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Capacitor Rating Selection for Voltage Sag Compensation in DVR System

H.P.Tiwari

Abstract—**In this paper an attempt is being made on to present critical literature review and up-to-date and exhausts bibliography on the capacitor element in the Dynamic Voltage Restorer (DVR). Various rating and sizing concerning the capacitor in the DVR power circuit problem have been highlighted. Capacitors types, size and its energy storage in the initial stage and final stage are discussed.**

Index Terms—**Capacitor, DVR, Power Quality, Voltage Sag Compensation.**

I. Introduction

Power quality problems in industrial application concern a wide range of disturbances, such as voltage sags and swells, flickers interruption, harmonics distortion [1]. Power quality issues have received much attention in recent years. Survey study suggests that roughly 92% of the interruptions in industrial installations are related to voltage sag [2]. As the reliability and availability of the power system continue to improve, power interruption has become rare events in power distribution system [3]. A voltage sag is a momentary decrease in the RMS ac voltage (10% to 90%) of the nominal voltage), at the power frequency, of duration from 0.5 cycles to a few second [4]. The DVR is a series connected device whose function is to protect a sensitive industrial load from voltage sags [5]. The DVR is a voltage sag compensator based on a voltage source inverter (VSI). It regulates voltage within an acceptable tolerance for sensitive load. In less than a cycle of alternating current, it restores the quality of electrical power to the load [6]. The DVR supplies the active power with the help of DC energy storage and required reactive power is generated internally without any means dc storage. DVR can compensate voltage at both transmission and distribution sides. Usually a DVR is installed on a critical load feeder. During the normal operating condition (without sag condition) DVR operates in a low loss standby mode [7]. During this condition the DVR is said to be in steady state. When a disturbance occurs (abnormal condition) and supply voltage deviates from nominal value.

In transient state DVR supplies voltage for compensation of voltage sag. Capacitors are used as an input for power inverters. The capacitor provides a unique value in high energy storage and low device impedance. How you go about selecting the right capacitor or capacitors, however, is not an inconsequential matter. Selecting the right capacitor for an inverter application requires knowledge of all aspects of the electrical application. The goal of this paper is to assist in selecting the right capacitor for the design at hand.

Dr. H. P. Tiwari is Associate Professor in Department of Electrical Engineering with the Malaviya National Institute of Technology Jaipur, Rajasthan, INDIA (e-mail:harpaltiwari@yahoo.co.in)

II. DVR Structure

The basic structure of a DVR is shown in Fig.1. It consists of DC energy storage unit, capacitor bank, voltage source inverter (VSI), low pass filter and a voltage injection transformer.

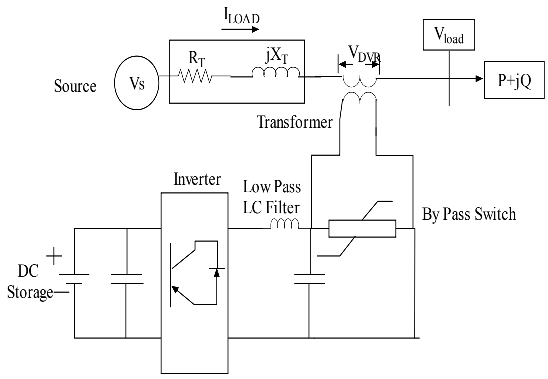

Fig.1. Basic Structure of Dynamic Voltage Restorer

A. Energy Storage Unit:

It is responsible for energy storage in DC form, Flywheels, Lead Acid batteries, Superconducting Magnetic Energy Storage (SMES) and Super-Capacitors can be used as energy storage devices. It supplies the real power requirements of the system when DVR is used for compensation [8].

B. Capacitor:

DVR has a large DC capacitor to ensure constant input supply to inverter. A large capacitor connected at the input inverter terminals tends to make the input DC voltage constant. A capacitor can store electric energy when disconnected from its charging circuit, so it can be used like a temporary battery. Capacitors are commonly used in electronic devices to maintain power supply while batteries are being changed. The value of a capacitor (the capacitance), is designated in units called the Farad (F).

C. Inverter:

An Inverter system is used to convert from dc storage to ac [9]. Rating of the VSI converter is of low voltage and high current type due to step up injection transformer in the DVR compensation technique [8].

D. Passive Filters:

Filters are used to convert the PWM inverted pulse waveform into a sinusoidal waveform. This is achieved by removing the unnecessary higher order harmonic components generated during the DC to AC conversion in the Voltage Source Inverter (VSI), higher orders harmonic components distort the compensated output voltage [10].

E. By-Pass Switch:

This is used to protect the inverter from high currents. A by-pass switch (crowbar circuit) is incorporated to by-pass the inverter circuit.

F. Voltage Injection Transformers:

In a three-phase system, three Single-phase transfer units or one three phase transformer unit can be used [10].

III. Capacitor Rating

A large capacitor connected at the input inverter terminals tends to make the input DC voltage constant. This capacitor also suppresses the harmonics feed back to the source [11]. Aluminum electrolytic capacitors are widely used in all types of inverter power systems [28]; It provides a unique value in high energy storage and low device impedance. By comparing of aluminum electrolytic and the film capacitors, it is observed that the electrolytic capacitors have some advantage as compared to film capacitor like:

1) Electrolytic capacitor has much greater capacitance/volume ratio than film capacitors.
2) Ambient temperature of electrolytic capacitors is up to 105°C, where film capacitor it is only 85°C. Hence, film capacitors work at 105°C with significant derating [12].

When the voltage sag compensation is subjected by using DVR circuit; inverter is supplied the active and reactive power. Capacitor is provided the active power in the inverter input. It works as a DC source into the inverter input. Capacitor size has important role in the DVR .The following equation is used to determine the size of the capacitor, C_{DC},

$$\frac{1}{2}C_{DC}\left[V_{CMAX}^{2}-V_{DC}^{2}\right]=\frac{1}{2}V_{S}\,\Delta\, I_{Li}T \quad (1)$$

Where

$\boldsymbol{V_{DC}}$**:** Preset lower limit voltage of energy storage capacitor.

$\boldsymbol{\Delta I_{Li}}$**:** Step increase of the peak value of the real fundamental component of the load current.

***T*:** Period of the utility voltage source.

From equation (1) the dc capacitor value for a three-phase system can be derived as [13]

$$C_{dc}=3\frac{V_{S}\Delta I_{L}T}{V_{C\max}^{2}-V_{dc}^{2}} \quad (2)$$

Where:

$$V_{dc}=\frac{3\sqrt{3}}{\Pi}V_{S}$$

The DVR is designed to compensate for voltage sag at the load side. When the voltage sag condition occurs due to fault in the system, this sag is compensated by injected required percentage of voltage from DVR into the system. During the restoration, required ac voltage is supplied by the inverter. The required input inverter; dc-link voltage should be maintained at a certain level to ensure proper voltage injection. A large capacitor bank or a rectifier circuit with a relatively small dc capacitor bank can be used for this purpose. The rectifier can ensure the voltage restoration for both short and long term voltage sags [14].

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 decreases. Therefore, there is a minimum voltage required below which the inverter of the DVR cannot generate the required voltage. the size and rating of capacitor is very important for DVR power circuit [15]. The DC capacitor value for a three phase system can be derived [16]. 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 [17].

Previous to the voltage sag conditions means without voltage sag condition, the DC-link capacitor charging current is nearly zero. I_H is equal to the load current i_{LOAD}, which is sinusoidal. When the DVR is started to compensate for the voltage sag condition then required active power is supplied from the dc link of the inverter input to the via voltage injected transformer to the power system. Thus there is a current i_s through the rectifier to the dc-link capacitor and it causes the dc-link voltage to drop. Therefore $i_H=i_{LOAD}+i_{rac,}$

Since the rectifier current i_{rac}, contains harmonic components, i_H, also contains harmonics. The distorted i_s, results in the harmonic voltage drop across the DVR which then appears in the load voltage [14].

In presence of the DC voltage controller, the DC voltage should be kept constant during normal operation means; without voltage sag condition. However, during the voltage sag condition means abnormal condition like; transient changes in the reactive power command signal, which results in changes in the inverter line current amplitude, generate voltage fluctuations across the DC capacitor. Therefore, a suitable capacitance value for the DC capacitor must be chosen to eliminate DC voltage variation [18].

The dc capacitor in between the DC energy storage and the inverter serves as the energy buffer to the DVR, generating and absorbing power during voltage sags and voltage swells conditions[19],

Capacitor is discharged when the voltage sag occurs in the system and the DC link capacitor can provide energy as[12].

$$\Delta W_{DC}=\frac{1}{2}C\times\left(V_{DCMAX}^{2}-V_{DCMIN}^{2}\right) \quad (3)$$

C : DC link capacitance

V_{DMAX} : Maximum permissible DC link voltage

V_{DMIN}: Minimum permissible DC link voltage.

The capacitor size depends on the required active power to be injected through DC storage capacity when the voltage sag occurs in the faulty condition and the voltage drop at its terminal during the discharge period. The capacitor size is characterized as a time constant τ , defined as the ratio between the stored energy at rated DC voltage and the rated apparent power of the converter as:

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$$\tau = \frac{1}{2}\frac{CV_{DCN}^2}{S_N} \quad (4)$$

Where V_{DCN} is the nominal DC-converter voltage and S_N is its rated apparent power. The capacitor cost is around proportional to the square of its terminal voltage [20].

Capacitor are the most commonly used energy storage for the inverter input supply because they provide a fast discharging response and have no moving parts, DC-side capacitors are large enough to maintain a ripple free DC bus voltage, even for unbalanced input voltage [21].

When the energy is drawn from the energy storage capacitors during the voltage sag condition the inverter draw the active power from the capacitors and the capacitor terminal voltage decreases. Therefore, there is a minimum voltage (V_{DCMIN}) below which the inverter of the DVR cannot generate the required voltage. Thus, the size of the DC capacitor needed to supply active power (P_{ING}) can be expressed as in (5) in terms of maximum allowable DC-link voltage (V_{DMAX}), minimum allowable dc-link voltage (V_{DCMIN}), sag duration (T_{SAG}), and power loss (P_{LOSS}). According to (5), it is clear that large capacitors in the dc-link energy storage are needed to effectively mitigate voltage sags of large depths and long durations.

$$C = \frac{2\,(P_{ING} + P_{LOSS})T_{SAG}}{V_{DCMAX}^2 - V_{DCMIN}^2} \quad (5)$$

Initial transient real power is transferred from the DC-link energy storage capacitors until the DC-bus regulator reacts for the dc-link voltage drop [20].

The DC storage capacitance can be designed though (6), it aims to keep the DC link voltage in an acceptable fluctuant situation. The voltage fluctuation of the DC capacitor can be described by equation (6)

$$\Delta U_{DC} = \left| \frac{I}{C_{DC}} \int_0^T \frac{T}{2}\sqrt{2}\, I_m \sin\omega t\, dt \right| \quad (6)$$

$$C_{DC} = \frac{\left(2\sqrt{2}\right) I_m}{\omega\,\Delta U_{DC}}$$

Where

T is the fundamental time period,

C_{DC} represents the DC storage capacitance,

I_m represents the nominal rated current and

ΔU_{DC} is the DC bus allowable fluctuation voltage level.

from equation (6), the design of the minimum DC storage capacitance required can be found [22].

The DC capacitor does not play any role in feeding electric DC energy to the series inverter during voltage-sag compensation, but acts as a DC capacitor for smoothing the common dc-link voltage. This means that the DC capacitor is no longer an energy source for compensation of voltage sags [23].

The energy stored in the dc capacitor, W_{STORE} is given by following equation (7)

$$W_{STORE} = \int (P_R - P_C)dt = -\int \frac{\delta V_S I_S}{\sqrt{3}}(\cos 2\omega t)dt$$

$$= \bar{W}_{STORE} - \frac{\delta V_S I_S}{(\omega)2\sqrt{3}}\sin 2\omega t \quad (7)$$

Where W_{STORE} is the average energy

It is assumed that the DC-capacitor voltage v_{DC} is the sum of the average voltage V_{DC} and the voltage fluctuation Δv_{DC}.

$$V_{DC} = V_{DC} + \Delta v_{DC} \quad (8)$$

The stored energy W_{STORE} is given by following equation (9)

$$W_{STORE} = \frac{C_{DC} v_{DC}^2}{2}$$

$$W_{STORE} = \frac{C_{DC}(V_{DC}^2 + 2V_{DC}\Delta v_{DC} + \Delta v_{DC}^2}{2} \quad (9)$$

Assuming that $\Delta v_{DC} \angle\angle V_{DC}$, the voltage fluctuation is represented by equations (10-a) and (10-b).

$$\Delta v_{DC} = \frac{(-)\delta V_S I_S \sin 2\omega t}{\left(2\sqrt{3}\right)\omega C_{DC} V_{DC}} \quad (10\text{-a})$$

$$\Delta v_{DC} = \frac{(-)\delta P_L \sin 2\omega t}{(2)\omega C_{DC} V_{DC}(3-\delta)} \quad (10\text{-b})$$

Thus, the required capacity of the dc capacitor, C_{DC} is obtained by

$$C_{dc} = \frac{\delta P_L}{(2)\omega\alpha V_{DC}^2(3-\delta)}$$

Where α is the ratio of the amplitude of the voltage fluctuation with respect to the DC capacitor voltage V_{DC}.

The unit capacitance constant H is given by (11) [23].

$$H = \frac{\delta}{(4)\omega\alpha(3-\delta)} \quad (11)$$

Thus, there is a lower limit on the energy of the capacitor in order to ensure that this failure can be avoided. Let the capacitance of the storage device be C. The minimum value of C can be obtained from the following equation (12).

$$\frac{1}{2}CV_{DC}^2 - \frac{1}{2}CV_{MIN}^2 = E_{INJ} \quad (12)$$

Where $V_{MIN} = \sqrt{2}\left|V_{INJ}\right|V_{DC}$ is the initial DC-side voltage of the inverter input in DVR power circuit.

$$C = \frac{2E\left(\frac{V_{INJ}}{V_S}\right)}{\left(V_{DC}^2 - 2\left|V_{INJ}\right|^2\right)}$$

The energy E_c stored in the dc capacitors is equal to (13) [24].

$$E_C = \frac{1}{2}\frac{v_{DC}^2 C_{DC}}{2} \quad (13)$$

It can be see that as the value of capacitor increases, the level of severity of voltage dropped capacitor increases, the level of severity of voltage dropped also will improve until it reaches at certain stability condition [25].

These capacitors can be a very effective energy storage element of a power quality compensator regarding to the cost effectiveness. However, a periodic maintenance requirement, a bulky size, and a large space installation requirement can be main drawbacks [26].

The initial energy stored in the dc capacitor W is given by the following:

$$W = \frac{1}{2}C_{DC}V_{DC}^2 \quad (14)$$

On the other hand, the DC-capacitor voltage v_{DC} decreases from the initial voltage V_{DC} to the final voltage $V_{DC} - \Delta V_{DC}$ for the time interval of Δt.

The final energy stored in the DC capacitor is given by the following (15).

$$W = P_C \Delta t = \frac{1}{2} C_{DC} (V_{DC} - \Delta V_{DC})^2 \qquad (15)$$

The required capacitance of the dc capacitor as follows:

Thus, the initial energy stored in the dc capacitor W is obtained by the following; [25]

$$W = \frac{\delta P_L \Delta t}{\left[\frac{2 \Delta V_{DC}}{V_{DC}} - (\frac{\Delta V_{DC}}{V_{DC}})^2 \right]} \qquad (16)$$

The electric double layer capacitor, which is much higher density of energy storage compared to electrolyte capacitor and requires small space for installation, and has highly reliable performance. The cost of electric double layer capacitor is expected to decrease rapidly, and cheaper than that of the superconducting coil, which requires very expensive cooling system. Battery is not a proper energy storage unit for the DVR application, because it has slow charging characteristic due to the chemical reaction [27].

IV. Conclusion

This paper presents a critical review of the present philosophies in the area of capacitor. Due attention has also been paid to recent developments in the area of capacitor electrical issues like type, size, energy, power. Although the author have sincerely attempted to present the most comprehensive set of references on capacitor issues, they would like to apologize for exclusion of many good papers due to space constrains and hope that additional references will be advanced as discussed on this publication. It is envisaged that this paper will serve as a valuable resource to any future worker in this important area of research.

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H.P. Tiwari received the B.E. degree in electrical engineering in year 1982 and M.Sc. Engineering degree in Electrical Engineering in year 1986. and the **Ph.D.** degree awarded from University of Rajasthan in year 2000. He is working as Associate Professor in Department of Electrical Engineering of Malaviya National Institute of Technology (MNIT), Jaipur (INDIA. His research interests include power electronics, electrical machines and drive and non- conventional energy sources.