**Indian Journal of Science and Technology,** *Vol 9(34), DOI: 10.17485/ijst/2016/v9i34/91317, September 2016*
*ISSN (Print) : 0974-6846*
*ISSN (Online) : 0974-5645*

# Comparative Study of FACTS Devices for Mitigation of Voltage Sag-Swell in Distribution System

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## Abstract

**Objectives:** In this paper, performance comparison of various FACTS devices has been carried out for mitigating voltage sag/swell and also balancing the active and reactive power of the system. **Methods/Statistical Analysis:** Fuzzy logic controller has been incorporated in shunt and series converter control of FACTS devices. The system stability performance with different FACTS devices has also been studied using Integral of Squared Error (ISE) performance index. Simulation has been carried out in MATLAB/SIMULINK environment. **Findings:** It has been found that multiline FACTS devices perform better as compared to single line FACTS devices during the voltage compensation and power quality improvement. **Application/Improvements:** FACTS devices can improve the system performance by controlling the power flow and bus voltages of system and thus maintaining the power system quality and stability.

**Keywords:** Distribution System, FACTS, Fuzzy Logic, Power Quality, Voltage Sag, Voltage Swell

## 1. Introduction

Ever since the evolution of the science and electricity in this world, the electric power requirements kept on increasing to placate our advanced life style, which in turn has resulted as liability on the transmission and distribution network[1].

Increased consumption of electrical energy is a consequence of implementation of power electronic devices, industrial growth, high technology communication devices, control and automation, and on-line service with advanced control. All these factors have made power quality and stability an utmost important research area. To maintain the voltage supply on the receiving end within standard limits should be the prime criterion during design. These days interconnected networks must run coherently to avoid the adverse consequences due to a failure in any component[2,3].

During the last decades worldwide blackouts have increased the challenge for competitive electricity market to achieve power quality crucially[4]. Ultimately to maintain the stability and the quality of electric power, the transmission and distribution system has to operate in the vicinity of their preset limits while serving the load even during the increased demands[5]. Therefore economic distribution and transmission systems are required to transfer bulk power to consumers[6].

Flexible Alternating Current Transmission Systems (FACTS) technology was introduced firstly in the 1980s as remedy to overcome the various power quality problems. Generally VSC (voltage source converter) based FACTS devices can control various variables like the power flow and bus voltages of system. FACTS devices can be deployed differently in the system on the basis of their arrangements, for example single series converter based devices like Dynamic Voltage Restorer (DVR), single shunt converter based devices like Distribution static compensator (D-STATCOM), combined series-series devices like Interline Power Flow Controller (IPFC) and combined series-shunt devices like Unified Power Flow Controller (UPFC) and Generalised Unified Power Flow Controller (GUPFC). D-STATCOM can be

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considered as special case of GUPFC whereas DVR can be said as a special case of IPFC. However UPFC is said to be the more simplified version of GUPFC, in which a D-STATCOM is installed for shunt reactive compensation and for active and reactive compensation a separate series converter is installed. Multi-line FACTS devices like IPFC and GUPFC are installed for compensating two or more lines combining multiple converters and thus overcoming UPFC[7-13].

Among various working modes of operation, GUPFC's shunt converter normally operates in voltage control mode and the series converters operate in power flow control mode. Mainly GUPFC extends the concepts of UPFC and IPFC. In contrast to UPFC, the Generalised Unified Power Flow Controller provides two more degrees of freedom via extra series converter added[14-16].

The present paper has been organized as follows: Section 2 provides a brief description of the different FACTS devices considered in this study. Section 3 presents brief summary of the implemented control architecture based on fuzzy logic. Integral of Squared Error performance index is defined in Section 4. Simulation results are presented and analyzed in Section 5. Lastly, conclusions are drawn in Section 6.

## 2. FACTS Devices under Consideration

In this paper five FACTS devices are considered for the comparative study and their connection topologies are as follows:

### 2.1 Dynamic Voltage Restorer (DVR)

It is a single VSC based device which is connected in series with the system as shown in Figure 1.

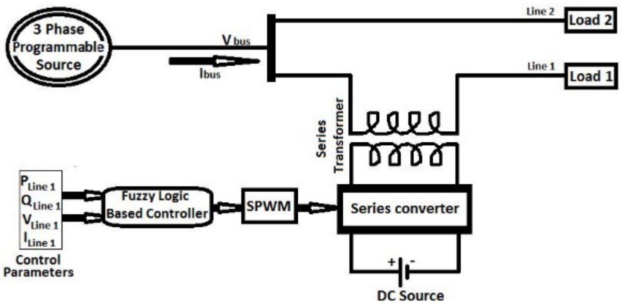

**Figure 1.** DVR.

### 2.2 Distribution static compensator (D-STATCOM)

It is a single shunt VSC based device and attached to system as per Figure 2.

### 2.3 Interline Power Flow Controller (IPFC)

It is a multiline VSC based series-series FACTS device sharing a common dc link, and is installed in the system as in Figure 3.

### 2.4 Unified Power Flow Controller (UPFC)

It is single line VSC based series-shunt compensating device sharing a common dc link and connected as shown in Figure 4.

### 2.5 Generalised Unified Power Flow Controller (GUPFC)

It is the latest generation multi line combined (single shunt and 'n' series) compensating device where 'n' is number of lines. It can be installed as in Figure 5.

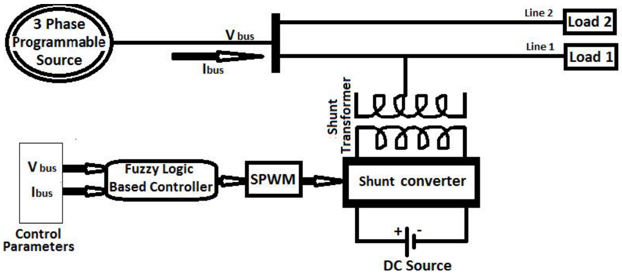

**Figure 2.** D-STATCOM.

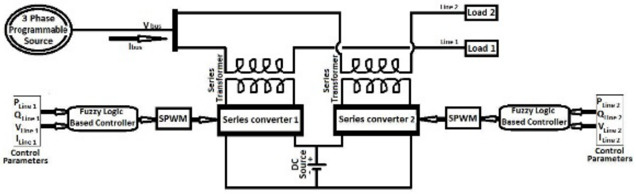

**Figure 3.** IPFC.

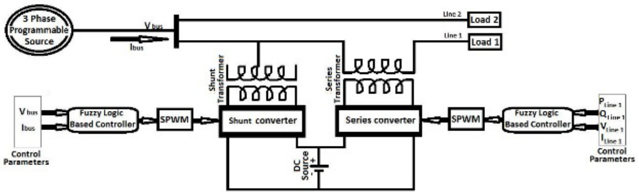

**Figure 4.** UPFC.

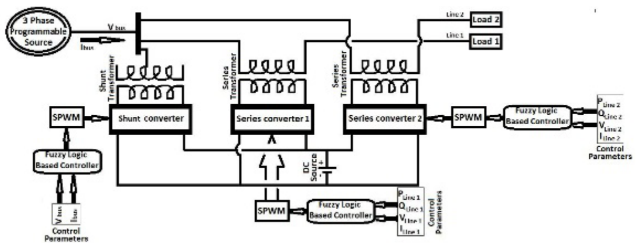

**Figure 5.** GUPFC.

## 3. Fuzzy Logic based Control

Various artificial intelligence techniques have been used in controlling the FACTS devices and the most widely implemented controller technique is fuzzy logic since 20 years. Basic function of fuzzy logic controller is to generate an appropriate fuzzy output for a fuzzy input given to it by following the series of steps in fuzzy inference system[17,18].

In this study the fuzzy logic controller is implemented in both the shunt and series converter controller. Fuzzy output is given to sinusoidal pulse width modulator (SPWM) so as to generate pulses for respective VSC.

### 3.1 Shunt Converter Control

Voltage and current of main bus are controlled during the shunt compensation.

### 3.2 Series Converter Control

Control design of series converter being used here is to control parameters: P, Q, V and I of that particular line.

### 3.3 Membership Functions

### *3.3.1 Error*

Membership function for error input has been shown in Figure 6.

### *3.3.2 Error rate*

Membership function for error rate input can be represented as shown in Figure 7.

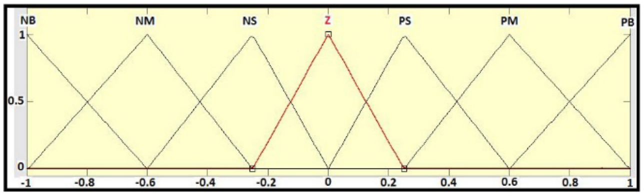

**Figure 6.** Membership function for error signal.

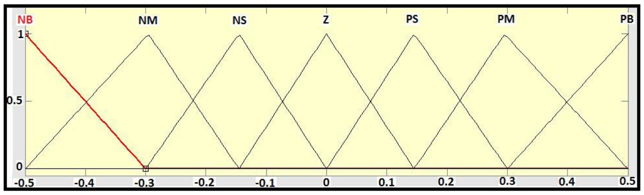

**Figure 7.** Membership function for error-rate signal.

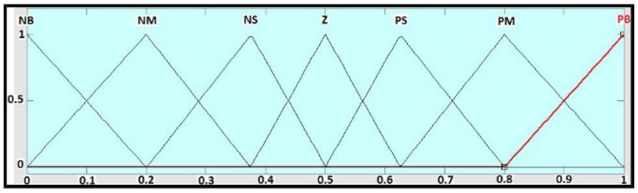

**Figure 8.** Membership function for output signal.

**Table 1.** Fuzzy rule base

| Error rate\ Error | ***NB*** | ***NM*** | ***NS*** | ***Z*** | ***PS*** | ***PM*** | ***PB*** |
|---|---|---|---|---|---|---|---|
| ***NB*** | NB | NB | NB | NM | NM | NS | Z |
| ***NM*** | NB | NB | NM | NM | NS | Z | PS |
| ***NS*** | NB | NM | NM | NS | Z | PS | PM |
| ***Z*** | NM | NM | NS | Z | PS | PM | PM |
| ***PS*** | NM | NS | Z | PS | PM | PM | PB |
| ***PM*** | NS | Z | PS | PM | PM | PB | PB |
| ***PB*** | Z | PS | PM | PM | PB | PB | PB |

### *3.3.3 Output*

Membership function for output has been shown in Figure 8.

Fuzzy rules implied in this work are given in Table 1.

## 4. Performance Index

The effectiveness of a controller is measured with the help of performance indices. ISE performance index is easy to simulate and it gives the performance over a considerable simulation time period which is useful in any deviation from the minimum of squared error[19,20]. Mathematically ISE for any error (e) can be expressed as below:

$$ISE = \int_{0}^{\infty} e^2(t)dt \tag{1}$$

In the present investigation, ISE has been implemented on value of voltage magnitude (in p.u).

## 5. Simulation Results

During this study two major power quality problems have been considered; i) voltage sag and ii) voltage swell in a distribution system. A distribution system with three phase supply of 11 KV having two identical loads of 500KW connected to different lines is considered (system without voltage sag/swell) and is shown in Figure9. MATLAB/SIMULINK is used for obtaining the simulation results for simulation time of 1second.

The parameters like voltage, real & reactive power and integral of squared error are measured as below:

These results are used as reference for comparing with the results obtained from different FACTS devices installed consecutively in the system. ISE performance index has been used for extended performance comparison between these devices. The ISE value obtained i.e 0.02(for both loads) is taken as reference value for all FACTS device cases.

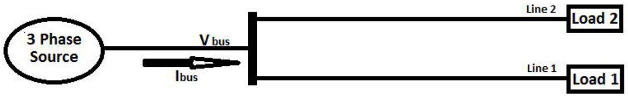

**Figure 9.** Base System.

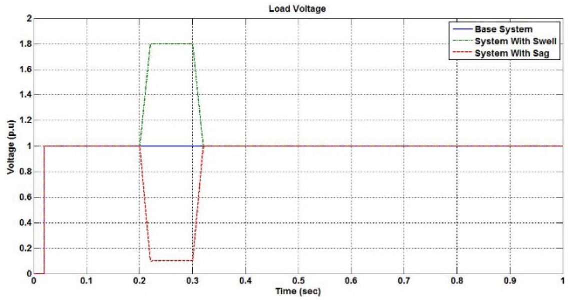

**Figure 10.** Voltage across loads.

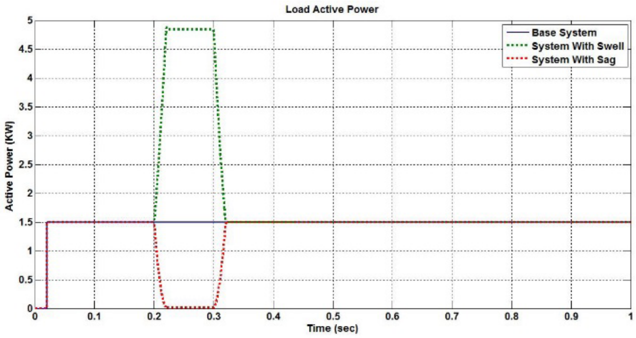

**Figure 11.** Active power across loads.

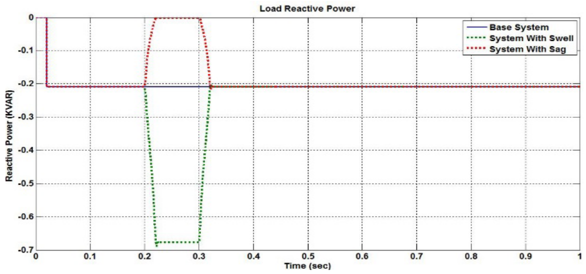

**Figure 12.** Reactive power across loads.

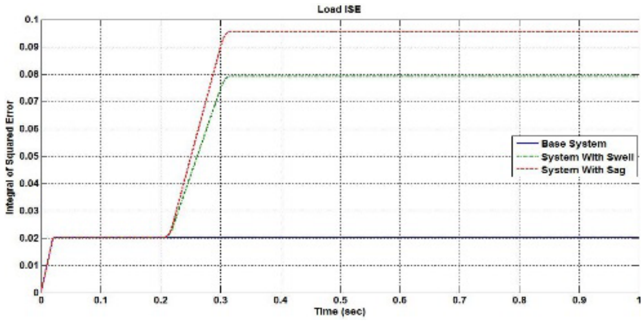

**Figure 13.** Integral of squared error across loads.

### 5.1 System with Voltage Sag

Three phase programmable source has been used to introduce voltage sag of (-0.9 p.u) in the system, being the maximum limit of voltage sag from 0.2sec to 0.3 sec.

Its simulation results are as follows:

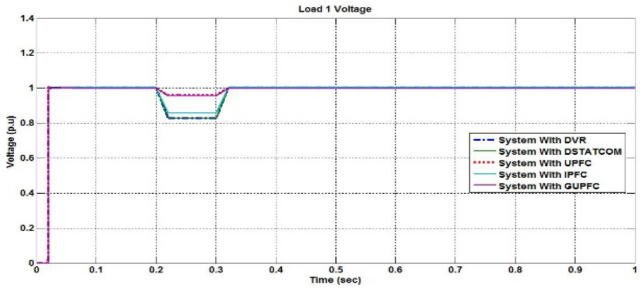

**Figure 14.** Voltage across load 1.

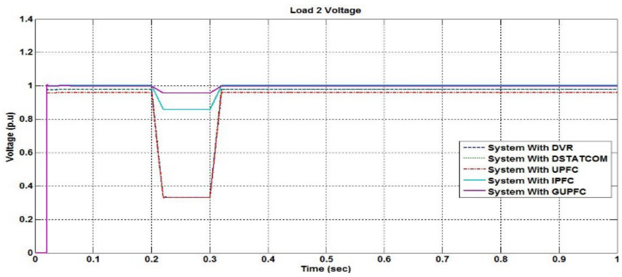

**Figure 15.** Voltage across load 2.

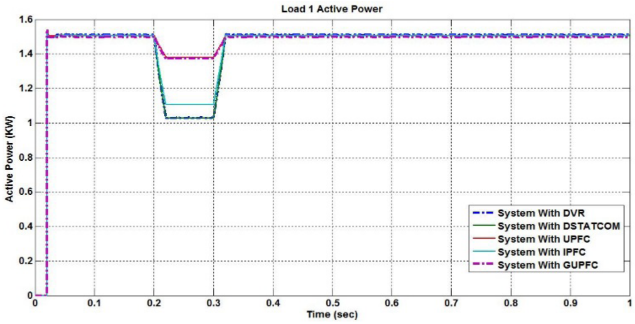

**Figure 16.** Active power across load 1.

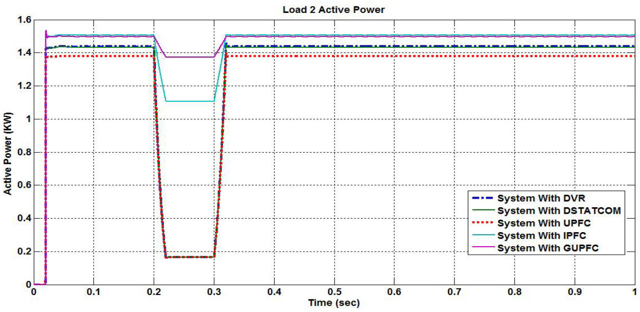

**Figure 17.** Active power across load 2.

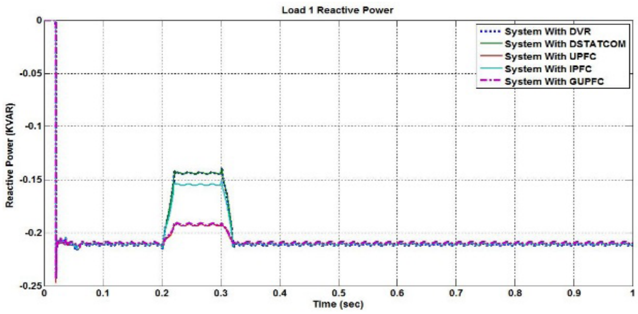

**Figure 18.** Reactive power across load 1.

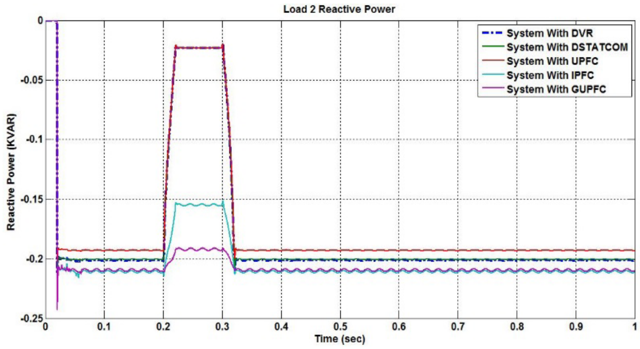

**Figure 19.** Reactive power across load 2.

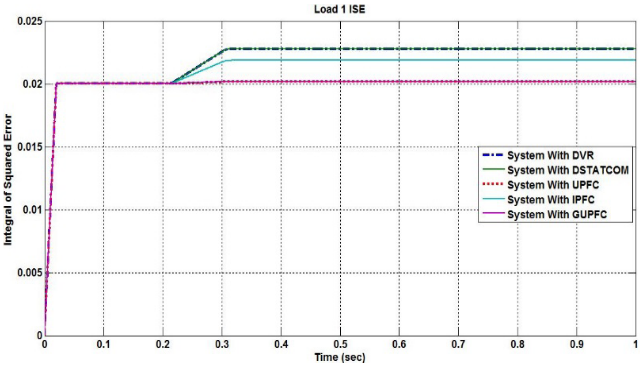

**Figure 20.** Integral of squared error across load 1.

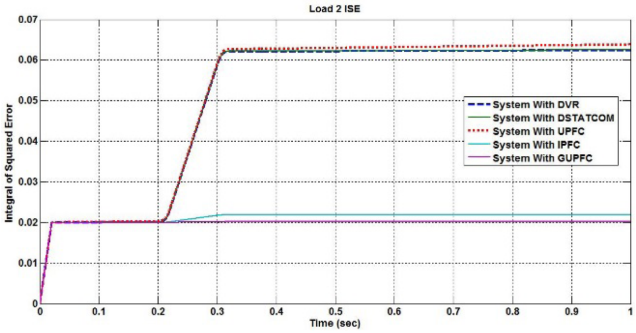

**Figure 21.** Integral of squared error across load 2.

From Figure10 to Figure13, it can be observed that when voltage sag is introduced in the system then during that interval, the active and reactive power flow also gets effected and the system performance gets hampered. Refer Figure 14 to Figure 21 when the single line FACTS device is installed in line 1, then there is quite similar sag compensation done by DVR and DSTATCOM for line 1 but UPFC gives best performance as compared to DVR and DSTATCOM which can be depicted from the results. However small amount of compensation is also achieved for line 2 by using these single line FACTS devices but there is slightly reduced overall voltage magnitude for line 2. When the multiline FACTS device is connected to the system, both the load lines get equally compensated. As compared to DVR, DSTATCOM and UPFC, the GUPFC and IPFC give better voltage sag compensation. Table 2 gives the performance index values for different FACTS devices being installed in the system in case of voltage sag. When the sag is introduced to the system then ISE value for both load lines rises from 0.02 to 0.09568 and thus system performance reduces. Out of all five FACTS devices, GUPFC gives best performance in voltage sag compensation and power quality improvement as well,

**Table 2.** ISE Performance Index for Voltage Sag

| *System* | *Load1* | *Load 2* |
|---|---|---|
| Without FACTS | 0.09568 | 0.09568 |
| With DVR | 0.02277 | 0.06240 |
| With DSTATCOM | 0.02278 | 0.06252 |
| With UPFC | 0.02016 | 0.06383 |
| With IPFC | 0.02187 | 0.02187 |
| With GUPFC | 0.02018 | 0.02018 |

that is illustrated in table 2, where GUPFC has least ISE value for both load 1 and 2 which is quite close to reference value of ISE i.e. 0.02.

## 5.2 System with Voltage Swell

Maximum limit of voltage swell (0.8p.u) is introduced in the system through three phase programmable source from 0.2sec to 0.3 sec.

The simulation results are as follows:

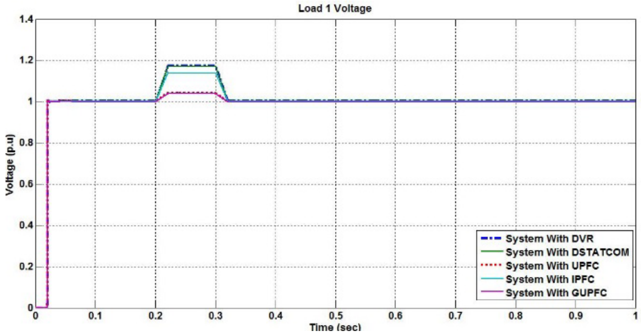

**Figure 22.** Voltage across load 1.

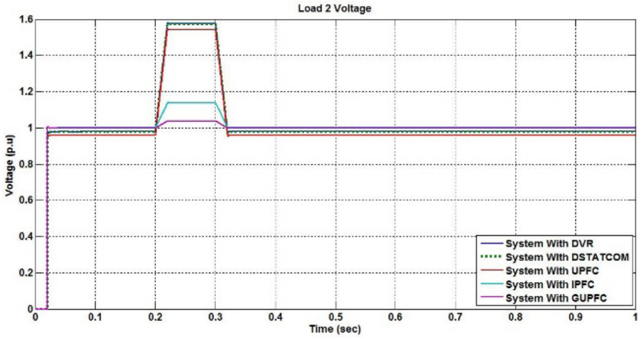

**Figure 23.** Voltage across load 2.

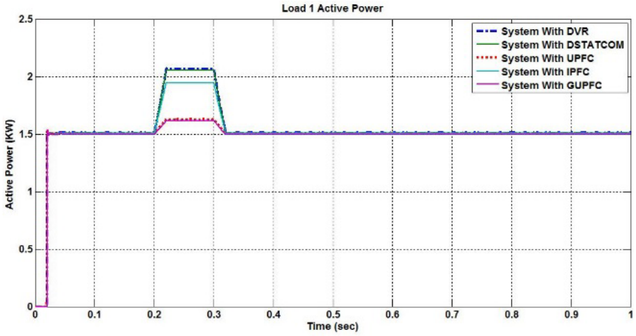

**Figure 24.** Active power across load 1.

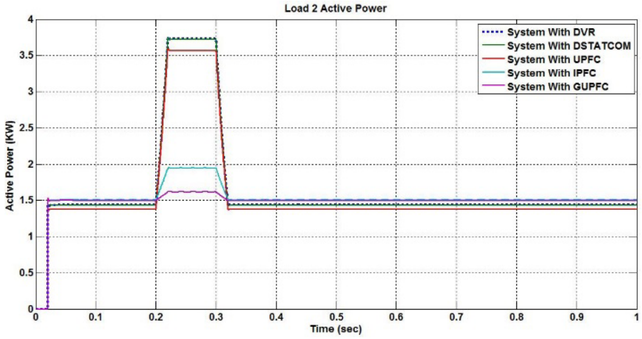

**Figure 25.** Active power across load 2.

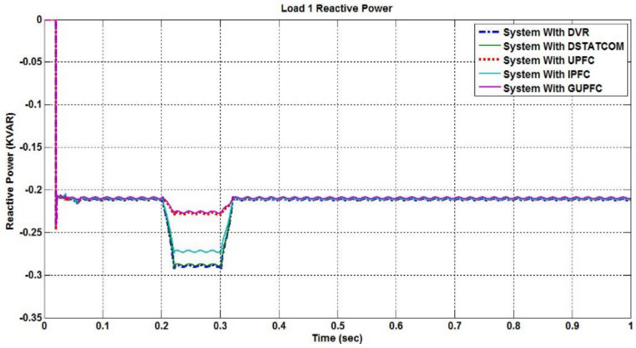

**Figure 26.** Reactive power across load 1.

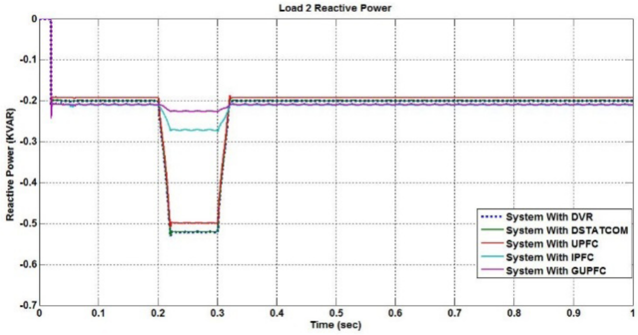

**Figure 27.** Reactive power across load 2.

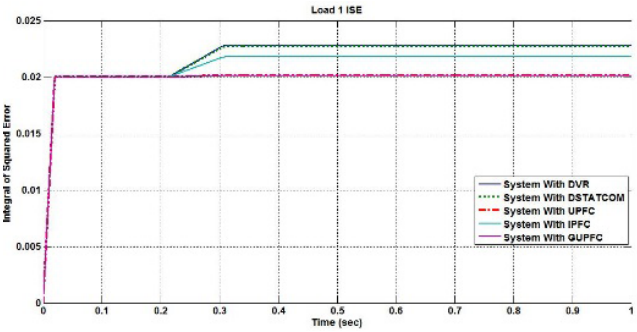

**Figure 28.** Integral of squared error across load 1.

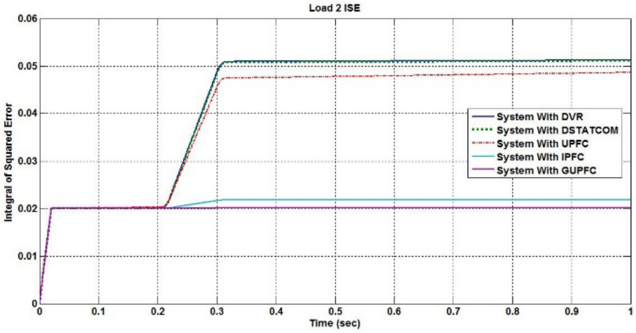

**Figure 29.** Integral of squared error across load 2.

**Table 3.** ISE Performance Index for Voltage Swell

| *System* | *Load1* | *Load 2* |
|---|---|---|
| Without FACTS | 0.07921 | 0.07921 |
| With DVR | 0.02283 | 0.05124 |
| With DSTATCOM | 0.02274 | 0.05111 |
| With UPFC | 0.02016 | 0.04863 |
| With IPFC | 0.02180 | 0.02180 |
| With GUPFC | 0.02013 | 0.02013 |

When voltage swell is introduced in the system, it can be observed (from Figure 10 to Figure 13) that during this interval, the system performance and power flow gets effected. Refer Figure 22 to Figure 29, when the single line FACTS device is connected in line, then almost identical results are obtained by DVR and DSTATCOM but UPFC gives best results for line 1. However small amount of swell is also mitigated from line 2 by using these single line FACTS devices but there is slightly reduced overall voltage magnitude for line 2. When the multiline FACTS device is installed to the system, then both the load lines get equally compensated. GUPFC and IPFC mitigates voltage swell much better as compared to DVR, DSTATCOM and UPFC. Out of all five FACTS devices, GUPFC gives best performance in case of voltage swell also as shown in Table 3where the performance index values for different FACTS devices are given. When the swell is introduced then ISE value for both load lines rises from 0.02 to 0.7921 and thus system performance reduces. Again from the following table, the ISE value is least for GUPFC and is very close to 0.02 of the reference base system.

## 6. Conclusion

From the comparative results of the FACTS devices, it can be concluded that the multiline FACTS devices perform better as compared to the single line FACTS devices as they can mitigate voltage sag-swell for both the load lines identically without any side effect on the amplitude of voltage on either line. GUPFC has been found to be the best FACTS device out of all devices being considered. GUPFC not only compensate the voltage level but also maintain the active and reactive power flow and thus enhancing the overall system performance.

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