Suitable Capacitor Requirements for Dynamic Desired Voltage Sag Compensation on Distribution Network Using DVR

Sunil Kumar Gupta and H. P. Tiwari

Abstract—**Dynamic voltage restorers (DVR) are connected in series with the distribution feeder at low and medium voltages. The mitigation capability of these devices are mainly limited by the capacitor rating. It is an important task for DVR system operation and appropriate desired voltage sag compensation. This paper is intended to assimilate capacitor ratings unit of a DVR power circuit with distribution voltage. this ratings information are available in a convenient manner for DVR power circuit.**

Index Terms—**Capacitor rating, DC energy storage, dynamic voltage restorer, power quality, voltage sag.**

I. Introduction

Presently, the majority of power quality problems are due to different fault conditions. These conditions cause voltage sag [1]. Dynamic voltage restorer (DVR) can provide the cost effective solution to mitigate voltage sag by establishing the appropriate voltage quality level, required by the customer [2], [3].

The basic structure of a DVR is shown in Fig.1. It is divided into six categories: 1) *Energy Storage Unit:* It is responsible for energy storage in DC form. Flywheels, batteries, superconducting magnetic energy storage (SMES) and supercapacitors can be used as energy storage devices. It is supplies the real power requirements of the system when DVR is used for compensation [3]. 2) *Capacitor:* DVR has a large DC capacitor to ensure stiff DC voltage input to inverter. 3) *Inverter:* An Inverter system is used to convert dc storage into ac form [4]. Voltage source inverter (VSI) of low voltage and high current with step up injection transformer is used for this purpose in the DVR compensation technique [3]. 4) *Passive Filters:* Filters are used to convert the inverted PWM waveform into a sinusoidal waveform. This is achieved by eliminating the unwanted harmonic components generated VSI action. Higher orders harmonic components distort the compensated output voltage [1]. 5) *By-Pass Switch:* It is used to protect the inverter from high currents in the presence of faulty conditions. In the event of a fault or a short circuit on downstream, the DVR changes into the bypass condition where the VSI inverter is protected against over current flowing through the power semiconductor switches. The rating of the DVR inverters becomes a limiting factor for normal load current seen in the primary winding and reflected to the secondary winding of the series insertion transformer. For line currents exceeding the rating, a bypass scheme is incorporated to protect the power electronics devices [5]. 6) *Voltage Injection Transformers:* In a three-phase system, either three single-phase transformer units or one three phase transformer unit can be used for voltage injection purpose. [1].

Basic principal of DVR is to transfer the voltage sag compensation value from DC side of the inverter to the injected transformer after filter. The compensation capacity of a particular DVR depends on the maximum voltage injection capability and the active power that can be supplied by the DVR. When DVR's voltage disturbance occurs, active power or energy should be injected from DVR to the distribution system [6]. A DC system, which is connected to the inverter input, contains a large capacitor for storage energy. It provides reactive power to the load during faulty conditions. When the energy is drawn from the energy storage capacitors, the capacitor terminal voltage decrease. Therefore, there is a minimum voltage required below which the inverter of the DVR cannot generate the require voltage thus, size and rating of capacitor is very important for DVR power circuit [7]. The DC capacitor value for a three phase system can be derived [8]. The most important advantage of these capacitors is the capability to supply high current pulses repeatedly for hundreds of thousands of cycles. Selection of capacitor rating is discussed on the basis of RMS value of a capacitor current, rated voltage of a capacitor and VA rating of the capacitor [9].

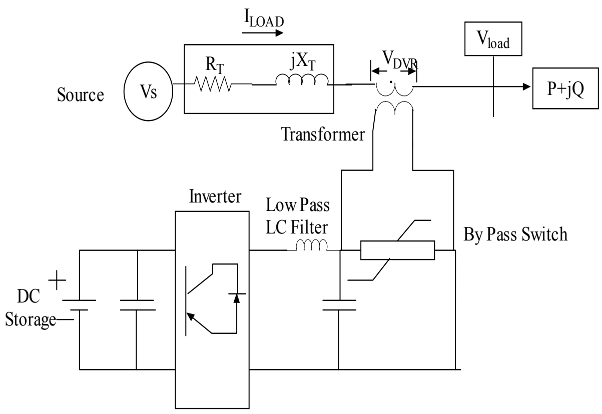

Fig. 1. Basic structure of dynamic voltage restorer.

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Capacitor is used as an input in voltage source inverters (VSI). The capacitor provides a unique value in high energy storage and low device impedance. Selecting the right capacitor for DVR application requirement is necessary for proper voltage sag compensation. The purpose of this capacitor is mainly to absorb harmonic ripple and hence it has a relatively small energy storage requirement [10].

Capacitor sizing is referred to the fault current in the system. The difference in current between the current before and after the fault is considered as current faults. In capacitor sizing, a suitable range of DC capacitor is needed to store the energy to mitigate the voltage sag. The DC capacitor, C is used to inject power to the VSI, when the voltage is in sag condition. In the design, the harmonic effects must be considered because the load is inductive and this may affect the value of C_{DC}. The following equation is used to calculate C (Chin-Yuan Hsu et al, 1995), for a three phase system the equation is given by,

$$C_{DC} = 3 \times \frac{V_s . \Delta I_L . T}{V_{C_{\max}}^2 - V_{DC}^2} \tag{1}$$

where,

V_S = peak phase voltage

I = step – drop of load current

T = period of one cycle of voltage and current

V_{CMAX} = pre-set upper limit of the energy storage C (per-phase),

V_{DC} = voltage across C (per-phase).

The value of ΔI_L can be found by measuring the load current before and during the voltage sag (Chin-Yuan Hsu et al, 1995) [11].

The value of V_{DC} is given form by

$$V_{DC} = \frac{3\sqrt{3}.\ V_s . \cos\alpha}{\pi} \tag{2}$$

where, α = delay angle

if α = 0, the equation become,

$$V_{DC} = \frac{3\sqrt{3}.V_s}{\pi} \tag{3}$$

II. Control Philosophy Used in DVR

Voltage sag is created at fault point X as shown in Fig.3. Load voltage is sensed and passed through a sequence analyzer. During an unbalanced fault situation, the phase voltage vectors may be altered to V_{a2}, V_{b2} and V_{c2}. The DVR can inject appropriate voltages V_{inja}, V_{injb} and V_{injc} in order to build a balanced three phase system of voltage vectors.

A sequence analysis based control strategy is adopted in this paper. The phase voltages are converted to balanced system of positive (V_1), negative (V_2), and zero (V_0) sequence components. The DVR control aims to maintain the positive sequence component at a predetermined value. Therefore, the injected voltage V_{inj} of a particular phase can be written as the vector sum of reference voltage (V_{ref}), positive (V_1) and negative (V_2) sequence voltages, as given in [12].

$$\overrightarrow{V_{inj}} = \overrightarrow{V_{ref}} - \overrightarrow{V_1} - \overrightarrow{V_2} \tag{4}$$

The control system consist of well known park transformation theory according to this the DQ transformation is a transformation of coordinates from the three-phase stationary coordinate system to the dq rotating co-ordinate system as shown in Fig.2.

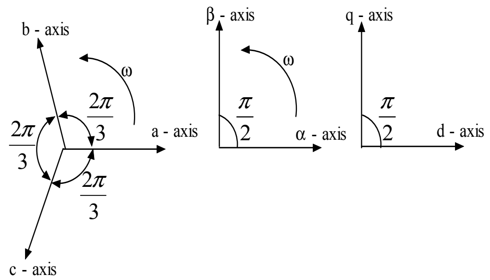

Fig. 2. Transformation co-ordinate system.

$$f_{0\alpha\beta} = V_m \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} \cos\omega t \\ \cos\left(\omega t - \frac{2\pi}{3}\right) \\ \cos\left(\omega t + \frac{2\pi}{3}\right) \end{bmatrix} \tag{5}$$

$$f_{abc} = V_m \begin{bmatrix} \cos\ \omega t \\ \cos\left(\omega t - \frac{2\pi}{3}\right) \\ \cos\left(\omega t + \frac{2\pi}{3}\right) \end{bmatrix} \tag{6}$$

The signal f_{abc} in the *a-b-c* stationery frame is rotating with the frequency of ω in radians/sec. The signals 0-α-β in stationery frame is obtained using (5). $f_{0\alpha\beta}$ in is still rotating with the frequency of ω radians/second. To eliminate this frequency, a step further is taken; a transformation from the 0-α-β stationery coordinate system to the 0-*d*-*q* rotating coordinate system is performed. The matrix in (7) is assigned such that when it is multiplied by 0αβ *f*, the 0-α-β coordinates which are in stationery frame will be rotating with the same frequency as that of 0-*d*-*q* rotating frame as given in (8)

$$[B] = \begin{bmatrix} \cos\omega t & \sin\omega t \\ -\sin\omega t & \cos\omega t \end{bmatrix} \tag{7}$$

$$f_{0dq} = \begin{bmatrix} \cos\omega t & \sin\omega t \\ -\sin\omega t & \cos\omega t \end{bmatrix} \begin{bmatrix} f_{0\alpha\beta} \end{bmatrix} \tag{8}$$

The d-q frame values V_d is compared with V_{dref} (load voltage set point) similarly V_q value is compared with the null reference. The errors component $V_{d\ error}$ and $V_{q\ error}$ are considered as a actuating signal. The algorithm is further carried a step forward, where the voltage reference signal in $0 - d - q$ rotating frame is converted back into $a - b - c$ stationery frame, the inverse transformation from $0 - d - q$

rotating frame to $a - b - c$ stationery frame is achieved using.

$$f_{abc} = \left[B^{-1}\right] f_{0dq}.\left[A\right] \tag{9}$$

$a - b - c$ stationery frame is used as the reference signal for switching of VSI which is based on the space vectors Pulse Width Modulation (PWM) technique [13-17].
Detailed simulations are performed on the DVR test system using MATLAB SIMULINK.

III. Parameters of DVR Test System

Electrical circuit model of DVR test system and Voltage sag is created at load terminals via a fault is shown in Fig.3 [18]. System parameters are listed in Table I. Load voltage is sensed and passed through a sequence analyzer.

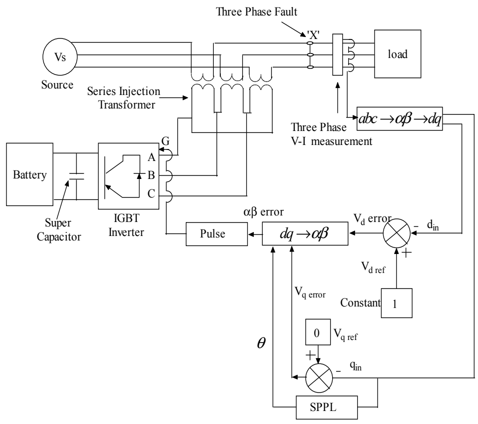

Fig. 3.Circuit model of DVR test system.

TABLE 1: DVR Test System Parameters

System Quantities	Standards
Inverter Specifications	IGBT based,3 arms, 6 Pulse, Carrier Frequency =1080 Hz, Sample Time= 5 μs
Fault Resistance	R= 0.66 ohms
Load	R=0.1 ohms, L=0.1926 H
Transmission Line Parameters	R=0.01273 (ohms / km) L=0.9337 (mH / km) C=12.74 (nf / km)
Transmission Line Length	10km

MATLAB Simulation diagram of the DVR test system is shown in Fig.3. System comprises of 11 kV, 50 Hz generator, feeding distribution line (load feeder) through a 3-winding transformer connected in Y/Δ/Δ, 11/132/ 11 kV.

IV. Practical and Theoretical Analysis of Different Capacitor Ratings in DVR Power Circuit

System performance is analyzed for compensating symmetrical and unsymmetrical voltage sag with different capacitor rating in DVR power circuit; so as to achieve rated voltage at a given load feeder.

System 1: 11 kV Distribution Line (Load Feeder)

Case 1: Three Phase Fault Analysis (By Using MATLAB Simulation)

In this case an 11 kV load feeder is considered, The DVR is designed to compensate for voltage sag at the load side. To illustrate voltage sag compensation by the DVR, firstly a three phase voltage sag condition is generated by initiating a fault at time t = 0.4 sec, the duration of the fault is 0.2 sec and the percentage of sag is 17.02% in which the voltage drops from 1.0 to 0.8598 p.u.. In this situation, the system needs 17.02% of voltage from DVR to inject into the system, Fig.4 shows the p.u. voltage into the system during voltage sag condition. Fig.5 to Fig.7 shows the DVR performance in presence of energy storage devices of 5 kV with different capacitor ratings viz. 450×10^{-3}F to 450×10^{-15}F in DVR circuit. The approximate battery capacity is 9050 Ampere-hour (AH).

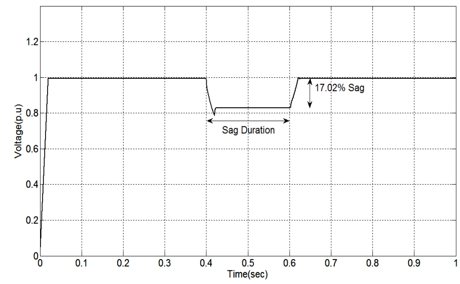

Fig. 4.Voltage p.u. at 11 kV distribution line (load feeder) without DVR System.

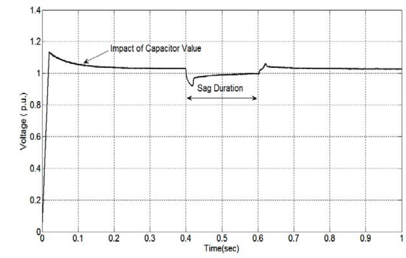

Fig. 5. Voltage p.u. at the Load Point with Capacitor Rating in between 450×10^{-3} F to 450×10^{-5} F.

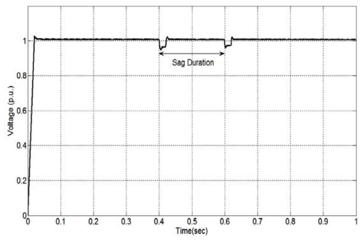

Fig. 6. Voltage p.u. at the load point with capacitor rating in between 450×10^{-6} F to 450×10^{-12} F.

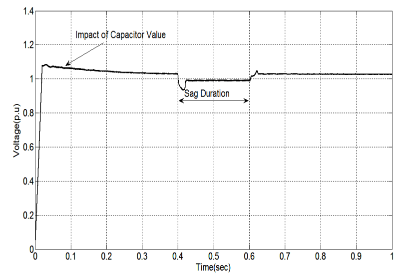

Fig.7. Voltage p.u. at the Load Point with Capacitor Rating of 450×10^{-14} F to 450×10^{-18}F.

Table II shows that voltage sag of 17.02% in 11 kV distribution line is fully compensated with the capacitor ratings in between range of 450×10^{-6} to 450×10^{-12} F in

DVR power circuit.

TABLE II: COMPARISON IN BETWEEN CAPACITOR VALUES AND VOLTAGE SAG COMPENSATION AT 11 KV FEEDER WHEN THREE PHASE FAULT

Capacitor Value in F	**Status about Voltage Sag Compensation**
450×10^{-3}	Not Compensate
450×10^{-5}	Not Compensate
450×10^{-6}	Compensate
450×10^{-7}	Compensate
450×10^{-8}	Compensate
450×10^{-9}	Compensate
450×10^{-10}	Compensate
450×10^{-11}	Compensate
450×10^{-12}	Compensate
450×10^{-14}	Not Compensate
450×10^{-15}	Not Compensate
$450\times10\text{-}^{18}$	Not Compensate

Three Phase Fault: Mathematical Analysis of Capacitor Ratings in DVR Power Circuit

In this case by using equations from 1 and 2

V_s = 5000; V_{DC} = 8274.12, T=0.02,

V_{cmax} =24,000, $\Delta I_L = 60.5\,A$

The calculated capacitance value is

$$C_{DC} = 554.5\times10^{-6}$$

Case 2: Single Line to Ground Fault Analysis (By Using MATLAB Simulation)

In this case an 11 kV load feeder is considered. The DVR is designed to compensate for single line to ground voltage sag at the load side. To illustrate voltage sag compensation by the DVR, firstly a voltage sag condition is generated by initiating a fault at time t = 0.4 sec the duration of the fault is 0.2 sec and the percentage of sag is 14% in which the voltage drops from 1.0 to 0.86 p.u. In this situation, the system needs 14% of voltage from DVR to inject into the system, Fig.8 show the p.u. voltage into the system during voltage sag condition. Fig.5 to Fig.7 shows the DVR performance in presence of energy storage devices of 4.5 kV with different capacitor ratings viz. 450×10^{-3}F to 450×10^{-15}F in DVR power circuit. The approximate battery capacity is 8145 Ampere-hour (AH).

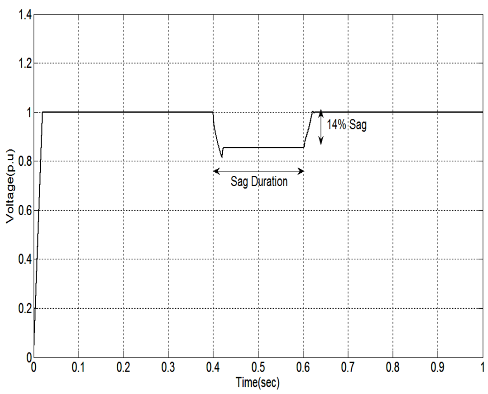

Fig. 8. Voltage p.u. at 11 kV distribution line (load feeder) without DVR System.

Table III shows that voltage sag of 14.02% in 11kV distribution line is fully compensated with the capacitor ratings in between range of 450×10^{-6} to 450×10^{-12} F in DVR power circuit.

TABLE. III: COMPARISON IN BETWEEN CAPACITOR VALUES AND VOLTAGE SAG COMPENSATION AT 11 KV FEEDER WHEN SLG FAULT

Capacitor Value in F	Desired Voltage sag Compensation
450×10^{-3}	Not Compensate
450×10^{-5}	Not Compensate
450×10^{-6}	Compensate
450×10^{-7}	Compensate
450×10^{-8}	Compensate
450×10^{-9}	Compensate
450×10^{-10}	Compensate
450×10^{-11}	Compensate
450×10^{-12}	Compensate
450×10^{-14}	Not Compensate
450×10^{-15}	Not Compensate
$450\times10\text{-}^{18}$	Not Compensate

SLG Fault: Mathematical Analysis of Capacitor Ratings in DVR Power Circuit

In this case by using equations from 1 and 2

Vs = 4500; VDC = 7446.49, T = 0.02, Vcmax = 20,000, $\Delta I_L = 80\,A$

The calculated capacitance value is

CDC = 626.4×10-7

System 2: 6.6 kV Distribution Line (Load Feeder)

Case 3: Three Phase Fault Analysis (By Using MATLAB Simulation)

In this case a 6.6 kV load feeder is considered, The DVR is designed to compensate for voltage sag at the load side. To illustrate voltage sag compensation by the DVR, firstly a three phase voltage sag condition is generated by initiating a fault at time t = 0.4 sec, the duration of the fault is 0.2 sec and the percentage of sag is 17.02% in which the voltage drops from 1.0 to 0.829 p.u.. In this situation, the system needs 17.02% of voltage from DVR to inject into the system, Fig.9 shows the p.u. voltage into the system during voltage sag condition. Fig.5 to Fig.7 shows the DVR performance in presence of energy storage devices of 2.5kV with different capacitor ratings viz. 450×10-3F to 450×10-15F in DVR circuit. The approximate battery capacity is 4525 Ampere-hour (AH).

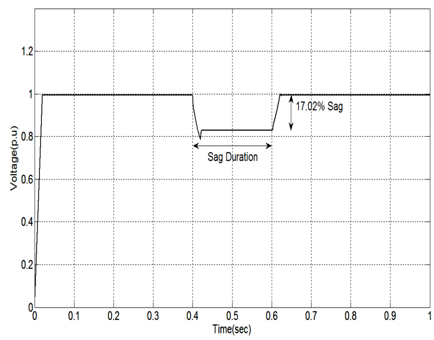

Fig. 9.Voltage p.u. at 6.6 kV distribution line (load feeder) without DVR System.

Table IV shows that voltage sag of 14.02% in 11 kV distribution line is fully compensated with the capacitor ratings in between range of 450×10^{-6} to 450×10^{-12} F in DVR power circuit.

Three Phase Fault: Mathematical Analysis of Capacitor Ratings in DVR Power Circuit

In this case by using equations from 1 and 2

V_s = 2500 ; V_{DC} = 4136, T=0.02,

V_{cmax} =12,000, $\Delta I_L = 40\,A$

The calculated capacitance value is

$C_{DC} = 472\times10^{-6}$

Case 4: Single Line to Ground Fault Analysis (By Using MATLAB Simulation)

TABLE IV: COMPARISON IN BETWEEN CAPACITOR VALUES AND VOLTAGE SAG COMPENSATION AT 6.6 KV FEEDER WHEN THREE PHASE FAULT

Capacitor Value in F	Desired Voltage sag Compensation
450×10^{-3}	Not Compensate
450×10^{-5}	Not Compensate
450×10^{-6}	Compensate
450×10^{-7}	Compensate
450×10^{-8}	Compensate
450×10^{-9}	Compensate
450×10^{-10}	Compensate
450×10^{-11}	Compensate
450×10^{-12}	Compensate
450×10^{-14}	Not Compensate
450×10^{-15}	Not Compensate
$450\times10\text{-}^{18}$	Not Compensate

In this case a 6.6 kV load feeder is considered. The DVR is designed to compensate for single line to ground voltage sag at the load side. To illustrate voltage sag compensation by the DVR, firstly a voltage sag condition is generated by initiating a fault at time t = 0.4 sec the duration of the fault is 0.2 sec and the percentage of sag is 14% in which the voltage drops from 1.0 to 0.86 p.u. In this situation, the system needs 14% of voltage from DVR to inject into the system, Fig.10 show the p.u. voltage into the system during voltage sag condition. Fig.5 to Fig.7 shows the DVR performance in presence of energy storage devices of 2.35 kV with different capacitor ratings viz. 450×10^{-3}F to 450×10^{-15}F in DVR power circuit. The approximate battery capacity is 4253 Ampere-hour (AH).

SLG Fault: Mathematical Analysis of Capacitor Ratings in DVR Power Circuit

In this case by using equations from 1 and 2

V_s = 2350; V_{DC} = 3888.7, T=0.02, V_{cmax} =12,000, $\Delta I_L = 55\,A$

The calculated capacitance value is $C_{DC} = 546\times10^{-6}$

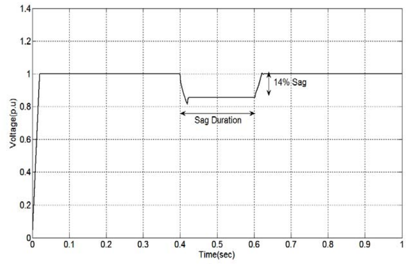

Fig. 10.Voltage p.u. at 6.6 kV distribution line (load feeder) without DVR system

Table V shows that voltage sag of 14.02% in 11kV distribution line is fully compensated with the capacitor ratings in between range of 450×10^{-6} to 450×10^{-12} F in DVR power circuit.

TABLE V: COMPARISON IN BETWEEN CAPACITOR VALUES AND VOLTAGE SAG COMPENSATION AT 6.6 KV FEEDER WHEN SLG FAULT

Capacitor Value in F	Desired Voltage sag Compensation
450×10^{-3}	Not Compensate
450×10^{-5}	Not Compensate
450×10^{-6}	Compensate
450×10^{-7}	Compensate
450×10^{-8}	Compensate
450×10^{-9}	Compensate
450×10^{-10}	Compensate
450×10^{-11}	Compensate
450×10^{-12}	Compensate
450×10^{-14}	Not Compensate
450×10^{-15}	Not Compensate
$450\times10\text{-}^{18}$	Not Compensate

TABLE VI: COMPARISON IN BETWEEN CAPACITOR VALUES AND VOLTAGE SAG COMPENSATION AT 11 & 6.6 KV FEEDER WHEN DIFFERENT FAULTS CONDITION

Feeder Rating »		11 kV Feeder		6.6 kV Feeder	
		Summary of Fault Compensation Result			
Fault »					
S. No.	Capacitor Value in (F) □	Symmetrical (3 Phase)	Un-Symmetrical (SLG)	Symmetrical (3 Phase)	Un-Symmetrical (SLG)
1	450×10^{-3}	Not Compensate	Not Compensate	Not Compensate	Not Compensate
2	450×10^{-5}	Not Compensate	Not Compensate	Not Compensate	Not Compensate
3	450×10^{-6}	Compensate	Compensate	Compensate	Compensate
4	450×10^{-7}	Compensate	Compensate	Compensate	Compensate
5	450×10^{-8}	Compensate	Compensate	Compensate	Compensate
6	450×10^{-9}	Compensate	Compensate	Compensate	Compensate
7	450×10^{-10}	Compensate	Compensate	Compensate	Compensate
8	450×10^{-11}	Compensate	Compensate	Compensate	Compensate
9	450×10^{-12}	Compensate	Compensate	Compensate	Compensate
10	450×10^{-14}	Not Compensate	Not Compensate	Not Compensate	Not Compensate
11	450×10^{-15}	Not Compensate	Not Compensate	Not Compensate	Not Compensate
12	$450\times10\text{-}^{18}$	Not Compensate	Not Compensate	Not Compensate	Not Compensate

Overall Capacitor Rating PerformanceVoltage sag compensation is done through DVR power circuit by using capacitors of different values and rating. It is used for maintaining the load terminal voltage at different distribution level as shown above from Case-1 to Case-4. Results show in tabular form in Table VI. Above results show that capacitor rating below 450 μF causes systems to be unstable i.e. not provides proper voltage sag compensation. Similarly, capacitor rating above from 450 pF causes systems to be unstable. But the capacitor's range from 450 pf to 450 μF for the system work in stable position. It is shown that the proper voltage sag compensation happens in this capacitor values' range. Suppose that the DVR is designed to compensate for the voltage sag with depth of up to D_x p.u. ($0.0 < D_x > 1$), it is suggested that capacitor value between 450 pf to 450 μF gives proper voltage sag compensation for all different distribution level voltages as discussed above. It is considered that the capacitor rating should be in the micro farad range. It is not considered below this range means milli or nanofarad range. When the capacitor is used in the range of nanofarad, it affects a milli ampere (mA) current to the earth. This means that it is a high impendence fault. When the capacitor rating is considered in the range of milli amperes, it means that it would inject a large value of energy into the system, and transient will be appeared. But when the suitable rating in the range of microfarad values of the capacitor bank is used, it depends on the value of the voltage, the reactance drop of the supply. It is also analyzed that the theoretical results in the case-1 to case-4 are in the nearly equal range as discussed in given practically range from 450 pf to 450 µF.

V. Conclusion

Based on the analysis of test system, it is suggested that percentage sag and operating voltage are major factors in estimating the capacitor value and rating. The effectiveness of a DVR system mainly depends upon the rating of capacitor value. Investigations were carried out for various cases of voltage sag at different distribution voltage levels with increasing and decreasing range of capacitor rating in DVR power circuit. Results show that capacitor ratings ranging from 750 pF to 750 µf are suitable for any distribution voltage of desired voltage sag compensation using DVR system.

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