Voltage Sag Assessment and Mitigation Techniques of a Solar PV Integrated 110 kV/13.8 kV Saudi Substation

Abdullah Saeed Al-Qarni and Sreerama Kumar Ramdas

Abstract — The point of common coupling of a photovoltaic energy conversion system (PVES) to the utility grid is the most critical interface point where voltage sag issues arise. This paper involves a comparative evaluation of Dynamic Voltage Restorer (DVR) and Distribution Static Compensator (D-STATCOM) in mitigating the voltage sag at the point of common coupling of a photovoltaic energy conversion system integrated onto AC auxiliary distribution system in a 110 kV/13.8 kV transmission substation in the national power grid in Saudi Arabia. The voltage sag due to a three-phase short circuit at the point of common coupling of the photovoltaic system with the AC auxiliary distribution system is investigated. The results indicate that the DVR is better than the D-STATCOM in mitigating the voltage sag issue.

Keywords — Photovoltaic Systems, PSCAD Program, Transmission Substation, Voltage Sag.

I. INTRODUCTION

The integration of renewable energy resources with power grid has become a global trend due to the possibilities of secure and advanced technology of power production. Photovoltaic systems are the most key sources of renewable energy which have many advantages such as sustainability, wide availability and free of charge of energy from the sun. Saudi Arabia owns high levels of solar radiation and sustainable availability of sunlight throughout the year. The government has recently adopted solar energy conversion technologies to produce clean energy and meet the increasing demand of electricity as one of the aims of Vision 2030. As the penetration of solar photovoltaic energy conversion systems (PVES) into grid is set to increase along with the expected expansion of distributed generation (DG). Many power quality issues will arise at the point of common coupling (PCC). One of the most critical PQ issues is voltage sag which is defined as a reduction in the nominal voltage between 0.1 to 0.9 p.u. extending over a period of half a cycle to one minute [1]. It is caused by fault incidents, load increase and energization of motors or transformers. Voltage sag which is caused by fault incidents is a common issue in distribution networks. Its magnitude is affected by many factors such as fault type, fault impedance, the distance of the fault from the PCC. To mitigate the voltage sag, there are different effective techniques. The most effective solution is using the power conditioning devices such as Dynamic Voltage Restorer (DVR) and Distribution Static Compensator (D-STATCOM) at PCC.

Michael and Miri [2] have developed an improved model of a STATCOM (Static Synchronous Compensator) using NETOMAC software. The proposed model was investigated in a three-phase electrical network. The performance of the model is analyzed under different faults disturbances.

Zhang et al. [3] have presented in their book analysis of new control methods used in flexible AC transmission systems (FACTS). The book presented many topics in power system control such as power flow controller, voltage and reactive power controller extended to voltage stability controller in FACTS.

Khalifa and El-Saadany [4] have studied a three-phase grid-connected photovoltaic arrays with a maximum power point tracker. The study has proposed an open loop controller for tracking the maximum power point of the PV arrays considering the effect of temperature and irradiation variation. The results have proven that the proposed open loop controller is effective and practical in PV systems tied to the grid. Han et al. [5] have investigated many of power quality issues such as harmonic distortion, under voltage and transient voltage in a photovoltaic system tied to power grid. The study has proposed a controller using STATCOM to mitigate these power quality issues. Simulation results in PSCAD/ EMTDC software have proven the feasibility of the proposed controller.

Mosobt et al. [6] have presented a power quality analysis for many of renewable energy systems as isolated from the grid. The study was focused on mitigating voltage harmonic distortion and voltage sag using STATCOM. The study results have shown, improved system voltage and reduced voltage and current harmonics under varying load. Weng [7] has investigated many of power quality issues in a microgrid grid using PSCAD.A power distribution system is modeled and integrated with a photovoltaic system. The simulation results have shown that the microgrid suffers from various power quality issues such as inrush current, voltage and frequency fluctuation and harmonic distortion.

Ramya et al. [8] have developed a multilevel inverter in DSTATCOM and DVR for mitigating voltage sag in a local power distribution network. The proposed inverter is implemented using MATLAB/Simulink. The simulation results have shown that the model is effective in high voltage distribution networks.

Al-Shetwi et al. [9] have discussed the standard requirements for voltage sag, voltage flicker, harmonics frequency variation, and voltage unbalance. They proposed compliance controllers to meet these power quality requirements. A modified inverter controller is adopted to mitigate the voltage sag incident. A dynamic voltage restorer with its controller is designed to control the voltage fluctuation, flicker, and unbalance at PCC. The voltage and current harmonic distortion are reduced using a RLC filter.
The evaluation study has shown that the proposed controllers helped to meet the standard requirements.

Al-Mathnani et al. [10] have proposed a DVR with two continuous vectors and phase-locked loop (PLL) controllers to control the voltage sag. The simulation was implemented using PSCAD/EMTDC. The simulation results have shown that the voltage sag and total harmonic distortion (THD) have been improved significantly.

This paper investigates the voltage sag issue at PCC of a typical photovoltaic energy conversion system integrated with the auxiliary distribution system of a transmission substation in the Saudi Electricity Company power grid. The investigation is further extended to the evaluation of the effectiveness of dynamic voltage restorer (DVR) and distribution static compensator (D-STATCOM) to identify the most effective approach in mitigating voltage sag at the PCC.

II. SYSTEM DESCRIPTION

The photovoltaic energy conversion system is proposed to be integrated with the AC auxiliary distribution system of a typical transmission substation in the Saudi national grid as shown in Fig. 1. The single line diagram of the 110 kV/13.8 kV substation is represented as source impedance, the impedance of 13.8 kV power cable, the 13.8 kV /400 V auxiliary transformer, the LV power cable connection between the auxiliary transformer to the AC distribution board. Substation load is represented as a single lumped load including AC loads and DC loads. AC loads mainly comprise of lighting systems, air conditioning units and battery chargers. DC loads include protection and control systems in the substation. The proposed PVES is composed of solar panel arrays, a DC-DC power converter, a voltage source inverter, and a coupling transformer.

In Fig. 1, the PV array consists of solar cells. A solar cell is a semiconductor device that is used to convert solar energy into electrical energy, with no pollutant emission. Depending on its application, the PV cells can be connected either in series or in parallel to obtain the required voltage or current. From PV cells, a PV module is accomplished. Modules also are connected in series or parallel to form a PV array to achieve the desired power. DC-DC Boost Converter is utilized to operate the PV array at its maximum power point during the change of temperature and radiation. DC-AC inverter is a power electronic device that consists of switching components to generate an AC sinusoidal voltage of the required magnitude, frequency, and phase angle. The switching components used in the inverter can be a thyristor, GTO or IGBT. The solid-state switching components are switched on and off based on the sinusoidal pulse width modulation technique (SPWM). Coupling transformer is used to couple the PV output voltage with the grid voltage.

This paper investigates the effectiveness of DVR and D-STATCOM in minimizing the voltage sag that may occur at PCC. A brief description of these devices is given in this section.

A. Dynamic Voltage Restorer (DVR)

Dynamic Voltage Restorer is a series compensator used in power distribution systems that can mitigate voltage sag. DVR can be used also for mitigating unbalance in voltage, voltage harmonics and voltage fluctuation. As shown in Fig. 2, DVR consists of Voltage Source Inverter (VSI) which is used to inject the missing voltage of the required magnitude and phase angle. Energy storage unit such as batteries can be used to enhance the power capability of DVR. A series transformer is used to couple the DVR with the power distribution network.

B. Distribution Static Compensator (D-STATCOM)

Distribution Static Compensator is a shunt compensator used in power distribution systems that can inject or absorb reactive power at PCC. D-STATCOM employs power electronic devices to control the voltage magnitude by reactive power exchange between the D-STATCOM and the network. As shown in Fig. 3, the voltage source inverter (VSI) is used to control the AC voltage of required magnitude and phase angle. DC supply Unit can be batteries, flywheels, capacitors, or super magnetic energy storage (SMES). A series transformer is used to Couple the D-STATCOM with the network.
III. SYSTEM MODELING

The modeling of various system components discussed in the previous section is presented in this section.

A. Solar Photovoltaic Cell

As shown in Fig. 4, the solar PV cell is represented by a single diode, a series resistance ($R_s$), and a parallel resistance ($R_{SH}$).

The solar PV cell current output is given in (1).

$$I = I_L - I_D - I_{SH}$$  (1)

The diode current is given in (2).

$$I_D = I_0 \left( \frac{V + IR_s}{q} \right) e^{-\frac{V + IR_s}{q}} - 1$$  (2)

The parallel branch current is given in (3).

$$I_{SH} = \frac{V + IR_s}{R_{SH}}$$  (3)

After substituting (2) and (3) in (1), one obtains (4).

$$I = I_L - I_0 \left[ \frac{V + IR_s}{q} e^{-\frac{V + IR_s}{q}} - 1 \right] - \frac{V + IR_s}{R_{SH}}$$  (4)

B. DC-DC Converter

DC-DC boost converter has a capacitor, an inductor, diode and IGBT. The circuit diagram of the boost converter is shown in Fig. 5.

The duty cycle of a boost converter is determined as (5).

$$D = 1 - \frac{V_{in}}{V_{out}}$$  (5)

The current through the inductance is given in (6).

$$I_L = \frac{V_{in}}{(1-D)^2 R_{load}}$$  (6)

The ratio of V output to V input is given in (7).

$$\frac{V_{out}}{V_{in}} = \frac{1}{1-D}$$  (7)

The minimum value of the capacitor can be obtained with (8).

$$C = \frac{D}{\frac{L}{f_{load}} \times 0.000001}$$  (8)

C. Voltage Source Inverter

Voltage Source Inverter is represented of six switches with each phase sinusoidal voltage output is generated in the middle of each inverter leg. The switching component selected to be used is IGBT. The circuit Model of the Voltage Source Inverter (VSI) is shown in Fig. 6.

The inverter equations when considering the access to the utility grid are (9), (10), and (11).

$$V_{ia} = R_{ia} \frac{dV_{ia}}{dt} + V_{ga}$$  (9)

$$V_{ib} = R_{ib} \frac{dV_{ib}}{dt} + V_{gb}$$  (10)

$$V_{ic} = R_{ic} \frac{dV_{ic}}{dt} + V_{gc}$$  (11)

where

- $V_g$: Grid Voltage (V)
- $V_i$: Inverter Voltage (V)

D. Dynamic Voltage Restorer

DVR is represented as a voltage source with an impedance and in series with the source circuit as shown in Fig. 7.

Fig. 7. Circuit Model of Dynamic Voltage Restorer.
From Fig. 7, the DVR voltage is found by using (12).

\[ V_{DVR} = V_L + Z_{TH}I_L - V_{TH} \]  

(12)

The load current is given in (13).

\[ I_L = \left( \frac{(P_L + jQ_L)}{V_L} \right)^* \]  

(13)

When \( V_L \) is considered as a reference voltage, it is given as (14).

\[ V_{DVR} < \alpha = V_L < 0 + Z_{TH}I_L < (\beta - \theta) - V_{TH} < \delta \]  

(14)

Load power angle can be given as (15).

\[ \theta = \tan^{-1} \frac{Q_L}{P_L} \]  

(15)

The injected complex power of DVR is (16).

\[ S_{DVR} = V_{DVR}I_L \]  

(16)

### E. Distribution Compensator

D-STATCOM is represented as a voltage source with the transformer reactance and parallel with the source circuit, as shown in Fig. 8.

![Fig. 8. Circuit Model of Distribution.](image)

The D-STATCOM current is given in (17).

\[ I_{sh} = \frac{V_{sh} - V_t}{jX_t} \]  

(17)

The active and reactive power exchange with the network is given in (18).

\[ P = \frac{V_SV_{sh}}{X_t} \sin \delta_{sh} \]  

(18)

\[ Q = \frac{V_S^2}{X_t} - \frac{V_SV_{sh}}{X_t} \cos \delta_{sh} \]  

(19)

where

- \( V_S \): Source Voltage (V)
- \( V_{sh} \): Inverter Voltage (V)
- \( V_L \): Load Voltage (V)

### IV. System Data

The single-line diagram of the transmission Substation is shown in Fig. 9, which represents the equivalent parameters of the grid side. Equivalent source, Substation load, power cable and auxiliary transformer data are given in Table I through Table IV, respectively. The technical data related to PVES are given in Table V and Table VI, respectively. The data relating to the booster converter, voltage source inverter and coupling transformer are given in Table VII to Table IX, respectively.

#### TABLE I: SOURCE PARAMETERS

| Parameter       | Value     |
|-----------------|-----------|
| Bus voltage     | 13.8kV    |
| Short circuit current | 22.42kA |
| Source reactance| 0.355 Ω   |

#### TABLE II: SUBSTATION POWER CABLE

| Parameter                  | Value          |
|----------------------------|----------------|
| Medium Voltage Cable       | 20 kV          |
| Length of cable            | 93 m           |
| Conductor size             | 630 mm²        |
| 3-phase inductance          | 0.334 mH/km    |
| AC Resistance              | 7.966 x 10⁻⁵ Ω/m |
| Low Voltage Cable          |                |
| Length of cable            | 18 m           |
| Conductor size             | 400 mm²        |
| Single core reactance      | 0.0959 Ω/km    |
| AC Resistance              | 0.062 Ω/km     |

#### TABLE III: AUXILIARY TRANSFORMER

| Parameter                  | Value        |
|----------------------------|--------------|
| Rating (KVA)               | 500 kVA      |
| Impedance Z%               | 4%           |
| Primary Voltage (HV)       | 13.8 kV      |
| Secondary Voltage (LV)     | 400 V        |
| Vector Group               | Dyn 11       |

#### TABLE IV: SUBSTATION LOAD

| Parameter                  | Value        |
|----------------------------|--------------|
| Total Load                 | 375 kVA      |
| Power factor               | 0.85         |
| Real Power                 | 319 kW       |
| Reactive Power             | 197 kVAR     |

![Fig. 9. Single Line Diagram of the Substation.](image)
TABLE V: PHOTOVOLTAIC CELL

| Parameter                        | Value   |
|----------------------------------|---------|
| Effective surface area of cell   | 0.01 m² |
| Series resistance                | 0.02 Ω  |
| Parallel resistance              | 1000 Ω  |
| Rate of diode factor             | 1.5     |
| Rate of band gap                 | 1.103   |
| Saturation current               | 1 x 10⁻¹² kA |
| Short circuit current            | 0.0025 kA |
| Temperature coefficient          | 0.001   |

TABLE VI: PHOTOVOLTAIC ARRAY

| Parameter                        | Value   |
|----------------------------------|---------|
| Number of modules connected in series/array | 20      |
| Number of strings in parallel/array | 20      |
| Number of cells connected in series/module | 108     |
| Number of cell strings connected in parallel/module | 4       |
| Irradiation level                | 1000 W/m² |
| Temperature degree               | 25 °C   |
| Total output power               | 350 kW  |

TABLE VII: DC-DC BOOST CONVERTER

| Parameter                        | Value   |
|----------------------------------|---------|
| Input Voltage                    | 1.5 kV  |
| Output Voltage                   | 3.5 kV  |
| Duty Cycle                       | 0.5     |
| Inductance                       | 100 uH  |
| Capacitance                      | 3000 uF |
| Switching Frequency              | 3600 Hz |

TABLE VIII: VOLTAGE SOURCE INVERTER

| Parameter                        | Value   |
|----------------------------------|---------|
| Number of phases                 | 3       |
| Type of switch                   | IGBT    |
| Capacitance                      | 3900uF  |
| Carrier frequency                | 8000Hz  |

TABLE IX: COUPLING TRANSFORMER DATA

| Parameter                        | Value   |
|----------------------------------|---------|
| Rating (kVA)                     | 750 kVA |
| Leakage reactance                | 0.05    |
| Turns ratio                      | 1000/400|
| Frequency                        | 60 Hz   |
| Winding connection               | Δ/Y     |

V. SIMULATION RESULTS

To investigate the voltage sag issue during a fault incident, a three-phase to ground fault through a 0.01 Ohm resistance is simulated. The simulation is implemented for PVES with the grid for a duration of five cycles of 60 Hz supply (0.083 s) as shown in Fig. 10.

Fig. 11 shows that the voltage sag percentage is approximately 53% during five cycles at PCC. The fault current has been fed from both the grid and the PVES. The grid has contributed significantly to the voltage sag due to its higher MVA short circuit. In Fig. 12, the RMS voltage at PCC is illustrated for a duration of one second. The voltage sag is shown approximately 0.47 p.u of the nominal voltage at PCC.

A. Voltage Sag Mitigation

To mitigate the voltage sag issue at PCC during the three-phase fault incident, DVR and D-STATCOM are proposed to be used. PSCAD simulations for DVR and D-STATCOM are conducted and then introduced during the voltage sag occurrence for a duration of 1 second. The results are shown in the following figures.
B. DVR based Voltage Sag Mitigation

Fig. 13 shows the simulation diagram of the system with DVR at the PCC. As shown in Fig. 14, it has been observed that during the three-phase fault, the voltage level gets improved to 0.97 p.u. This is a significant improvement when compared to the scenario without DVR.

C. D-STATCOM based Voltage Sag Mitigation

Fig. 15 shows the simulation diagram of the PVES and grid with D-STATCOM at the PCC. As shown in Fig. 16, it has been observed that the voltage sag gets improved to 0.96 p.u during the three-phase fault at PCC. This is a significant improvement when compared to the scenario without D-STATCOM.

The voltage sag during the three-phase fault incident is 0.47 p.u. at PCC. Both DVR and D-STATCOM improved significantly the voltage sag up to an acceptable level within the fault duration. DVR has exhibited comparatively better performance in mitigating the voltage sag than D-STATCOM at PCC as illustrated in Table X.

| Mitigation Technique | Voltage Sag at PCC (p.u) |
|----------------------|--------------------------|
| DVR                  | 0.97                     |
| D-STATCOM            | 0.96                     |

The voltage sag during the three-phase fault incident is 0.47 p.u. at PCC. Both DVR and D-STATCOM improved significantly the voltage sag up to an acceptable level within the fault duration. DVR has exhibited comparatively better performance in mitigating the voltage sag than D-STATCOM at PCC as illustrated in Table X.
VI. CONCLUSION

This paper has proposed a typical photovoltaic energy conversion system (PVES) integrated into AC auxiliary distribution system in a 110 kV/13.8 kV transmission substation in the national power grid in Saudi Arabia. The Paper has investigated the voltage sag issue caused by a three-phase fault at PCC. DVR and D-STATCOM have been introduced at PCC to verify their effectiveness in mitigating the voltage sag during the fault incident. The simulation results have shown that DVR is marginally better than the D-STATCOM in voltage sag improvement with less DC storage capacity in comparison with D-SATCOM.
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