ABSTRACT: Severe power quality problem can arise when a large number of single-phase distributed energy resources (DERs) are connected to a low voltage power distribution system. Due to random location and size of DER, it may so happen that a particular phase generates excess power than its load demand. In such an event, the excess power will be fed back to the distribution substation and will eventually find its way to the transmission network, causing undesirable voltage/current unbalance. As a solution to this problem, the paper proposes the use of a distribution static compensator (DSTATCOM), which regulates the voltage at the point of common coupling (PCC), thereby ensuring a balanced current flow from/to the distribution substation. Additionally this device can also support the distribution network in the absence of the utility connection, making the distribution system work as a microgrid. The proposals are validated through extensive digital computer simulation studies using PSCAD.

Keywords: DSTATCOM, DER, power circulation

I. INTRODUCTION

RENEWABLE energy resources are becoming very popular now-a-days for their environment friendliness and efficiency. Also the depletion of fossil fuel sources has drawn significant attention to the field of distribution generation (DG) [1-3]. At distribution level DGs, such as solar PVs, fuel cells, micro wind turbine along with storage such as batteries are collectively called DERs. A DER is usually installed in low-voltage side of the network. Amongst the DGs, the photovoltaic cell (PV) is most popular, especially in the countries that get intense and longer period of sunlight such as India and Australia. Government initiatives have accelerated rooftop PV installation in some countries. Another technology which is going to be eminent in future is electrical vehicle (EV). At the first stage, it is going to run on G2V (Grid to Vehicle) mode. That means it will only get charged from the grid. But with the improvement of battery technology and vehicle efficiency, it will be also operating on V2G (Vehicle to Grid) mode where it can send back extra power to the grid.

As the DERs are installed close to customer, they have low transmission expense as well as less power loss. Due to their high reliability, it is expected that there will be multiple DER connections in the near future. However at the same time, they add complexity to the network. They can cause power quality problems like voltage sag and swell, unbalanced voltage and current etc. In addition to these, major protection issues arise as integration of DERs in the LV network corrupts its radial nature. So the traditional relay setting algorithms for overcurrent devices cannot used [1, 4]. Unequal distribution of single phase loads in LV distribution network can create unbalance in the system even though the utility is supplying balanced voltage [5]. In future single-phase DERs of different ratings will be randomly located in LV networks. As a result, the unbalance in LV side will affect the MV side due to the flow of large unbalanced currents [6].

Custom power devices have been used to alleviate power quality problems [5]. Amongst them, DSTATCOM is the most popular. It can inject reactive power to balance the supply side currents and to improve power factor. At the same time it acts as an active filter to suppress harmonics in the network [7, 8]. In [9-11] the authors have investigated power loss and harmonics. As previously mentioned, DERs are going to be installed randomly all over the network. So it is possible for a particular phase to have excess power generation than its load demand. This excess power will be fed back to the transmission system causing unbalance. But at the same time, there may be one or two phases that require power supply from the substation. Therefore, if there exists a way to circulate the excess power from one phase to other phases, the power quality could be improved. In this paper, the power circulation capability of DSTATCOM has been investigated.

II. STRUCTURE AND CONTROL OF DSTATCOM

The DSTATCOM structure is shown in Fig.1. Three H-bridge converters are connected to common DC bus. The output of each H-bridge is connected to primary side of a transformer. The secondary side of the transformer is connected to a capacitor (C0). Thus the transformer leakage reactance (L2) and the capacitor together form an LC filter. The transformer secondary sides are connected in wye. The transformer provides galvanic isolation and voltage boost. The transformer turns ratio is assumed to be 1:n. To represent transformer losses and switching, the resistance Rf is used. The DSTATCOM operation is based on the output feedback of voltage control mode using poles shift control [12].

A typical DSTATCOM connection of a distribution system with DER is shown in Fig. 2. In this the DSTATCOM is represented by the voltage source $\left| V_{i} \right| \leq \delta$. The DSTATCOM needs to circulate excess power from one phase to the other phases in such a way so that a set of balanced power is drawn from the source. Therefore the DSTATCOM must be connected at the first node of the feeder as shown in Fig. 2 in which $L_{1}$ and $R_{1}$ represent the feeder impedance.

Note from Fig. 2 that the average real power entering the PCC must be equal to the sum of average load power and power flowing into the DSTATCOM. Otherwise the battery connected to the dc bus of the DSTATCOM will continuously charge or discharge.
Let us assume that the DSTATCOM regulates the magnitude of the PCC voltage. Therefore the angle of this voltage must be set such that the power balance in the circuit occurs. To obtain the angle ($\delta$), the PI controller is used \cite{[13]}

$$e = P_{sh_{ref}} - P_{sh}$$

$$\delta = K_p e + K_i \int e \, dt$$  \hspace{2cm} (1)

where $P_{sh}$ is the shunt power flowing towards the DSTATCOM and $P_{sh_{ref}}$ is its reference value, $K_p$ and $K_i$ are respectively the proportional and integral gains.

As mentioned above the magnitude of the PCC voltage is held constant. Once its angle is obtained from (1), the instantaneous reference voltages of the three phases are obtained from

$$v_{ta_{ref}} = \frac{V_p}{\sqrt{3}} \sin(\omega t + \delta)$$  \hspace{2cm} (2)

$$v_{tb_{ref}} = \frac{V_p}{\sqrt{3}} \sin(\omega t + \delta - 120^\circ)$$  \hspace{2cm} (3)

$$v_{tc_{ref}} = \frac{V_p}{\sqrt{3}} \sin(\omega t + \delta + 120^\circ)$$  \hspace{2cm} (4)

These voltages are then tracked in an output feedback pole shift control \cite{[12]}.  

Note that ordinarily the power should flow from the source ($v_s$) to PCC. Therefore the PCC voltage angle $\delta$ should lag the source voltage angle, which is taken as the reference angle. Therefore the constants $K_p$ and $K_i$ should assume negative values.

Referring to Fig. 1, the instantaneous power flow from the PCC to DSTATCOM is given by

$$p_{sh} = v_{ta} i_{fa} + v_{tb} i_{fb} + v_{tc} i_{fc}$$  \hspace{2cm} (5)

Here, $v_{ta}$, $v_{tb}$, and $v_{tc}$ are PCC voltages of phases a, b and c respectively and $i_{fa}$, $i_{fb}$ and $i_{fc}$ are three shunt currents flowing to DSTATCOM. The average power ($P_{sh}$) is calculated by averaging the instantaneous power $p_{sh}$ over a cycle.

### III. DSTATCOM Modes of Operation

The DSTATCOM can operate in two different modes. These are discussed below.

#### A. Grid Connected Mode

In this mode, the network is connected with the utility. The DSTATCOM consumes a fixed amount of power from the utility to cover its losses ($P_{loss}$). Therefore $P_{sh_{ref}}$ is set equal to $P_{loss}$. Since the DSTATCOM balances the PCC voltage and the source voltage $v_s$ is balanced, the source current $i_s$ (see Fig. 2) will also be balanced. Therefore the DSTATCOM circulates the excess phase power amongst the other phases. However, when the utility is absent, the DSTATCOM cannot absorb power from the utility. Therefore the reference has to be calculated differently.

#### B. Islanded Mode

In this mode, the DSTATCOM need either to supply the balance load power or absorb any excess power that cannot be used by the loads. In order to achieve this, the power reference $P_{sh_{ref}}$ needs to be changed. Note from Fig. 2 that the instantaneous load power is given by

$$p_l = v_{ta} i_{fa} + v_{tb} i_{fb} + v_{tc} i_{fc}$$  \hspace{2cm} (6)

This power is averaged over a cycle to obtain $P_{lav}$.

Now it can be seen from Fig. 2 that $i_l + i_t = 0$ in the absence of the utility. Therefore in order for the DSTATCOM to supply or absorb power, we must have

$$P_{sh_{ref}} = -P_{lav}$$  \hspace{2cm} (7)

Note that in this paper fault studies are not performed and it is assumed that the source disconnects inadvertently. The islanding condition is detected when the absolute values source currents in all the three phases fall below a small number.

### IV. Simulation Results

To validate the proposal, extensive simulation studies are performed using EMTDC/PSCAD.

**Example 1 (System Response without DSTATCOM Connection):** For this example, the system shown in Fig. 2 is used. The system parameters used are given in Table I. It is assumed that a single DER is connected to phase-a, which comes online at 0.3 s. The DER is injects 100 kW and 1 kVAR. The DSTATCOM is not connected for this case.

The source currents before and after DER connection are shown in Fig. 3. It can be seen that the peak of phase-a current reduces from 21 A to 5.5 A after the DER connection. Also, the angle of this phase current shifts from $-21^\circ$ to $-111^\circ$, as shown in Fig. 4. The angle, after DER connection, falls in the 3rd quadrant, indicating a reversal in direction of current flow.
The active power supplied by the three phases of the source before and after DER connection is shown in Fig. 5. It can be seen that phase-a was drawing 90 kW power before the DER connection, which then becomes –10 kW once the DER injects 100 kW.

### Table 1: System Parameters

<table>
<thead>
<tr>
<th>System Quantities</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Systems frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Source voltage</td>
<td>11 kV (L-L, rms)</td>
</tr>
<tr>
<td>Feeder impedance</td>
<td>$R_s = 3.025 , \Omega$, $L_s = 57.8 , \text{mH}$</td>
</tr>
<tr>
<td>Load impedance</td>
<td>Phase-a: $400 + j131.48 , \Omega$ Phase-b: $640 + j210.36 , \Omega$ Phase-c: $2400 + j788.85 , \Omega$</td>
</tr>
<tr>
<td>DSTATCOM parameters</td>
<td>$R_f = 1.0 , \Omega$ $C_f = 50 , \mu\text{F}$ $V_{dc} = 2.5 , \text{kV}$ Transformer: 1 MVA, $n = 7.33$, 2.5% leakage</td>
</tr>
<tr>
<td>Controller parameters</td>
<td>$K_P = -0.01$ $K_I = -10$</td>
</tr>
</tbody>
</table>

**Example 2 (System Response with DSTATCOM Connection):** This is an extension of Example-1, in which the DSTATCOM is connected 0.8 s. The peak magnitude reference PCC voltage is chosen as 8.98 kV (i.e., rms $|V| = 6.35 \, \text{kV}$). The angle of the PCC voltage is adjusted by the PI controller of (1), for which the power reference ($P_{sh,ref}$) is chosen as 10 kW (the loss in the DSTATCOM circuit).

The source power for the three phases is shown in Fig. 6. It can be seen that they become balanced within 0.1 s and attain steady state within 0.3 s. After 1.1 s, the power supplied by the three phases becomes constant at 22 kW.

**Fig. 6.** Source power before and after DSTATCOM connection (Example-2).

The PCC voltage is shown in Fig. 7. It can be seen that these are balanced once the DSTATCOM is operational and has a peak of 9 kV. The angle of this voltage is shown in Fig. 8. Since the total power flows from the utility to the network, the angle settles to a negative value. This angle however remains zero before the DSTATCOM connection. Since the PCC voltage becomes balanced, the source current also gets balanced as shown in Fig. 9. The active power consumed by the DSTATCOM is shown in Fig. 10. It can be seen that this is zero before the DSTATCOM connection but settles to its reference value of 10 kW once it is connected.

**Fig. 7.** PCC voltage after DSTATCOM connection (Example-2).

**Fig. 8.** PCC voltage angle (Example-2).

**Example 3 (DSTATCOM connection to a 4-bus system):** In this example, we consider a 4-bus system as shown in Fig. 11. The source voltage and feeder impedance are the same as those used in Examples 1 and 2. The load impedances that are connected to the four buses and their DER ratings are given in Table II. It is assumed that all the DERs are connected to phase-a at their respective buses.
In this example, the DERs are connected at 0.3 s, while the DSTATCOM is connected at 1.0 s. The source phase powers are shown in Fig. 12. It can be seen that phase-a feeds over 400 kW power back to the utility before the DSTATCOM connection. However once the DSTATCOM is connected, each phase sends back about 25 kW power back to the grid. This is obvious from the PCC voltage angle shown in Fig. 13. The angle settles to 0.5°, indicating a power flow from the PCC to the utility. The power consumed by the DSTATCOM is shown in Fig. 14. It can be seen that it consumes an average of 10 kW.

**Example 4 (Bus voltage control):** This is a continuation of Example 3. The rms values of the four load bus voltages are plotted in Fig. 15, as the system reaches steady state after DSTATCOM connection. It can be seen that the voltage of Bus-1 (Vba1) is tightly regulated as the DSTATCOM is connected to this bus. However the voltages in the other three buses drop, which increases as the length from PCC increases.
Since the DERs inject active power in a near unity power factor condition, they cannot control the bus voltage. Instead, if they are allowed to inject/absorb some amount of reactive power, the bus voltages can be controlled. To facilitate this, a PI controller is used at each bus that track a reference voltage to generate reactive power, as given by

\[ Q_i = K_{PQ} (V_{refi} - V_{hi}) + K_{IQ} \int (V_{refi} - V_{hi}) dt \]  (8)

for \( i = 2, 3, 4 \), where \( V_{refi} \) is the rms reference voltage of \( i \)th bus, \( V_{hi} \) being its rms voltage. Note that since Bus-1 voltage is controlled by the DSTATCOM itself, another voltage controller may cause system instability and therefore DER at this bus has been precluded from reactive control. For this study the following values are chosen

\[ K_{PQ} = 2.0, \quad K_{IQ} = 125, \quad V_{refi} = 6.35 \text{kV} \]

The rms bus voltages with reactive power control are shown in Fig. 16. It is assumed that the reactive power control occurs as soon as the DERs are connected (i.e., at 0.3 s). It can be seen that the bus voltages are constant irrespective of DSTATCOM connection at 1.0 s. The reactive power injection/absorption by the three DERs is shown in Fig. 17. It can be seen that DER at Bus-4 needs to inject more reactive power since its bus the lowest (see Fig. 15). As a consequence, buses 2 and 3 absorb reactive power.

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**Example 5 (Islanding operation with power consumption):** This is also a continuation of Examples 3 and 4. With the system operating in steady state, suddenly the utility system, to the left of the PCC, cuts off at 2.5 s. The three phase source powers are shown in Fig. 18. It can be seen that they become zero at 2.5 s. Furthermore, each phase supplies around 25 kW back to the utility with the DSTATCOM connection. Therefore the DSTATCOM must absorb this amount of power once the utility switches off. This is shown in Fig. 19, where it can be seen that the average power consumed by the DSTATCOM is 80 kW. The PCC voltage angle is shown in Fig. 20. It is rather difficult to comment on the nature of this angle since the source is not present. However, this angle reduces to accommodate power flow from the DERs to the DSTATCOM.

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**Example 6 (Islanding operation with power generation):** This example is similar to Example 5 except that the four DERs are now supplying 200 kW, 250 kW, 300 kW and 250 kW. The utility is disconnected at 2.5 s. The three phase source powers are shown in Fig. 21. Each phase supplies around 40 kW from the utility before disconnection. Therefore the DSTATCOM must supply around 120 kW once the utility is cut off. This is shown in Fig. 22. The PCC voltage angle is shown in Fig. 23. This angle is negative before the
disconnection of the utility since the power must flow from the utility to the PCC. However, this angle increases to accommodate power flow from the DSTATCOM to the loads.

It is shown that if one or more phase has excess power generation than the load demand due to large number of single phase DER presence, a single DSTATCOM is capable of circulating this extra power to other phases to make the source components balanced. Thus it can also prevent flow of large unbalanced current upstream. Furthermore, the capability of the DSTATCOM for supplying/absorbing active power in the absence of the utility source has been studied. It is shown that the DSTATCOM is able to hold the PCC voltage constant by either absorbing or supply power. This however will depend on the capacity (rating) of the device, which has not been studied here.

Also a reactive power control scheme based on PI controller is developed for the DERs to regulate the load bus voltages. It has been shown that without these controllers the load bus voltages drop (or rise) from their nominal values.

V. CONCLUSIONS

In this paper, through various simulation studies, the power circulation capability of the DSTATCOM has been investigated.

REFERENCES