Journal of Electrical Engineering & Technology Vol. 5, No. 3, pp. 415~422, 2010 ***415***

Transient Stability Enhancement by DSSC with Fuzzy Supplementary Controller

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Abstract – The distributed flexible alternative current transmission system (D-FACTS) is a recently developed FACTS technology. Distributed Static Series Compensator (DSSC) is one example of D-FACTS devices. DSSC functions in the same way as a Static Synchronous Series Compensator (SSSC), but is smaller in size, lower in price, and possesses more capabilities. Likewise, DSSC lies in transmission lines in a distributed manner. In this work, we designed a fuzzy logic controller to use the DSSC for enhancing transient stability in a two-machine, two-area power system. The parameters of the fuzzy logic controller are varied widely by a suitable choice of membership function and parameters in the rule base. Simulation results demonstrate the effectiveness of the fuzzy controller for transient stability enhancement by DSSC.

Keywords: D-FACTS, Simulation model, DSSC, Transient stability, Fuzzy logic controller

1. Introduction

A power system must be considered as a nonlinear system for large disturbances. Although power system stability may be broadly defined according to different operating conditions, one frequently considered important limitation is the problem of transient stability. It is concerned with the maintenance of the synchronism between generators following a severe disturbance [1].

Flexible alternative current transmission system (FACTS) devices are based on the application of power electronics as well as high voltage and high power converters, which are in a series, parallel, or a combination of both. These devices increase the power handling capacity of the line and improve transient stability and damping performance of the power system [2]-[8]. However, these devices have some limitations when used in power systems. Significant barriers limit the widespread commercial deployment of FACTS. Ratings of FACTS devices are often in the 100 MW range, with system voltages of 138 to 500 kV. Further, series injection devices, such as TCSC and SSSC, require platforms or custom transformers for isolation and must handle fault voltages and currents. This approach to system implementation has resulted in large and complex converter installations and barriers that have, so far, limited the commercial success of FACTS technology. These include:

- High cost resulting from device complexity and component requirements;
- Single point of failure causing the entire system to shut down;
- Maintenance and on-site repair requirements for a complex custom-engineered system adding significantly to system operating cost and increasing mean time to repair (MTTR);
- Lumped nature of system and initial over-rating of devices to accommodate future growth provides poor return on investment (ROI); and
- Custom engineered nature of the system resulting in long design and build cycles that, in turn, lead to high system cost that could not be easily scaled down with volume [9].

Recently, a new concept from the family of distributed FACTS (D-FACTS) has been introduced as a way to remove these barriers [9]. The distributed nature of the suggested system makes it possible to achieve fine granularity in the system rating. Moreover, it is possible to expand the system with the growing demand. This gives a salient benefit in planning the system, which allows the planner to have control on available transfer capacity (ATC). It is done in a way that the growing needs in power transfer (equal to 2% for every year) are satisfied by installing new D-FACTS modules in the line for 10 years; this is done in order to meet project growth needs without having to invest all the capital at the start of the project implementation.

The concept of distributed static series compensator (DSSC) is based on the use of a low-power single-phase inverter, which attaches to the transmission conductor and dynamically controls the impedance of the transmission line, allowing the control of active power flow on the line [10]. The DSSC concept overcomes most of the serious limitations of FACTS devices and points the way to a new approach for achieving power flow control.

In the literature, few studies have focused on the DSSC modeling and its capabilities. For example, [19] presents a graphical simulation model for DSSC, in which only a single DSSC has been placed in a single-phase system with ideal voltage source and without any generator.

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Received: April 17, 2010; Accepted: June 29, 2010

In this study, 1400 DSSCs is placed in a two-area, two-machine power system to study transient stability of the system. In order to improve transient stability, a supplementary fuzzy logic controller is added to the main control loop of DSSCs.

Fuzzy logic provides a general concept for description and measurement. Most fuzzy logic systems encode human reasoning into a program to arrive at decisions or to control a system [11], [12]. Fuzzy logic comprises fuzzy sets, which is a way of representing non-statistical uncertainty and approximate reasoning, including the operations used to make inferences in fuzzy logic [13], [14].

In recent years, fuzzy logic control (FLC) with its capabilities, has been applied to the supplementary control design of FACTS devices for transient stability enhancement of a power system [15].

Simulation results show that the fuzzy logic supplementary controller has an effective influence on transient stability enhancement. Subsequently, a conventional classic supplementary controller has been substituted for FLC. By comparing the simulation results for these two kinds of controller, it is deduced that the FLC has a better effect in transient stability enhancement and power oscillation damping.

2. DSSC Concept

The DSSC concept has been expressed based on FACTS devices; it is, in fact, an SSSC model but with a smaller size, lower price, and higher capability. For improved safety and controllability of power system, it is placed in a transfer lines in a distributed manner.

Fig. 1 shows a conceptual schematic of DSSC deployed in a power line so as to alter the power flow by changing the line impedance. Each module is rated at about 10 KVA and is clamped, floating electrically and mechanically on the line. Each module can be controlled so as to increase or decrease the impedance of the line or leave it unaltered. With a large number of modules operating together, it is possible that significant impact on the overall power flow in the line is obtained [16].

The low VA ratings of the modules are in line with mass manufactured power electronics systems in the industrial drives and UPS markets, suggesting the possibility of realizing an extremely low cost. Finally, the use of a large number of modules results in high system reliability because system operation is not compromised by the failure of a small number of modules [16].

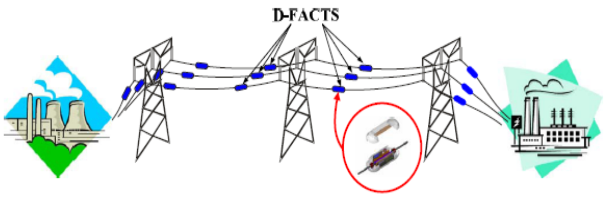


Fig. 1. D-FACTS deployed on the power line.

A DSSC module consists of a small rated single phase inverter (10 KVA) and a single turn transformer (STT) along with associated controls, power supply circuits, and built-in communications capability (Fig. 2) [17]. System commands for gradual changes are received from a central control center using a wireless or power line communication (PLC) technique [18].

The STT is a key component of the DSSC. It uses the transmission conductor as a secondary winding and designed with high turn ratio, which reduces the current handled by the inverter and allows the use of commercial *insulated gate bipolar transistors* (IGBTs) to realize low cost [19]. The transformer core consists of two parts that can be physically clamped around a transmission line to form a complete magnetic circuit [20].

The module can either be suspended from the conductor or configured as a replacement for the conductor support clamp on an insulator. Further, since the module does not require supporting phase–ground insulation, it can easily be applied at any transmission voltage level. The mechanical form of the module may either be clipped on to the conductor or incorporated into the insulator suspension clamp, avoiding any concern about weight and conductor vibration damage [9].

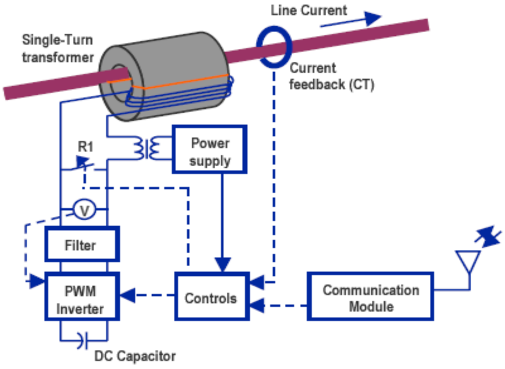


Fig. 2. Circuit schematic of a DSSC module.

3. Influence of DSSC on Power Flow

The DSSC is connected in series to the transmission line and has the ability of injecting a synchronous fundamental voltage, which is orthogonal to the line current directly into the transmission conductor. Therefore, the transmitted power becomes a parametric function of the injected voltage (Vq) and can be expressed as [20]:

$$P_{12}=\frac{V_1\ V_2}{X_L}\sin\delta-\frac{V_1\ V_q}{X_L}\cos\left(\frac{\delta}{2}\right)\left[\frac{\sin\left(\frac{\delta}{2}\right)}{\sqrt{\left(\frac{V_1+V_2}{2\ V_2}\right)^2-\frac{V_1}{V_2}\cos^2\left(\frac{\delta}{2}\right)}}\right], \quad (1)$$

where:

V1 and V2 = the bus voltage magnitudes;
δ = the voltage phase difference; and
XL = the impedance of the line, assumed to be purely inductive.

The DSSC can increase and decrease the transmittable power, simply by reversing the polarity of the injected ac voltage. Fig. 3 shows the variation of the transmitted power verses phase angle with different quadrate voltage injections for equal bus voltage magnitudes [21].

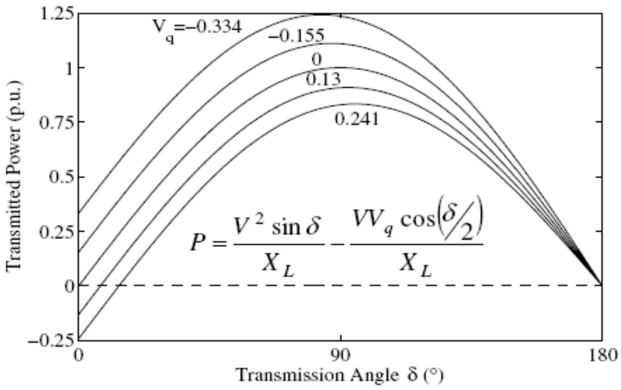


Fig. 3. Variations of transmitted power by quadrate voltage injection

4. Simulation Model

This section presents a graphic-based simulation model for the DSSC, which is suitable for further operational analysis of this device.

4.1 Inverter Model

The single-phase inverter of a DSSC consists of four IGBT devices in a full bridge configuration, along with an output LC filter and a dc bus capacitance (Fig. 4).

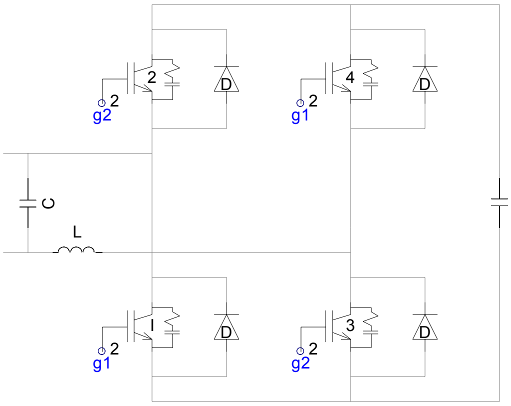


Fig. 4. Inverter of a DSSC.

The inverter switching strategy is based on a sinusoidal pulse width modulation (SPWM) technique, which offers simplicity and good response.

4.2 Control System

The primary function of the DSSC is to control the power flow in a transmission line. This objective can be achieved either by direct or indirect control; in the former, both the angular position and the magnitude of the output voltage are controlled, while in the latter, only the angular position of the output voltage is controlled and the magnitude remains proportional to the dc terminal voltage [22].

Directly controlled inverters are more difficult to operate and cost higher compared with indirectly controlled inverters. In addition, their function is usually associated with some penalty in terms of increased losses, greater circuit complexity, and increased harmonic content in the output. Therefore, the control structure used for the DSSC model presented in this paper is based on indirect control technique [19].

The purpose of the controller is to retain the charge on the dc capacitor and to inject a voltage, which is in quadrate with the line current. The dc capacitor voltage control is achieved by a small phase displacement, e, beyond the required 90° between the injected voltage and the line current. The phase-locked loop (PLL) provides the basic synchronization signal, θ, which is the phase angle of the line current. The error signal obtained by comparing Vdc with Vcref passes through a proportional-integral (PI) controller, which generates the required phase angle displacement or e [19].

5. Final DSSC Model

Fig. 5 shows the DSSC power circuit including inverter, transformer, filter circuit, and breaker. Fig. 6 shows the control system and sinusoidal PWM generator.

The simulation mode shown in Fig. 7 allows the user to define the essential control parameters of the module that are useful in controlling a number of DSSCs as a group; in

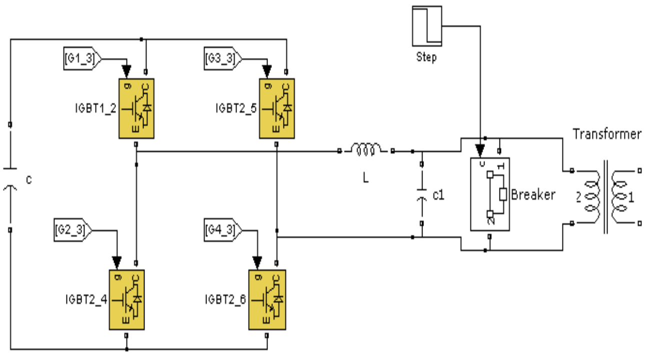


Fig. 5. DSSC power circuit.

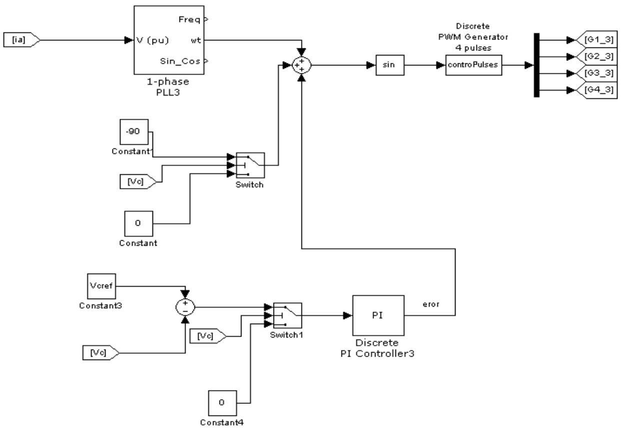


Fig. 6. DSSC control system and sinusoidal PWM generator.

turn, this realizes the active control of power flow on a transmission line. The definitions of the parameters are summarized in Table 1.

Vcref for each DSSC module is 2 KV, amplitude modulation ratio is set at 0.5, and the turns ratio of STT is 1:100. By adjusting these parameters, the injected voltage of each DSSC module is expected to reach a peak to peak value of 10 V.

Table 1. Definitions of user-defined DSSC model

U_{1D} & U_{2D}	Connections to the line
V_{cref}	DC bus voltage reference
T on	DSSC operation start time
T off	DSSC operation end time

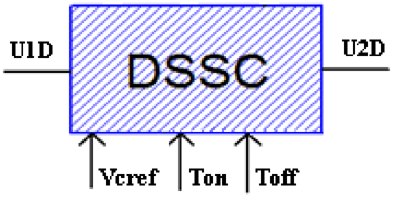


Fig. 7. User-defined DSSC simulation mode.

6. Enhancement of Transient Stability with DSSC

Fig. 8 shows the power system, which is used in subsequent simulations. A 1000 MW hydraulic generation plant (machine M1) was connected to a load center through a long 500 KV and 700 km transmission line. The load was modeled by a 5000 MW resistive load and was fed by the remote 1000 MW plant and a local generation of 5000 MW (machine M2). The system was initialized so that the line carries 950 MW, which was close to its surge impedance loading (SIL=977 MW).

DSSC can improve the transient stability by partial cancellation of the series impedance of the transmission line. In this work, the transmission line was series-compensated with DSS in order to increase system stability, thereby decreasing the series impedance of the line and increasing the maximum transmittable power.

Vcref for each DSSC module is 2 KV, amplitude modulation ratio is set at 0.5, and the turns ratio of STT is 1:100. By adjusting these parameters, the injected voltage of each DSSC module is expected to reach a peak to peak value of 10 V.

The injected voltage of each DSSC is 10 V peak to peak, according to Equation (2) for %4 compensation on transmission line, 1400 DSSCs are placed in each phase of the line. Fig. 8 shows the DSSCs in the transmission line.

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

$$\frac{X_{inj}}{X_L} \times 100 = \%Compensation \tag{2}$$

However, during the severe faults, the transient stability can be increased further by temporarily changing the compensation with a supplementary controller added to the main control loop of the DSSCs. The controller for the duration of the first acceleration period of the machine increases the transmitted power by increasing the injected voltage of DSSCs, which results in the decrease in the line impedance. Further, in the length of the deceleration period of the machine, the controller operates inversely and increases the deceleration of the machine. This supplementary controller may be classic, neural network, fuzzy logic controller, and so on. The proposed controller is a fuzzy logic supplementary controller for the DSSCs in order to improve the power system transient stability.

6.1 DSSC with Fuzzy Supplementary Controller

To increase the transient stability of the system, a supplementary fuzzy logic controller based on the Mamdani

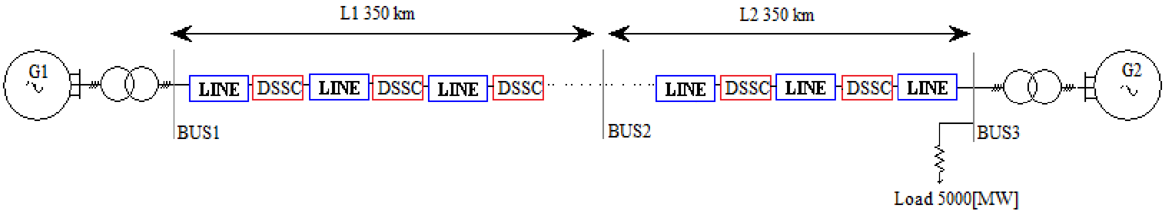


Fig. 8. Simulation model of two-machine system for transient stability study with DSSC.

type fuzzy logic controller was added to the main control loop of DSSCs. Fig. 9 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 in Fig.10.

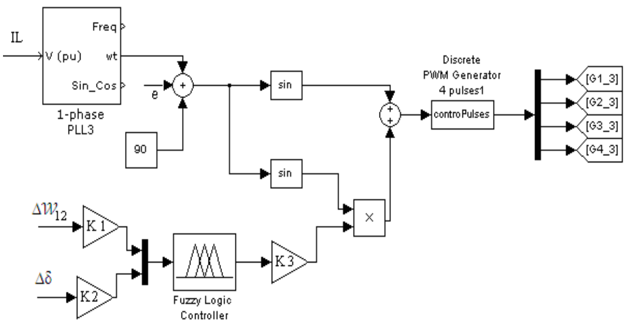
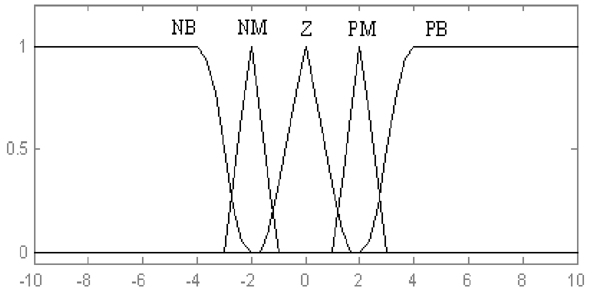
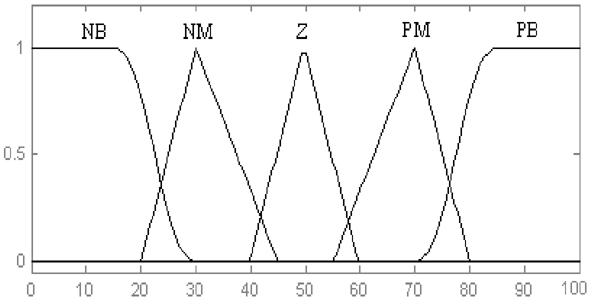


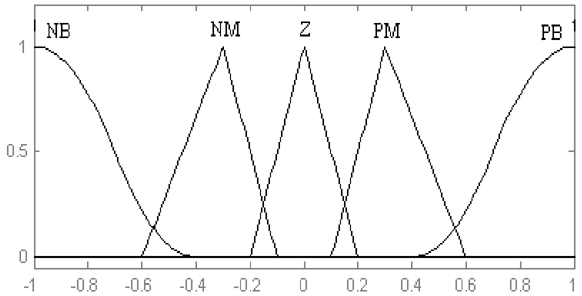
Fig. 9. Adding FLC to DSSC controller.



(a) ΔW_{12} Membership function



(b) Δδ Membership function



(c)

Fig. 10. (a), (b) inputs membership function, (c) output membership function.

Table 2. Rule Table of the Fuzzy Logic Controller

ΔW_{12} / Δδ	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 defuzzyfication technique was used in this fuzzy controller.

7. Simulation Results

7.1 Steady State Operation Point

Initially, 1400 DSSCs were placed in the line per phase for achieving %4 compensation. The rotor angle difference, d_theta1_2, between the two machines was about 53 degrees when the DSSCs were out of service (Fig. 11). When DSSCs were entered to the circuit, according to Equation (3), the rotor angle difference d_theta1_2 decreased to 51.8° because the power of the line is constant and the series impedance of the line is decreased. For this reason, the transient stability margin of the system is improved with compensation.

$$P_{12} = \frac{V_1 \; V_2}{X_L} \; Sin \; \delta \qquad (3)$$

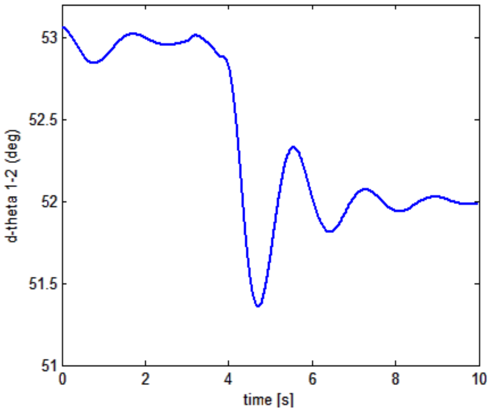


Fig. 11. Changing the rotor angle difference (d_theta1_2) when the DSSCs entered the circuit.

7.2 Three Phase Fault – Impact of DSSC without Damping Controller on Transient Stability Enhancement

In this condition, DSSCs entered the circuit, but there was no damping controller on the control system of such DSSCs. A three-phase fault with duration of 0.085 s was applied in bus1 near machine M1. The impact of DSSCs in stabilizing the system during the fault can be observed. When the DSSCs were out of service, the rotor angle between the machines increased rapidly and two machines fell out of sync after fault clearing. However, when the DSSCs were in circuit, the system was stable at the same fault. These are illustrated in Figs. 12 and 13.

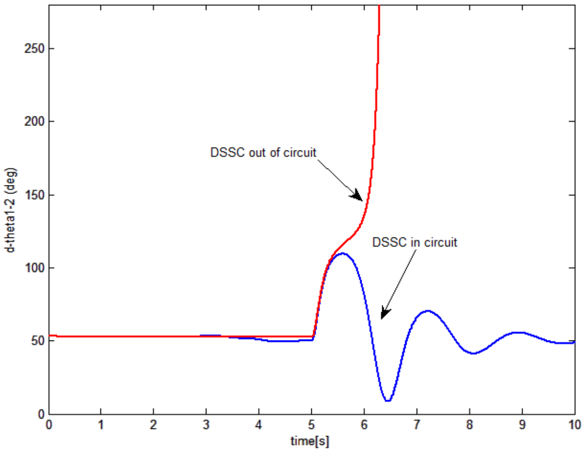


Fig. 12. Changing the rotor angle difference (d_theta1_2) after the fault with DSSC (without supplementary fuzzy logic damping controller) and without DSSC.

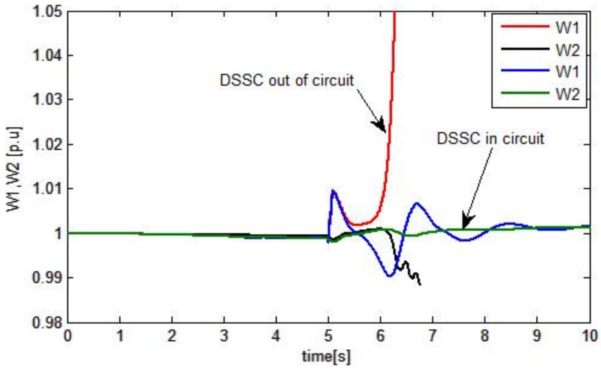


Fig. 13. Changing the angular speed of the machines after the fault with DSSC (without supplementary fuzzy logic damping controller) and without DSSC.

7.3 Three Phase Fault – Impact of DSSC with Supplementary Classic Controller and Fuzzy Logic Controller on Transient Stability Enhancement

Two types of supplementary damping controller including classic and fuzzy logic controller were added to the main control loop of DSSCs. To show the ability of each controller in transient stability and damping of oscillations in power system, a 3-phase to ground fault with duration of 0.08 s was applied in bus1. Figs. 14 and 15 show the simulation results. With respect to these figures, it is seen that the DSSCs with classic or fuzzy supplementary controller damps the oscillations after fault; however, the DSSCs with fuzzy controller showed a higher influence in oscillation damping in comparison with the classic controller.

In the next section, a 3-phase to ground fault with duration of 0.09 s was applied in bus1. Figs. 16 and 17 show the simulation results. In this case, the DSSCs are in service in three states, without supplementary damping controller, but with classic supplementary damping controller and fuzzy logic damping controller. These figures show that in two states including DSSCs. i.e., with the absence of damping controller and DSSCs and presence of classic damping controller, the system is completely unstable after a severe fault. It can be seen that two machines fell out of sync quickly. When DSSCs are equipped with a supplementary fuzzy logic controller, however, the system became stable after a severe fault.

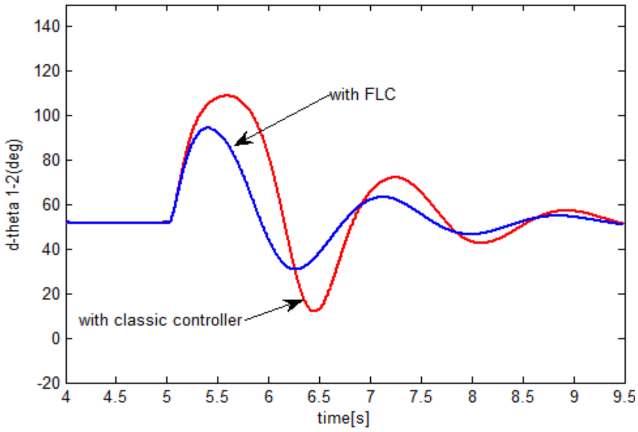


Fig. 14. Rotor angle difference (d_theta1_2) deviation after the fault with FLC and classic controller.

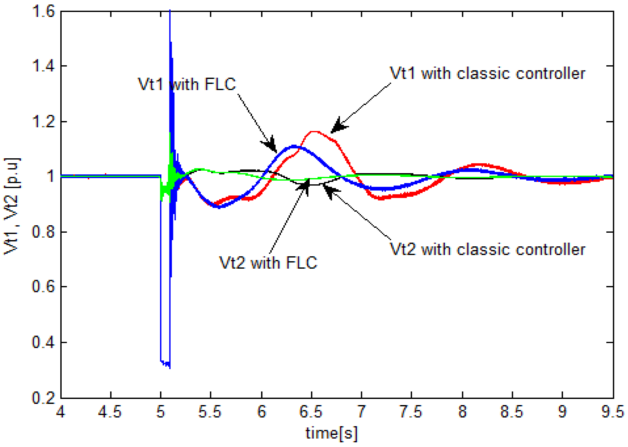


Fig. 15. Machine voltage variation after the fault with FLC and classic controller.

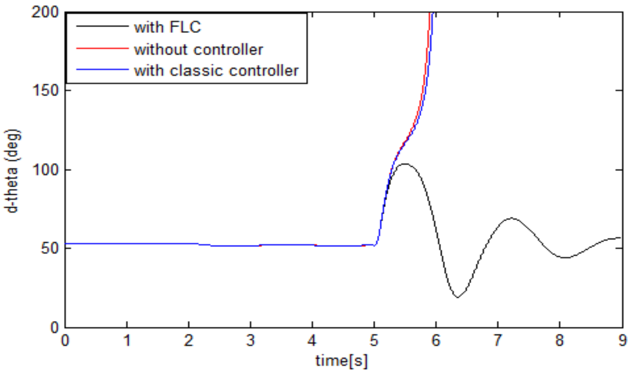


Fig. 16. Rotor angle difference (d_theta1_2) deviation after the fault with FLC and classic damping controller and without damping controller.

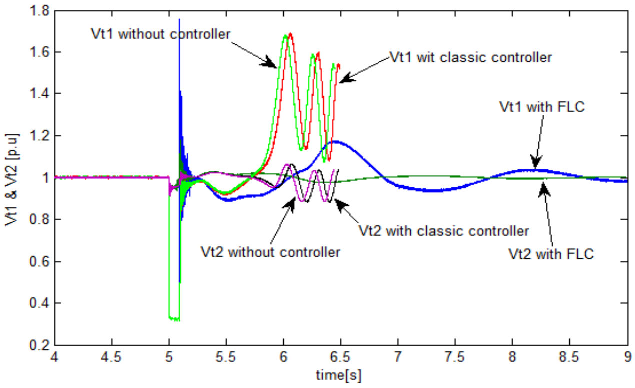


Fig. 17. Machine voltage variation after the fault with FLC and classic damping controller and without damping controller.

Fig. 18 shows the variation of FLC output signal after the fault in terms of transient stability enhancement of the system.

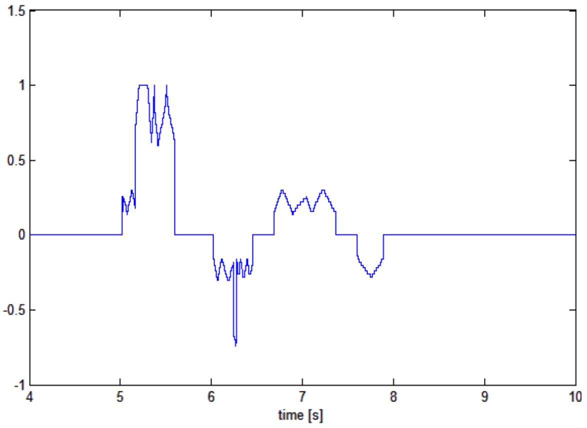


Fig. 18. Variation of FLC output signal after the fault.

8. Conclusion

In this study, we introduced a graphical-based simulation model of the DSSC. DSSC was placed in a sample two-machine power system to increase transient stability. Simulation studies presented in the paper showed that when the DSSCs were out of service, the rotor angle between the machines (d_theta1_2) increased rapidly and two machines fell out of synchronism after fault clearing. However, when the DSSCs were in circuit, DSSCs stabilized the system even without specific controller. Subsequently, an FLC was added to the main control system of the DSSC in order to improve the transient stability margin of the system. The simulation results show that specific to this case, DSSC can stabilize the system under severe fault. Moreover, a comparative study between the FLC and conventional classic controller shows that the proposed FLC has better performance and influence in transient stability enhancement and oscillation damping

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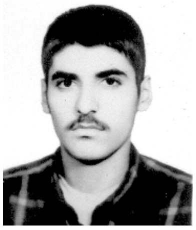

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