Voltage Dip Rating Reduction Based Optimal Location of DVR for Reliability Improvement of Electrical Distribution System

Mohammad Mohammadi
Department of Electrical Engineering, Borujerd Branch, Islamic Azad University, Borujerd, Iran
Corresponding Author email: Mohamadi.m@iaub.ac.ir

ABSTRACT: This paper presents a new method to reliability improvement of distribution system by optimal sizing and placement of Dynamic Voltage Restorer (DVR) based on reducing the number of sagged bus and outage load. The PSO based approach is used to solve the DVR optimization problem with considering capital cost of DVR installation and interruption costs due to interruption of loads in sensitive point. In this paper using ETAP software, with considering the three phase fault, the worst point that leads to the propagation of voltage sags to most number of system buses, is investigated and located. Simulation results show that the proposed method is efficient and feasible for improving the system reliability level by reducing the number of sagged bus and load outages and momentary interruptions. Finally in this paper, after optimal location of DVR, the reliability improvement is investigated through expected energy not supplied (EENS) index, average system interruption frequency index (ASIFI) and the momentary average interruption frequency index (MAIFI).

key word: Dynamic Voltage Restorer, Particle swarm optimization, Reliability, Voltage sag

INTRODUCTION

Voltage sag that is often occurred by short circuits may lead to malfunction and process interruption of sensitive loads. Once the process is interrupted it takes much time to continue the process, therefore influencing the reliability of distribution systems. In (IEEE_Std.1159, 1995), voltage sag is generally defined as any low voltage drop with magnitude between 10% and 90% of the nominal rms voltage and remaining for a long time between 0.5 cycles and 1 min. Many investigations have been implemented for voltage sag reduction in order to increase reliability of system. In a related work, a method was introduced for voltage sag assessment based on whether the equipment will trip or not. As a reliability indicator from the customer’s perspective voltage acceptability curves are introduced (IEEE_Std.493, 2007), (Bollen, 1996). Based on the above discussion, it can be concluded voltage sag may causes power supply interruption for many types of loads and therefore reliability of distribution system is highly affected due to voltage sag process. In other words, voltage sag mitigation techniques can be employed for improving the reliability of distribution systems. In another research, an algorithm for reliability improvement in presence of static series voltage regulator in distribution system for reducing interruption time is presented and discussed by (Hosseini et al., 2009). In (Carmen and Djalma, 2006), distributed generation (DG) as one of the main alternative source for reliability improvement of distribution system is introduced and investigated. By (Salman et al., 2010), (Nesrallah et al., 2012) DSTATCOM was utilized mainly to mitigate voltage sag propagation and avoid process interruption and finally reliability enhancement of distribution systems.

At present, many types of very flexible controllers which capitalize on newly available power electronics components are emerging for custom power applications. Among these, the distributed static compensator and the dynamic voltage restorer are the most effective devices; as discussed by (Slump et al., 1998) both of them are based on the voltage source converter (SVC) principle. Dynamic voltage restorers (DVRs) are now one of the main D-FACTS devices in industry to mitigate the effect of voltage dips on sensitive loads as investigated by (Ravi Kumar and Siva Nagaraju, 2007), (Nielsen, 2002) and (John Newman et al., 2005). In (Ghazi and Kamal, 2005) optimal placement of DVR is investigated only based cost of DVR without considering reliability assessment in distribution system.

This study focuses, on a new method for reliability enhancement of distribution system based on the optimal placement and sizing of the DVR. At first, the proposed method, in order to decrease the exposed area
of voltage sag propagation due to weak area is presented and analyzed. Then, DVR placement is optimized for decreasing the number of sagged buses in the distribution systems. Finally, in order to evaluate system reliability, a method for estimating the number of sags which may be experienced at each load point in distribution system is used along with reliability indices such as ENS, ASIFI and MAIFI.

**Dynamic Voltage Restorer (RVR) Configuration**

Basic configuration of dynamic voltage restorer is shown in Figure 1. It generally consists of a series inverter (VSI), a filter at the end of inverter for eliminating produced harmonic due to inverter switching process and finally an energy storage device connected to the DC link.

The main function of DVR is to inject an appropriate voltage in series with the supply through injection transformer whenever voltage sag is detected. Other tasks of DVR are harmonic compensation and power factor correction.

![DVR series connected topology](image)

Compared to the other custom power devices, the DVR clearly provides the best economic solution for its size and capabilities.

The various to inject DVR compensating voltage are reviewed as follows:

**a. Pre-Dip Compensation (PDC):**

The basic of PDC method is continuously tracking supply voltage and compensate load voltage during fault to pre-fault condition. In this technique, the load voltage can be ideally compensated, but the injected active power cannot be controlled and it is determined according external conditions such as the type of faults and load conditions. In this method due to lack of negative sequence detection in the case of single-line faults, the phase-oscillation appears in compensating voltage. By refer to (Ravi Kumar and Siva Nagaraju, 2007), The magnitude and the angle of the DVR voltage are presented as follows:

\[
V_{dvr} = \sqrt{V_s^2 + V_L^2 - 2V_s V_L \cos(\theta_s - \theta_L)} \quad (1)
\]

\[
\theta_{dvr} = \tan\left(\frac{V_s \sin \theta_L - V_L \sin \theta_s}{V_L \cos \theta_L - V_s \cos \theta_s}\right) \quad (2)
\]

And the active power of DVR is:

\[
P_{dvr} = I_L (V_L \cos \theta_L - V_s \cos \theta_s) \quad (3)
\]

**B. In-Phase Compensation (IPC):**

This approach is the most used method in compensating voltage in which the injected voltage by DVR is in phase with the supply side voltage regardless of the load current. The main feature of the IPC method is that, it is suitable for minimum voltage or minimum energy operation strategies as discussed by (Nielsen, 2002). In other word, this approach requires large amounts of real power to mitigate the voltage sag.

The voltage and active powers of DVR in IPC method are determined as follows:

\[
V_{dvr} = V_L - V_s \quad (4)
\]

\[
\theta_{dvr} = \theta_s \quad (5)
\]

\[
P_{dvr} = I_L V_{dvr} \cos \theta_s = I_L (V_L - V_s) \cos \theta_s \quad (6)
\]
Optimization Problem Formulation

In this work, the objective function of DVR sizing and sitting is formulated to minimize the total number of sagged buses with considering investment cost and interruption cost by DVR as follows:

Minimize

\[ C_{Total} = \alpha_1 \times C_1 + \alpha_2 \times C_2 \]  

(7)

Here \( C_1 \) represents the interruption cost due to load curtailment in buses affected by voltage sag and \( C_2 \) is related to total investment cost of the DVR devices. \( \alpha_1, \alpha_2 \), are weighting coefficients in objective function.

The interruption cost is represented as follows:

\[ C_1 = \sum_{j=1}^{N_{sag}} \sum_{i=1}^{N_{L,j}} C_{ij} \times L_{ij} \]  

(8)

Where \( N_{sag} \) is the total number of sag events in the specified simulation period. \( C_{ij} \) represents the adjusted per-unit interruption cost and \( L_{ij} \) indicates the adjusted average load. \( N_{L,j} \) represents the total number of load connected to jth bus encountered by voltage sag.

\( C_2 \) as investment cost of DVR can be expressed as follows:

\[ C_2 = N_{DVR} \times C_{DVR} \]  

(9)

The necessity of optimization in this work is to find optimal solution for voltage sag mitigation problem in distribution systems. The formulation of suitable objective function is the main step in optimization. The solution is by determining optimal placement and sizing of DVR in distribution system. This study deal with DVR placement based an objective function with aiming minimizing total costs including interruption cost and investment cost through minimizing the total number of sags. During the searching process, for every change in the device location, the number of sagged buses \( N_{sag} \) must be calculated. This maybe performs using calculation of healthy buses (Nhth).

The number of buses reaching the healthy condition (Nhth) due to the compensation of the DVR must be calculated. In this study a bus is said to be healthy when its voltage magnitude remains between 0.86 pu and 1.1 pu. With considering \( C_i \) as the healthy condition with values 0 or 1 for bus i during voltage sag interval, then it could be written as follows:

\[ N_{hlth} = \sum_{i=1}^{N_{nt}} C_i \]  

(10)

\[ C_i = \begin{cases} 1 & \text{if } 0.86 \leq V_i \leq 1.01 \\ 0 & \text{otherwise} \end{cases} \]  

(11)

Therefore the sagged buses of system could be calculated as follows:

\[ N_{sag} = N_{sys} - N_{hlth} \]  

(12)

The optimization procedure must be subjected to system operation constraints, where these constraints can be mentioned as:

\[ |V_{min}| \leq |V_i| \leq |V_{max}| \]  

(13)

\[ |\delta_{min}| \leq |\delta_i| \leq |\delta_{max}| \]  

(14)

\[ |I_i| \leq |I_{i,max}| \]  

(15)

Equation (13) represents the nominal bus voltages must be within standard limits, where \( V_i \) is voltage magnitude of bus i, \( V_{max} \) is the maximum limit of nominal voltage magnitude and \( V_{min} \) is lower limit of nominal voltage magnitude.

Equation (14) represents the angle bus voltages limitation.

Equation (15) indicates the current flows must be within the thermal limits of the lines. Where \( I_i \) denotes the current of line i and \( I_{i,max} \) represents the thermal limit of the line i.

After optimal placement of DVR, in order to evaluate the impact of DVR on reliability of distribution system, the reliability assessment is carried out based on load based index such as the average system interruption frequency index (ASIFI), momentary index such as the momentary average interruption frequency
index (MAIFI) and energy not supplied (ENS) are most suitable indices for reliability assessment related to voltage sag problems.

Using calculating of number of sags and translating into momentary interruptions and load outages, the corresponding reliability indices can be obtained. The sustained interruptions are considered for all downstream loads of the faulted bus. At the same time, all upstream loads of the same faulted bus may experience momentary interruptions due to voltage sags.

The ASIFI index is calculated on load outages rather than customers affected, where the voltage sag may cause load outages. This index is expressed by (IEEE_Std. 2007.493, 2007) as follows:

\[ ASIFI = \frac{\sum L_i}{L_T} \]  

Where \( L_i \) represents the connected kVA load interrupted for each interruption event, and \( L_T \) is the total connected kVA load served.

Another index, i.e. MAIFI which indicate the reliability level due to load outages can be expressed by (IEEE_Std. 2007.493, 2007) as follows:

\[ MAIFI = \frac{\sum IMi \times Nmi}{N_T} \]  

Where \( IMi \) denotes number of momentary interruptions for each event, \( Nmi \) represents number of interrupted customers for each momentary interruption event during the reporting period and \( N_T \) is total number of customers served for the areas.

Another reliability index is the energy not supplied, ENSi and is calculated as follows (Bollen, 1996):

\[ ENS = \sum_{i=1}^{N_{sys}} \sum_{j=1}^{N_{b,i}} C_{ij} \cdot r_{ij} \]  

Where \( r_{ij} \) represents the failure duration that can include any required adjustments.

In this study, the reliability improvement corresponding to the mitigating of voltage sag by DVR in distribution systems can be indicated by the calculation of (16-18).

**Weak area analysis for fault point location using ETAP software**

The fault analysis was performed for all buses of distribution system. Following the three phase fault in bus number 1 of system, the voltage magnitude for all buses of distribution system will be calculated using ETAP and so this procedure will be repeated for all buses of system from bus number 1 to \( N_{sys} \), in other words, when occurring fault in every buses of system from 1 to \( N_{sys} \) the voltage magnitude could be calculated by ETAP for each bus of system.

The results of this procedure will be set as three dimension matrix, where the X-axis represents the number of system buses, Y-axis indicates the fault locations and Z-axis denotes the bus voltage magnitudes. The voltage sag distribution on all system buses for three phase fault with zero fault resistance \( Zf \) will be obtained. These results could be depicted as a surface that the greatest darkness points of voltage sag distribution (Z-axis) denotes the sensitive buses in propagating voltage sag throughout the distribution system. Therefore, this group of buses is considered as a weak area in the system. Among the weak buses, the weakest bus that is exposed under the most propagation of voltage sags to most number of system buses will be considered for occurring fault as the worst point in system. The detail of this method is discussed by (Nesralh et al., 2012).

So the three phase fault will occur in the worst point and best locations and sizes of DVR with considering investment coast and interruption cost for minimize sagged bus numbers will be optimized.

**SIMULATION AND DISCUSSION**

A distribution network with 15 buses, connected to the transmission grid by a substation with 30 MVA, 115/10 kV is considered as case study. The topology of this distribution network is shown in figure 2. The system includes two large induction motors that are connected to buses of numbers 9 (50 kw) and 13 (75 kw) respectively. The load point data of test system is listed in Table I.
TABLE 1. Load and customers at respective load point

<table>
<thead>
<tr>
<th>Load</th>
<th>Total Load (MW)</th>
<th>No. of Customers</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>120</td>
<td>10</td>
</tr>
<tr>
<td>5</td>
<td>145</td>
<td>30</td>
</tr>
<tr>
<td>6</td>
<td>120</td>
<td>25</td>
</tr>
<tr>
<td>7</td>
<td>250</td>
<td>60</td>
</tr>
<tr>
<td>8</td>
<td>240</td>
<td>40</td>
</tr>
<tr>
<td>9</td>
<td>130</td>
<td>50</td>
</tr>
<tr>
<td>10</td>
<td>145</td>
<td>60</td>
</tr>
<tr>
<td>11</td>
<td>130</td>
<td>30</td>
</tr>
<tr>
<td>12,13</td>
<td>100</td>
<td>40</td>
</tr>
<tr>
<td>14,15</td>
<td>250</td>
<td>100</td>
</tr>
</tbody>
</table>

Also three DC loads rectified using converter, are connected to buses 4, 11 and 14 that as a result they generate and insert flickers and harmonics to network. The fault analysis is performed for all buses with rated 11kV voltage level except the main substations.

The voltage sag distribution on all system buses due to a three phase fault (LLL) without any fault impedance (Zf=0) is depicted in figure 3. It is clear from the voltage sag distribution on Z-axis that buses 4, 5, 6, 9 and 14 are the most sensitive buses in extending voltage sag throughout the system. So, this group of buses is considered as the weakest points in the system to extend voltage sag. Between the weak buses (15 in number), bus 5 is considered as the weakest bus in the system, because in case of occurring fault in this bus, the voltage sag can be easily extent to the most buses of system.

Short circuit analysis is performed using ETAP software; on all of buses of system. Figure 4 indicates the simulation model of system in ETAP for this purpose.
Figure 4. Etap (Power Station) model of studied distribution network

Figure 5 represents the distribution of voltage sag because of three phase fault at bus 5 in compared with base case voltage profile of the system. From this figure it is obvious that the voltage magnitudes of all buses of system are within standard limits during base case load flow but in case of considering three phase fault in bus 5, it leads to voltage sag propagation at the most buses of system.

Figure 5. Voltage magnitudes of system buses at base case and during three phase fault at bus 5

It is notable that determination of the weak area is a main step in the voltage sag assessment and mitigation, because it gives adequate information to optimize optimal placement and sizing of the studied system using the PSO algorithm as an optimization tool. Fig. 6 shows the convergence of the PSO algorithm to minimize the total costs including capital cost and interruption cost as objective function (7) and determine optimal placement and sizing of DVR.

The optimum size and placement can be selected by the algorithm within the range 0-1MVA. Table II gives this result.

Figure 6. Convergence characteristics of PSO for optimal placement
The voltage sag distribution on all system buses for three phase fault with zero fault impedance ($Z_f=0$) in presence of DVRs in optimal locations in comparison without any DVR is shown in figure 7.

### Table 2. The optimum size and placement of DVR

<table>
<thead>
<tr>
<th>DVR Location</th>
<th>Capacity (MVA)</th>
<th>Inset Voltage (p.u)</th>
<th>Angle Voltage (rad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feeder Between buses</td>
<td>6</td>
<td>16</td>
<td>0.2232</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>11</td>
<td>0.4123</td>
</tr>
</tbody>
</table>

Figure 7. Improvement of sag distribution in terms of system buses due to three phase fault at various fault locations after DVRs placement.

Figure 8 shows the simulation results of short circuit analysis due to a fault at bus 5 along with the base case voltage profile and obtained results after optimal placement of DVR. An improvement in the number of healthy buses can be observed as compared with the results of pre DVR installation.

Table III gives the improvement system indices using DVR in placement with optimal size.

As seen in table III, by DVR, the number of sagged buses of system, during fault in weakest point, decease from 10 buses to 6 buses. Therefore the more little load point will be interrupted, so this reduce interruption cost from 145 [$/yr$] to 113 [$/yr$].

![Figure 8. Voltage magnitudes of system buses at base case and during three phase fault at bus 5, after optimal placement of DVR](image)

Figure 8. Voltage magnitudes of system buses at base case and during three phase fault at bus 5, after optimal placement of DVR.
TABLE 3. DVR installation assessment

<table>
<thead>
<tr>
<th>Item</th>
<th>Before DVR Placement during Fault</th>
<th>After DVR Placement during Fault</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sagged Bus during fault in weakest bus with suppose Vcrit=0.86 p.u</td>
<td>10</td>
<td>6</td>
</tr>
<tr>
<td>Load Point Outage</td>
<td>10</td>
<td>6</td>
</tr>
<tr>
<td>ENS Index (kW/yr)</td>
<td>258</td>
<td>187</td>
</tr>
<tr>
<td>Interruption Cost ($/yr)</td>
<td>145</td>
<td>113</td>
</tr>
<tr>
<td>ASIFI Index</td>
<td>0.83540</td>
<td>0.45810</td>
</tr>
<tr>
<td>MAIFI Index</td>
<td>1.84847</td>
<td>1.32340</td>
</tr>
</tbody>
</table>

CONCLUSION

In this paper, reliability enhancement with considering installation cost of DFACTS device in distribution system has been investigated. The reliability improvement is investigated by optimal placement and sizing of dynamic voltage restorer (DVR) as voltage sag numbers reduction approach in order to minimizing interruption cost and capital costs. The simulation results indicate that the proposed technique is efficient to improve reliability of distribution network. The reliability assessment indices such as EENS, ASIFI & MAIFI are evidences of benefits of the proposed method. The main reason in selection of DVR as voltage sag mitigation device in this study is related to many capabilities of this device in mitigation various power quality phenomena in respect to other facts devices. Of course, this study focuses on voltage sag mitigation using DVR and so the optimal placement and sizing of this DFACT is considered and analyzed. The optimization is performed based on minimizing total cost including capital cost for DVR installation and interruption costs for considering reliability improvement due to sagged buses reduction and therefore reduction of outage load points.

REFERENCES