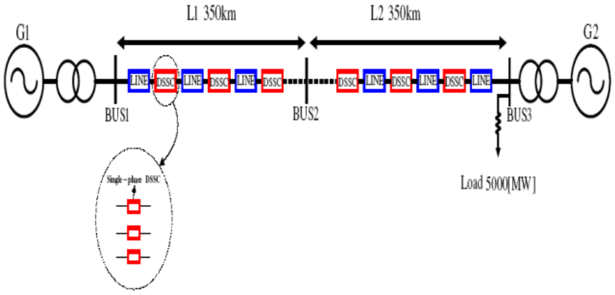


Fig.7: Simulation model of two-machine power system for transient stability study with DSSCs

The load is fed by a local generation of 4000 MW (machine G2) and a remote 1000 MW plant (machine G1) which is connected to the load center through a long 500 kV, 700 km transmission line. The system has been initialized so that then line transmits 950 MW which is close to its surge impedance loading (SIL=977 MW).Vdc(ref) for each DSSC module is fixed at 2 kV, amplitude modulation ratio is set at 0.5, and the turns ratio of STT is 1:100. Consequently, by applying these adjustments, the injected voltage of each DSSC module is anticipated to reach a peak to peak value of 10 V. Regarding that the injected voltage of each DSSC is 10 V

$$X_L = 230\Omega, X_{inj} = -9.5\Omega$$

$$\frac{X_{inj}}{X_L} \times 100 = \%Compensation$$

The negative sign for Xinj *denotes* the capacitive mode of DSSCs to series compensation of the line.

7. Simulation results

7.1. Impact of DSSC on steady state operation point

First of all, 6 DSSCs are considered in the line per phase for achieving %4 compensation. Fig.8 demonstrates that when the DSSCs are out of service, the rotor angle difference, between the two machines is about 20 degrees

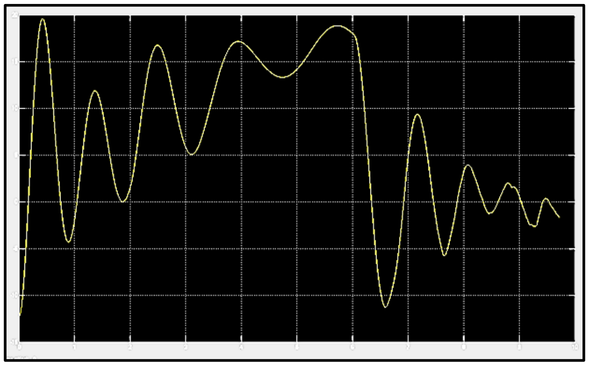


Fig. 8: Rotor angle difference between two generators without DSSC

Typically the line power is assumed to be constant; thus by entering the DSSCs to the power system at t = 6 sec, the series impedance of the line will decrease. As a result, the rotor angle difference is decreased to 12 degrees. For this reason the transient stability margin of the system is improved with compensation

7.2. Three Phase Fault Impact of DSSC without Damping Controller

Here, the DSSCs are initially placed in the circuit, but there is no damping controller on the main control loop, namely Auxiliary Damping Signal is set to zero. The bus1 near the machine G1 is subjected to a three phase to ground fault with duration of 0.085 second. It can be seen that, when the DSSCs are out of service, the rotor angle between the machines is increased rapidly and two machines fall out of synchronism after fault clearing. In contrast, when the DSSCs are in circuit, for the same fault circumstance the system remains stable

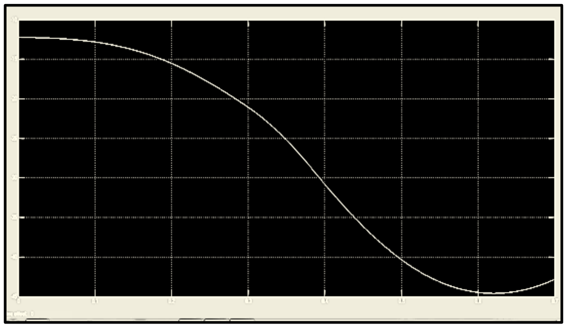


Fig. 9: Rotor angle difference between two generators without POD Controller

7.3.Three Phase Fault Impact of DSSC with Supplementary Controllers

Now the system is subjected to a severe fault with duration of 0.1 sec which is applied again near the bus1.Simulation results are presented. When DSSC lacks a power fluctuations damping controller, the system is completely unstable and two machines fall out of synchronism quickly. Also it can be noticed that when the DSSC control loop includes a power oscillation mitigating controller, the system is kept stable. The rotor angular difference between the two generators varies between 2 to 1 with PI-POD controller.

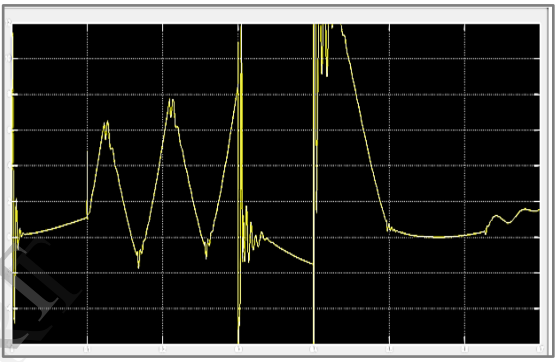


Fig. 10: Rotor angle difference between two generators with PI-POD Controller

The rotor angular difference between two generators varies between 0.085 to 0.13 with FUZZY-POD controller. Thus the transient stability margin of the system is improved with FUZZY-POD controller as compared to PI-POD controller.

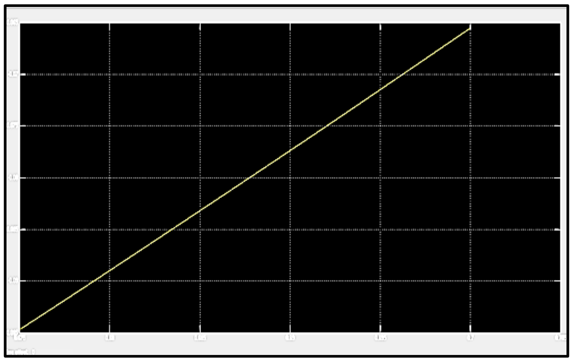


Fig. 11: Rotor angle difference between two generators with FUZZY-POD Controller

8. Conclusion

The distributed devices are apt to accomplish some duties such as transient stability enhancement, power oscillation damping, etc. This study served a review of graphical-based simulation model for the DSSC which is in fact a smaller counterpart of SSSC. A two-machine power system is put under investigation in order to verify the DSSC capability for increasing the transient stability of the whole system. Simulation results demonstrate that when the DSSCs are out of service, the rotor angle between the machines, is increased rapidly and two machines fall out of synchronism after fault clearing. But when the DSSCs are in circuit, they stabilize the system even without a specific controller. In the next, a severe fault is taken to occur in the system. It is shown that for this case, the system even with DSSCs in service becomes totally unstable. Hence, a POD controller is added to the main control loop of DSSC with PI& Fuzzy logic controllers for improving the transient stability margin of the system. Comparative analysis is done between PI & FUZZY by Simulation results that exhibit enhancement of transient stability to the highest degree with FUZZY-POD controller.

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