A Comparative Study on The Performance of Custom Power Devices for Power Quality Improvement

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Abstract- *This paper presents a review on the performance of four series and parallel custom power devices (CPDs) including active voltage conditioner (AVC), active power conditioner (APC), dynamic voltage restorer (DVR), and distribution static synchronous compensator (D-STATCOM). The CPDs are simulated on the modified IEEE 16-bus radial distribution system using Matlab/Simulink software to investigate performance efficacy of each devices under various power quality (PQ) disturbances including voltage sags, voltage interruption, and harmonic distortions. The simulation results demonstrate that the effectiveness of each device to compensate different types of power quality disturbances toughly depends on the device's arrangement and characteristics during PQ disturbances.*

Keywords- Active voltage conditioner; active power conditioner; power quality; DVR; D-STATCOM; power quality disturbance.

I. INTRODUCTION

Given the rapid development of advanced distribution systems, power disruptions with different levels of severity may pose a huge financial drawback to utility . Conversely, customers can feel the technical and economic consequences of poor power quality (PQ). To protect these sensitive loads, custom power devices (CPDs) can be applied in the system as an advanced power electronic based solutin.

In addition, the integration of multiple CPDs within a specific part of the system can form a Premium Power Park to meet customer's requirements and offer a high-quality power for end-users . Depending on the device topology and applied control strategy, CPDs can protect system components against various types of PQ disturbances, such as voltage sag and voltage and current harmonic distortions. In addition, depending on the structure and capacity limitation of the DC-link storage element, the performance and operation longevity of the CPDs under different PQ disturbances may vary. Therefore, a careful analysis is required to understand the dynamic behavior of CPDs in different situations for choosing an appropriate device based on technical and economy justifications at the time of system planning [6,7].

This paper presents a study on the performance of the most renowned CPDs including active voltage conditioner (AVC), active power conditioner (APC), dynamic voltage restorer (DVR), and distribution static synchronous compensator (D-STATCOM) under different PQ disturbances. Each device is modeled on the modified IEEE 16-bus radial distribution system using Matlab/Simulink software. Several PQ disturbances including voltage sag, momentary voltage interruption, and voltage and current harmonic distortions are generated to investigate the advantages and limitations of CPDs.

II. POWER QUALITYDISTURBANCES

Electrical supply is designed to operate under constant magnitude and frequency of sinusoidal voltage waveform. Any deviation from these predesigned magnitude and frequency can be interpreted as PQ problem . Power quality problems are usually due to inappropriate interactions between the utility grids and the customer equipment, and these disturbances can result in serious technical and financial problems for the system components. For example, voltage sags down to 80% of nominal voltage with a few tens of millisecond duration can cause interruption in processing plants, resulting in hours of downtime and more turnover losses . The most regular and important PQ issues that require practical solutions are as follows:

A. Voltage interruption

A voltage interruption can be defined as the complete loss of a supply voltage for a specific time, which can be categorized into momentary interruption (duration, between 0.5 cycles and 3 s), temporary interruption (lasting between 3 s to 1 min), and long voltage interruption (duration, more than 1 min). These disturbances occur due to the normal or false operation of protection system and isolation of the power source from the loads which may cause severe financial losses due to the decrease in the operational life of the equipment such as transformers or equipment downtime in processing plants.

B. Voltage sag

Voltage sags are short-term reductions in the rms voltage to a value between 10% and 90% for a duration of 1 min (0.5 cycle). These voltage reductions are caused by motor starting, transformer energizing, or faults. Voltage sags are characterized by magnitude and duration. Analyzing voltage sags is a complicated task which requires considering a large variety of random factors, such as type of short circuits, location of faults, and protective system performance. Voltage sags can be harmful to equipment with insufficient internal energy storage for riding through sags or sensitive semiconductor-based devices that may cause shut down, lock up, or garble data .

C. Harmonic distortion

Generally, voltage waveform generated in the AC generators under constant frequency is pure. However, when a nonlinear load is fed by a pure sinusoidal voltage, the resulting current is not completely sinusoidal. The current drawn by the nonlinear load produces voltage distortion at the load terminal under the effect of system impedance. The distorted voltage contains harmonic which is defined as a perfectly sinusoidal component of a periodic waveform that has a frequency equal to an integer multiple of the fundamental frequency [12]. Voltage and current harmonic distortions may increase losses in transformers and electro motors, overheating of equipment, and misoperation of protective devices.

III. CUSTOM POWERDEVICES

A. Active voltage conditioner

The AVC is an IGBT-based series CPD which is used to protect sensitive loads from the most common PQ disturbances in the utility grid. AVC can effectively mitigate voltage sags down to 70% and also voltage imbalance for critical loads with a very fast response to meet most PQ standard requirements, such as . The AVC structure is based on a direct AC/AC converter to supply the required compensation power from the grid, an LC low-pass filter with damping resistor (R), an injection transformer, and a bypass switch as shown in Fig.

1. This topology allows AVC to provide long-duration compensation without using any DC-link, significantly reducing the device cost . From the figure, the terminal voltage of the converter, $v_C(t)$, can be defined as [16]

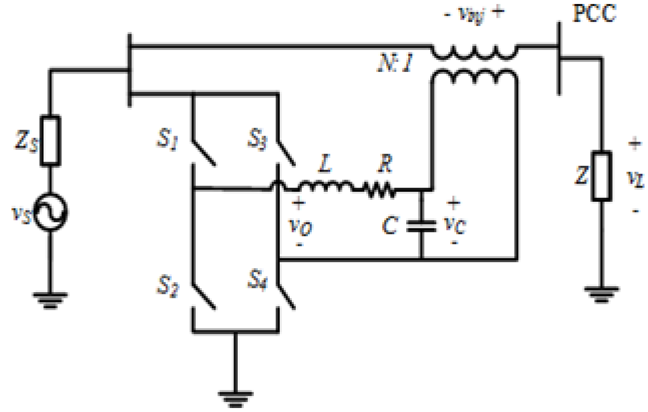

Figure 1. Single-line diagram of AVC

B. Dynamic voltage restorer

The DVR is a solid-state power electronic-based compensator which is connected in series to the utility's primary distribution system. The DVR is able to inject a three-phase voltage with a controllable magnitude and phase to recover the load voltage at the point of common coupling. The main components of DVR are very similar to those in AVC, but the main difference is the presence of DC energy storage unit in DVR to provide the required power for correcting voltage disturbances as shown in Fig.2.

$$v_C(t) = \frac{t_1 \cdot v_{PCC}(t)}{T_s} \quad (1)$$

where,

$$T_s = t_1 + t_2 \quad (2)$$

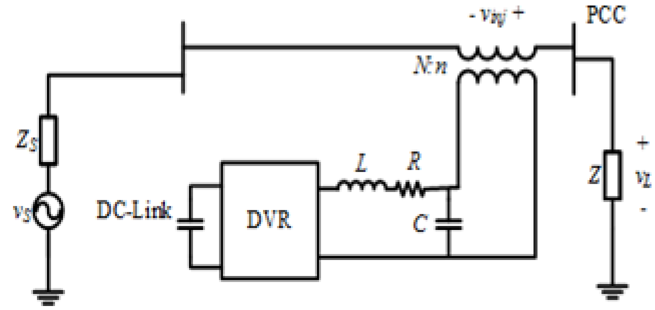

Figure 2. Single-line diagram of DVR

C. Active power conditioner

The APC is known as a parallel CPD with voltage source inverter topology which can be used in the utility's t_1 and t_2 are the sampling period time intervals between 0 to T_s, and $v_{PCC}(t)$ is the measured voltage at the point of common coupling (PCC).

$$v_L(t)=v_{PCC}(t)+v_{inj}(t) \quad (3)$$

where

$$v_{inj}(t)=\frac{c\;k(t)}{N} \quad (4)$$

To compensate voltage sags and swells, the nominal load voltage, $v_L(t)$ can be expressed as distribution systems to regulate voltage variations and mitigate PQ disturbances . The main components of APC are a buffer capacitor, an AC/DC, and a DC/AC power converter, where the AC/DC unit provides the required DC compensation power for APC and the DC/AC unit injects the required current to compensate PQ disturbances as shown in Fig. 3. From the figure, the instantaneous load

current, $i_{Load}(t)$, and the PCC voltage, $v_{pcc}(t)$, shown in Fig. 3 can be defined as ,

$$i_{Load}(t)=I_1\sin(\omega t+\varphi_1)+\sum_{h=2}^{\infty}I_h\sin(h\omega t+\varphi_h) \quad (5)$$

$$v_{pcc}(t)=V_m\sin(\omega t) \quad (6)$$

where ω, h, and φ are radial frequency, harmonic order, and phase angles of the load current and the PCC voltage, respectively.
test system is considered as shown in Fig. 5 . Each CPD is individually planned to be placed at bus 11 to compensate PQ issues seen by loads L6 and L7. To create different
The source current supplied by the PCC, i'
(t), after
levels of voltage sag and voltage interruption caused by
compensation should be purely sinusoidal as

$$i'_{pcc}(t)=p_f(t)/v_{pcc}(t)=I_1\cos(\varphi_1)\sin(\omega t) \quad (7)$$

motor starting current, a heavy induction motor with different power ratings is placed at bus 15, where other
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$$i_{comp}(t)=i_{Load}(t)-i'_{pcc}(t) \quad (8)$$

nonlinear loads contribute in harmonic distortion.
where $p_f(t)$ is the fundamental components of power. If the APC compensates the total reactive and harmonic power, then the PCC current, $i'_{pcc}(t)$, can be in phase with the PCC voltage. Therefore, the injected compensation current, $i_{comp}(t)$, can be expressed as,

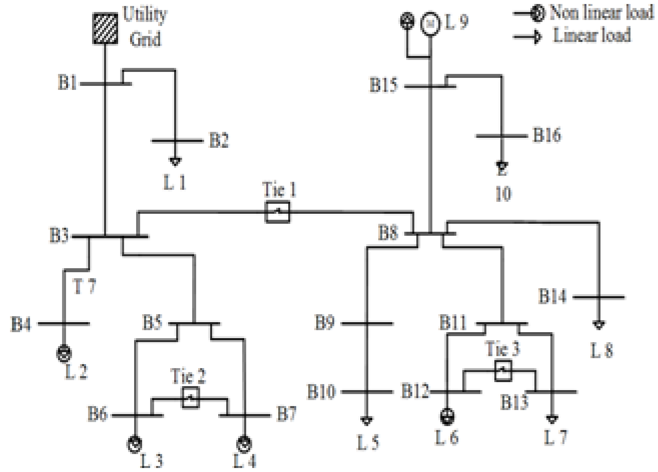

Figure 5. Single-line diagram of the 16-bus test system

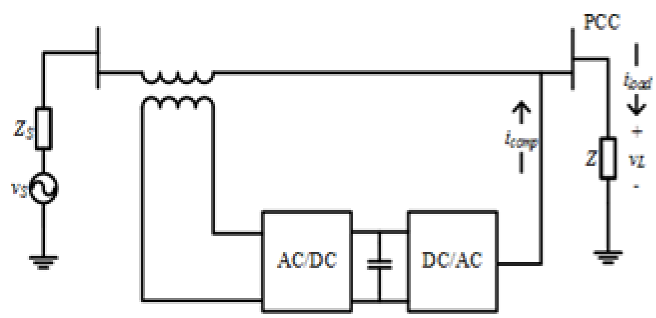

Figure 3. Single-line diagram of APC

D. Distribution static synchronous compensator

D-STATCOM is a shunt-connected CPD which can be used to regulate voltage variation resulting from the motor starting condition or in-rush current and to mitigate current harmonic distortions . The structure of D- STATCOM is similar to that of the APC but without the AC/DC converter, as shown in Fig. 4. Thus, the required power for recovering PQ disturbances should be directly provided through CD energy storage.

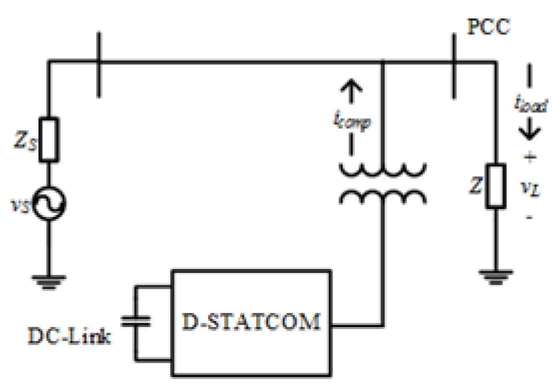

Figure 4. Single-line diagram of D-STATCOM

IV. SIMULATIONRESULTS

To investigate the performance of CPDs on distribution systems under different PQ disturbances, a modified 16-bus

To investigate the performance of CPDs, a voltage sag withdepthsof0.6p.u. followed by a voltage interruption are created. The measured rms value of voltage waveform at bus 11 is shown in Fig.6.

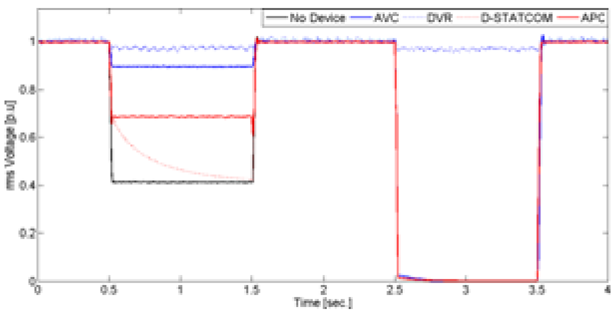

Figure 6. Measured rms voltage at bus 11 for voltage sags with depth of 0.6 and voltage interruption

Fig. 6 shows that parallel devices cannot accurately mitigate voltage sag when the depth of sag increases. This restriction occurs given the limitation of the DC-link storage in D-STATCOM (capacitor rapid discharges) or inverter limitations in APC. In addition, parallel devices are advised to be disconnected from the protection system to prevent them from feeding upstream faults. In case of series compensators, the results show that these devices have better performance for PQ improvements. DVR is able to recover accurately all the voltage sags and voltage interruptions that occurred. However, limited DC-link storage may limit DVR as to cost of device and duration of voltage sag compensation, although not as much as D-STATCOM. To illustrate the limitations of the devices better, the injected voltages and currents are shown in Figs. 7 and8.

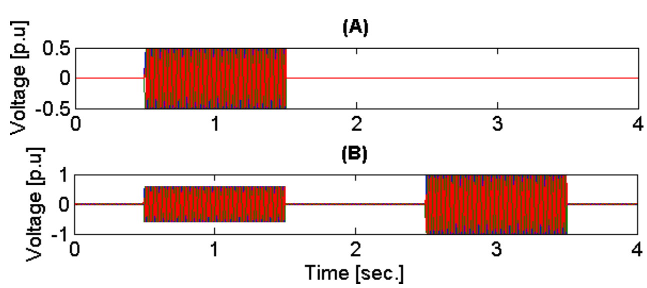

Figure 7. Injected voltages during a 0.6 voltage sag and voltage interruption, (A) AVC voltage. (B) DVR voltage

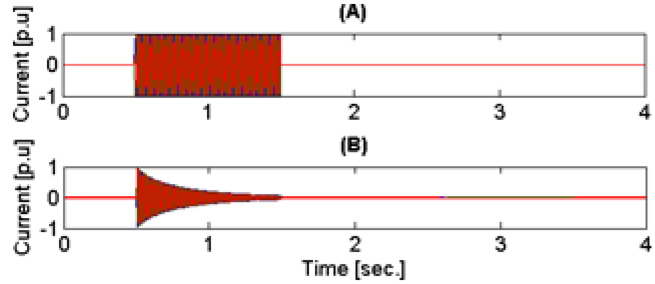

Figure 8. Injected currents during a 0.6 voltage sag and voltage interruption, (A) APC current. (B) D-STATCOM current

Fig. 7 shows that DVR has the superior performance for recovering deep voltage sags and voltage interruption due to the DC-link storage element. However, given the capacity limitation of the DC source, DVR may be limited during long voltage interruption. Note that the performance of AVC can be improved by installing an external battery or capacitor bank to allow the AVC to compensate deep voltage sags and voltage interruptions. However, the improvement may significantly increase the device cost. From Fig. 8, APC is able to mitigate moderate voltage sags but faces limitations when deeper voltage sags or voltage interruption occur. APC's performance can be improved partially by installing an additional DC source. Results show that D-STATCOM is suitable for compensating slight voltage sag with short duration (depending on the DC source capacity).

To investigate the performance of CPDs in mitigating voltage and current distortion, the voltage and current total harmonic distortion(THD)atbus11ismeasuredandshown in Table 1. The table clearly shows that all CPDs can significantly mitigate both voltage and harmonic distortions but the performance of parallel devices is much superior especially in current harmonic distortion. In addition, the ability of parallel CPDs in injecting compensation current to both upstream and downstream loads can improve the voltage and current THD index of the entire system.

TABLE I. MEASURED VOLTAGE AND CURRENT THD AT BUS 11

Device	THD_V (%)	THD_I (%)
No CPD	15.79	26.04
AVC	3.98	4.60
DVR	4.07	4.66
APC	3.88	2.58
D-STATCOM	4.03	2.53

V. CONCLUSIONS

This paper presents a review on the performance of four CPDs under different types of PQ disturbances. The CPDs including AVC, APC, DVR, and D-STATCOM are modeled on a 16-bus test system with nonlinear loads using Matlab/Simulink software, and a voltage interruption and a voltage sag with a depth of 0.6 p.u are created to test the performance of each device. The simulation results showed that the performance and effectiveness of each device depends on the device's structure and characteristic during the duration of PQ disturbances.

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