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Estimation of DC Voltage Storage Requirements for Dynamic Voltage Compensation on Distribution Network using DVR

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Abstract—**Voltage sags and momentary power interruptions are probably the most significant power quality problems affecting industrial and large commercial customers. The installation of mitigation devices can be seen as a short term solution. DVR is a very effective series-compensation device for mitigating voltage sags. The mitigation capability of these devices is mainly limited by the energy storage capacity. This paper is intended to assimilate voltage capacity of DC storage unit of a DVR with transmission voltage so that the information is available in a convenient manner and can be used as a basis for continued research in this area.**

Index Terms—**DC Energy Storage, DVR, Power Quality, Voltage Sag.**

I. INTRODUCTION

One of the most important power quality issues is voltage sag which is due to increasing usage of voltage sensitivity devices. These devices have made industrials processes more susceptible to supply voltage sags [1]. Voltage sag is not a complete interruption of power; it is a temporary drop below 90 percent of the nominal voltage level. Most voltage sags do not go below 50 percent of the nominal voltage, and they normally last from 3 to 10 cycles or 50 to 170 milliseconds. These sags are caused by abrupt increases in loads such as short circuits or faults, motors starting, or electric heaters turning on, or they are caused by abrupt increases in source impedance, typically caused by a loose connection [2]. Voltage sag mitigation devices are classified into three categories; (i) Traditional Solutions: Voltage Control included Transformer, Tap Changers both mechanical and SCR switched units and servo-variac technology and ferro-resonant transformers are used as a voltage sag mitigation devices [3]. These devices are heavy, bulky and inefficient so they are rarely used [4]. (ii) Uninterruptible Power Supplies (UPS): The main disadvantage, with the UPS is that it uses batteries as its DC storage system making it more expensive than the DVR which uses a bank of capacitors [5]. (iii) Dynamic Voltage Restorer (DVR): The voltage source converter (VSC) connected in series with the grid as a static series compensator (SSC) is also known as the Dynamic Voltage Restorer (DVR); It is power electronics based device and used to protect for any voltage sags caused by different types of faults and abnormal condition.. The basic operating principle of the DVR is to inject an appropriate voltage in series with the supply through injection transformer whenever voltage sag or voltage swell is detected [6]. The DVR using pulse width modulation technology is used to control Phase and amplitude [7]. The efficiency of the DVR depends on the performance and the efficiency of control technique involved in switching the inverters [8]. The basic structure of a DVR is shown in Fig.1.

In this paper Section I briefly describes the sag and sag mitigation devices. Section II discusses the DVR basic structure and component. Section III discusses the electrical circuit model of DVR as a series controller, section IV discusses the PI controller strategy employed for inverter switching in the DVR [9], the simulation model is developed using the simulink utility of MATLAB in section V. Section VI discusses the DC Storage calculations and conclusions are presented in section VII.

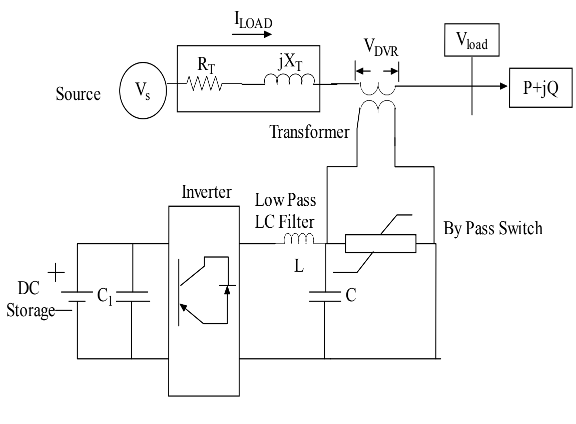

Fig.1. Basic Structure of Dynamic Voltage Restorer

II. DVR STRUCTURE

The DVR device consists of five main sections;

(i) 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, the estimates of the typical energy efficiency of four energy storage technologies area: batteries 75 %, Fly wheel 80 %, Compressed air 80%, SMES

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90% [9].(ii) Inverter: It is used to convert from DC storage to ac [10]. (iii) Passive Filters: It is clear that higher order harmonic components distort the compensated output voltage. Filter is used to convert the PWM inverted pulse waveform into a sinusoidal waveform. This is achieved by removing the unnecessary higher order harmonic components generated from the DC to AC conversion in the VSI, (iv) By-Pass Switch: It is used to protect the inverter from high currents. When 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[14]. (v) Voltage Injection Transformers: In a three-phase system, three Single-phase transformer units or one three phase transformer unit can be used for voltage injection purpose [11].

III. Series Voltage Controller

The electrical circuit model to indicate voltage injection by a DVR system is shown in Fig.2.

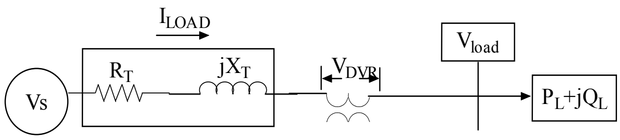


Fig.2. Electrical Circuit Model for DVR Voltage Injection

The series injected voltage of DVR can be written can be as [12].

$$V_{DVR} + V_{sf} = V_{Load} + Z_T I_{Load} \quad (1)$$

or $$V_{DVR} = V_{Load} + Z_T I_{Load} - V_{sf} \quad (2)$$

And

$$Z_T = R_T + jX_T$$

Where V_{DVR} is voltage supply by the DVR,
V_{Load} is the desired load voltage magnitude,
Z_T is the load impedance,
I_{Load} is the load current,
V_{sf} is the system voltage during fault condition,

Current is the load side can be calculated as

$$V_{load}\ I_{Load} = P_L + j\,Q_L \quad (3)$$

$$I_{Load} = \left(\frac{(P_L + j * Q_L)}{V_{Load}}\right) \quad (4)$$

Where load voltage consider as a reference, P_L is load active power, and Q_L is load reactive power.

Then DVR voltage can be written as

$$V_{DVR}\angle\alpha = V_L\angle 0^o + Z_T I_{Load}\angle(\beta-\theta) - V_{sf}\angle\delta \quad (5)$$

Where α, β and δ are the angle of V_{DVR}, Z_T, and V_{sf} respectively

$$\theta = \tan^{-1}\left(\frac{Q_L}{P_L}\right)$$

Where θ is load power factor angle.

The apparent power injection by the DVR is given by

$$S = V_{DVR} * I_L \quad (6)$$

IV. Control Philosophy

Voltage sag is created at load terminals by a three-phase fault as shown in Fig.4. Load voltage is sensed and passed through a sequence analyzer. The magnitude is compared with reference voltage (V_{ref}). Pulse width modulated (PWM) control technique is applied for inverter switching so as to produce a three phase 50 Hz sinusoidal voltage at the load terminals. Chopping frequency is in the range of a few KHz. The IGBT inverter is controlled with PI controller in order to maintain 1 p.u. voltage at the load terminals i.e. considered as base voltage =1p.u.

A Proportional-Integral (PI) controller (Fig.3) drives the plant to be controlled with a weighted sum of the error (difference between the actual sensed output and desired set-point) and the integral of that value. An advantage of a proportional plus integral controller is that its integral term causes the steady-state error to be zero for a step input. PI controller input is an actuating signal which is the difference between the V_{ref} and $V_{in.}$ Output of the controller block is of the form of an angle δ, which introduces additional phase-lag/lead in the three-phase voltages. The output of error detector is $V_{ref} - V_{in.}$ (7)

where V_{ref} equal to 1 p.u. voltage
V_{in} voltage in p.u. at the load terminals.

The controller output when compared with PWM signal results in the desired firing sequence.

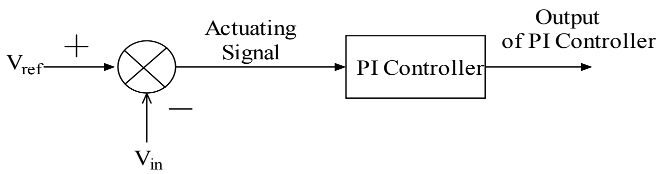


Fig.3. Schematic Diagram of A Typical P I Controller.

The modulated angle is applied to the PWM generators in phase A. The angles for phases B and C are shifted by 120° and 240°, respectively as shown in (9) and (10). In this PI controller only voltage magnitude is taken as a feedback parameter in the control scheme [12].

The sinusoidal signal $V_{control}$ is phase-modulated by means of the angle δ and the modulated three-phase voltages are given by

$$V_a = \sin(\omega t + \delta) \quad (8)$$

$$V_b = \sin(\omega t + \delta + 2\pi/3) \quad (9)$$

$$V_c = \sin(\omega t + \delta + 4\pi/3) \quad (10)$$

V. Parameters of DVR Test System

Electrical circuit model of DVR Test System is shown in Fig4. System parameters are listed in Table 1. Voltage sag is created at load terminals via a three-phase fault as shown in Fig.4. Load voltage is sensed and passed through a sequence analyzer. The magnitude component is compared with reference voltage (V_{ref}).

Table 1: System Parameters

S.No.	System Quantities	Standards

1.	Capacitance	750 µs
2.	Inverter Specifications	IGBT Based, 3 Arms , 6 Pulse, Carrier Frequency =1080 Hz, Sample Time= 5 µs
3.	Fault Resistance	0.66 Ohms
4.	Load	R=0.1 Ohms, L=0.1926 H
5.	Transmission Line Parameter	R=0.001 Ohms, L=0.005 H
6.	PI Controller	K_P=0.5 K_i=50 Sample Time=50 µs

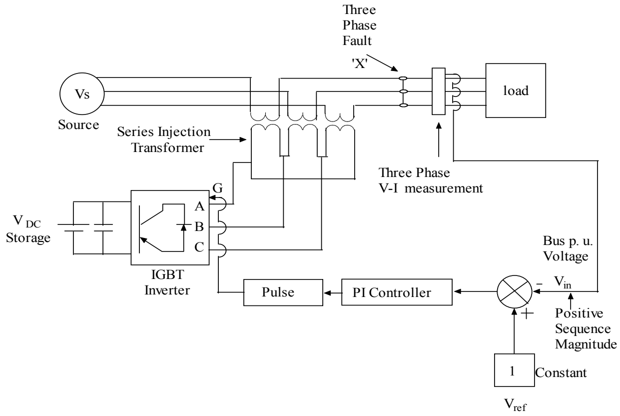
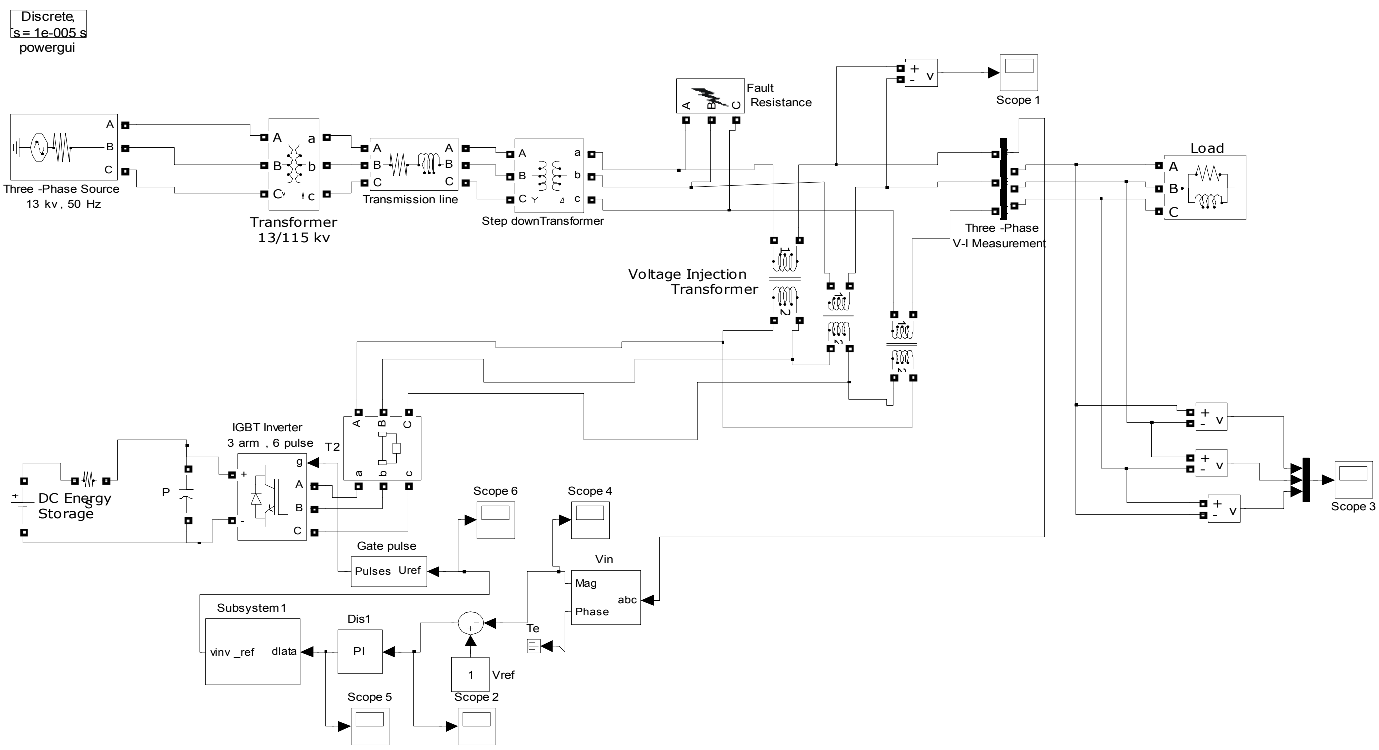


Fig.4. Circuit Model of DVR Test System

MATLAB Simulation diagram of the test system is shown in Fig.5. System comprises of 13 kV, 50 Hz generator, feeding transmission lines through a 3-winding transformer connected in Y/Δ/Δ, 13/115/ (11/16/25/40/60) kV.



VI. Simulation Results

Detailed simulations are carried out on the DVR test system. System performance is analyzed for compensating voltage sag with different energy storage capacities so as to achieve rated voltage at load. Various cases (I to V) of different voltage levels are considered for studying the impact of energy storage capacity on sag compensation. An exhaust study is made for five cases.

Case I: A three-phase fault is created at point X via a resistance of 0.66 Ω which results in a voltage sag of 17.02 %. Transition time for the fault is considered from 0.4sec to 0.6sec as shown in Fig.6. The simulation results without an energy storage system are shown in Fig.7.

Fig.8, 9, 10, 11, 12 and 13 shows the DVR performance in presence of energy storage devices of different capacities of viz.1 kV, 2 kV, 3 kV, 4 kV, 5 kV, and 6 kV respectively.

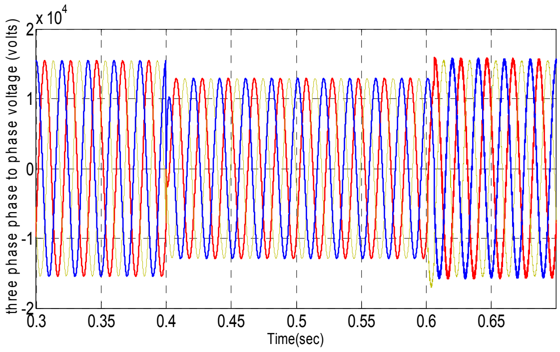


Fig.6. Three Phase, Phase to Phase Voltage with Out DVR Energy Storage

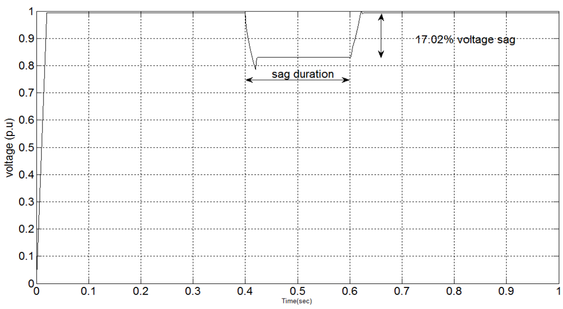


Fig.7.Voltage p.u. at the Load Point: without DVR Energy Storage.

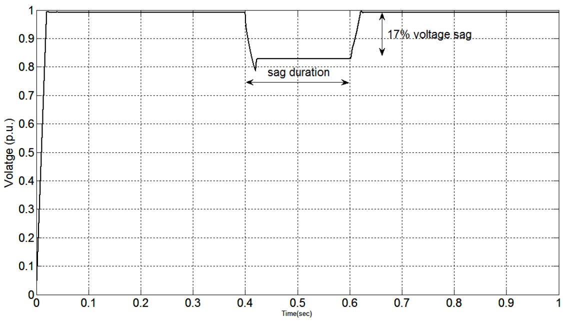


Fig.8. Voltage p.u .at the Load Point: with DVR Energy Storage of 1 kV.

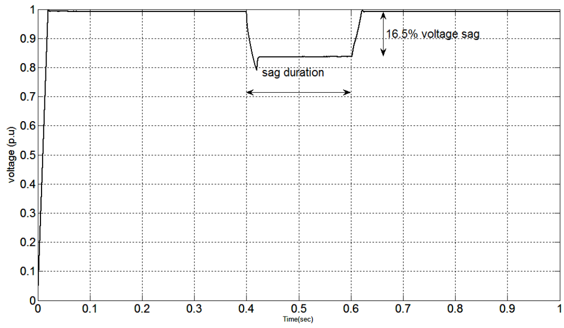


Fig.9. Voltage p.u. at the Load Point: with DVR Energy Storage of 2 kV.

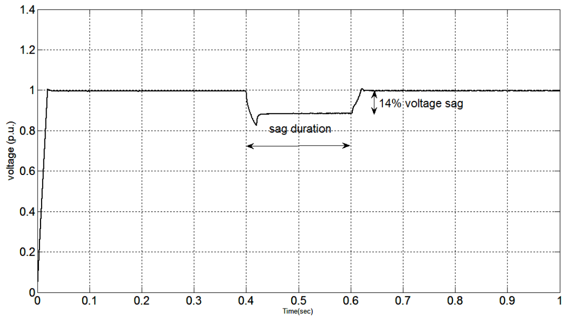


Fig.10.Voltage p.u. at The Load Point: with DVR Energy Storage of 3 kV.

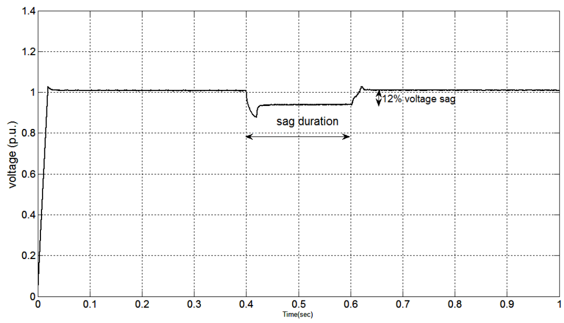


Fig.11. Voltage p.u. the Load Point: with DVR Energy Storage of 4 kV.

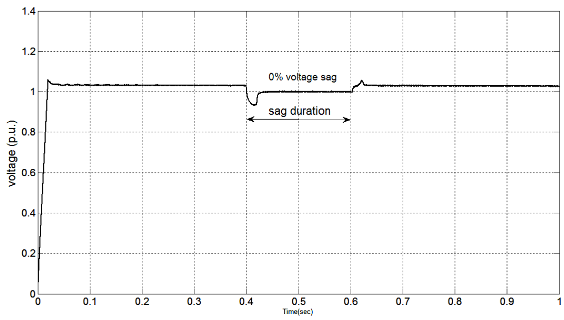


Fig.12. Voltage p.u. at the Load Point: with DVR Energy Storage of 5 kV.

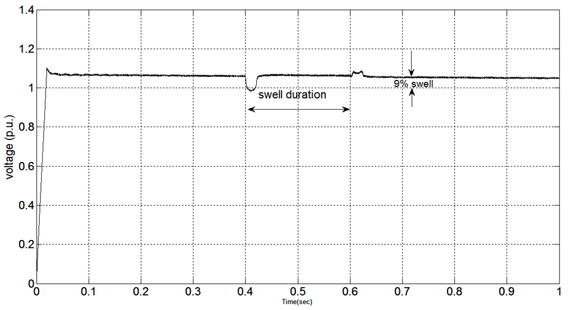


Fig.13. Voltage p.u. at the Load Point: with DVR Energy Storage of 6 kV.

Table 2: Voltage Required 11 kV at Load Terminal

DC Voltage Supply	Voltage (p.u.)	Voltage sag
1kV	0.83	17%
2kV	0.835	16.5%
3kV	0.86	14%
4kV	0.88	12%
5kV	1	0%
6kV	1.09	9% swell

Fig.5 shows that voltage sag of 17.02 % in 11 kV transmission line is fully compensated with the DC energy storage voltage of 5 kV.

***Case II*:** In this case a 16 kV transformer feeds the load. A load voltage is subjected to sag of 36%. DVR system is operating to maintain rated voltage (16 kV) at load terminals. Simulations are carried out to investigate the performance of energy storage device with capacities of 6, 8, 8.5 and 9 kV. Waveforms illustrating the sag compensation are shown in Fig. 14 to Fig. 17.

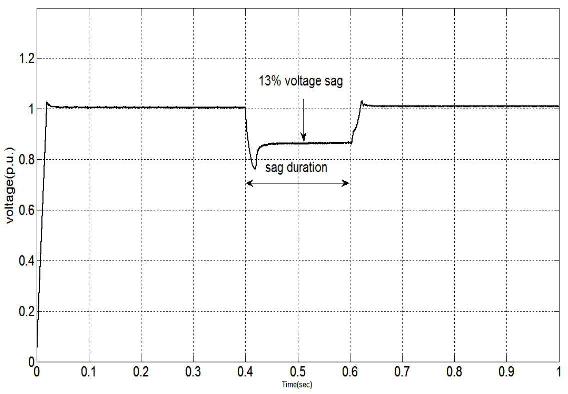


Fig.14. Voltage p.u. at the Load Point: with DVR Energy Storage of 6 kV.

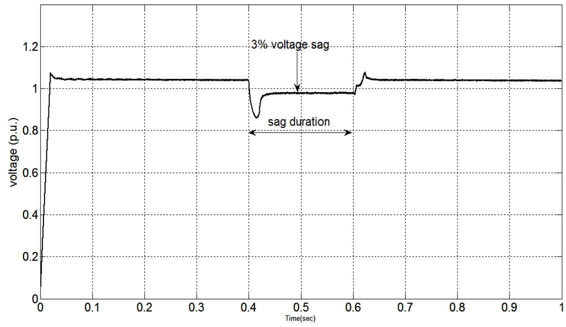


Fig.15. Voltage p.u. at the Load Point: with DVR Energy Storage of 8 kV.

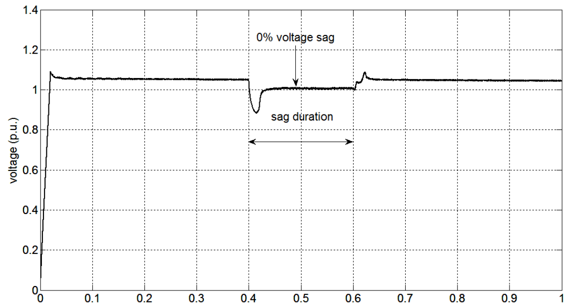


Fig.16. Voltage p.u. at the Load Point: with DVR Energy Storage of 8.5 kV.

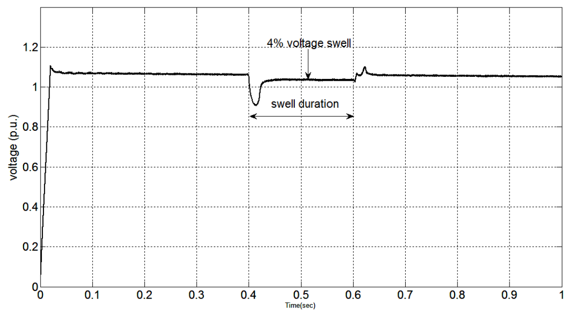


Fig.17. Voltage p.u. at the Load Point: with DVR Energy Storage of 9 kV.

Table 3: Voltage Required 16kv at Load Terminal

DC Voltage Supply	Voltage p.u.	Voltage sag
6 kV	0.87	13%
8kV	0.97	3%
8.5kV	1	0%
9	1.04	4% swell

Fig.16 shows that voltage sag of 17.02 % in 16 kV transmission line is fully compensated with the DC energy storage voltage of 8.5 kV.

Case III: In this case a 25 kV transformer feeds the load. Voltage sag of 64% is created at load terminals. DVR system is operating to maintain rated voltage (25 kV) at load terminals. Simulations are carried out to investigate the performance of energy storage device with capacities of 12, 14, and 16 kV. Waveforms illustrating the sag compensation are shown in Fig. 18 to Fig. 20.

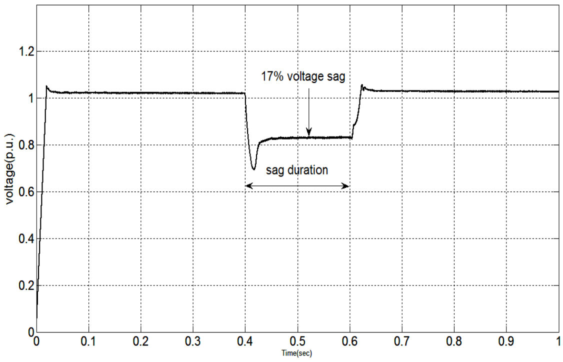


Fig.18. Voltage p.u. at the Load Point: with DVR Energy Storage of 12 kV.

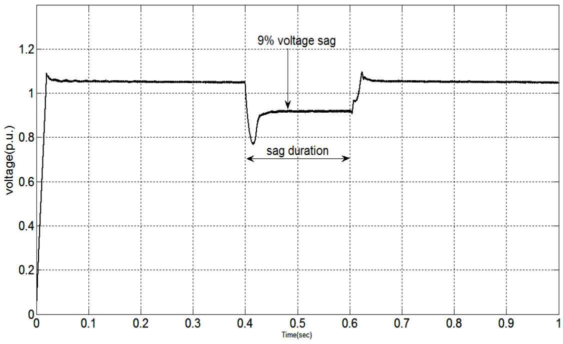


Fig.19. Voltage p.u. at the Load Point: with DVR Energy Storage of 14 kV.

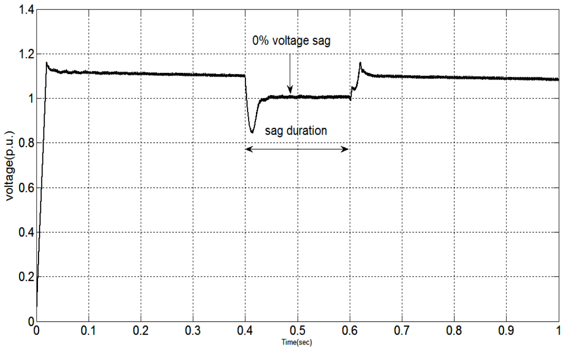


Fig.20. Voltage p.u. at the Load Point: with DVR Energy Storage of 16 kV.

Table 4: Voltage Required 25kv at Load Terminal

DC Voltage Supply	Voltage p.u.	Voltage sag
12 kV	0.87	17%
14kV	0.91	9%
16kV	1	0%

Fig.20. shows that voltage sag of 64 % in 25 kV transmission line is fully compensated with the DC energy storage voltage of 16 kV.

***Case IV*:** In this case a 40 kV transformer feeds the load. Load voltage is subjected to sag of 36%. DVR system is operating to maintain rated voltage (40 kV) at load terminals. Simulations are carried out to investigate the performance of energy storage device with capacities of 25, 27, 29 and 30 kV. Waveforms illustrating the sag compensation are shown in Fig. 21 to Fig. 24.

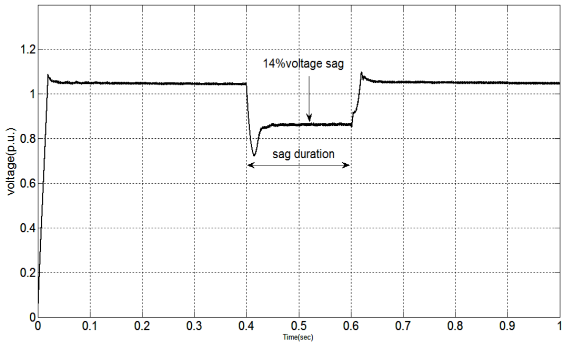


Fig.21. Voltage p.u. at the Load Point: with DVR Energy Storage of 25 kV.

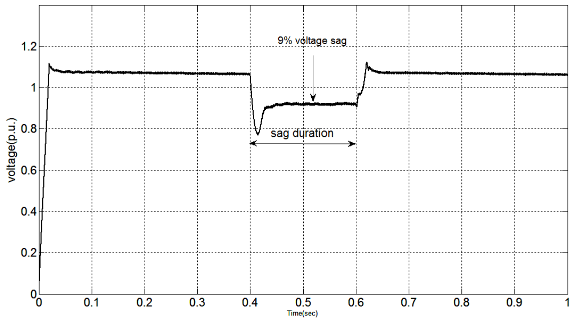


Fig.22. Voltage p.u. at the Load Point: with DVR Energy Storage of 27 kV.

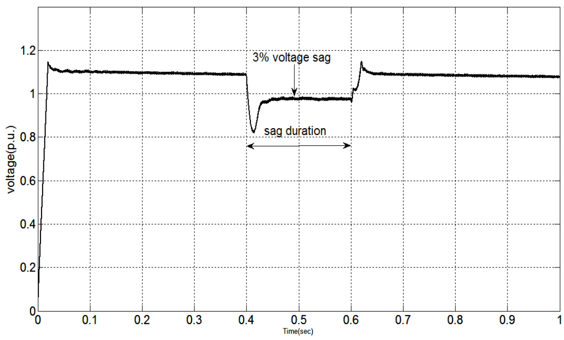


Fig.23. Voltage p.u. at the Load Point: with DVR Energy Storage of 29 kV.

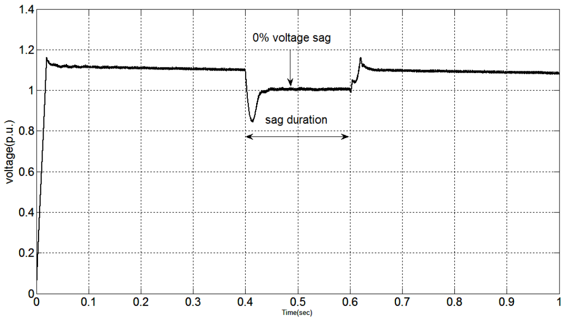


Fig.24. Voltage p.u. at the Load Point: with DVR Energy Storage of 30 kV.

Table 5: Voltage Required 40kv at Load Terminal

DC Voltage Supply	Voltage p.u.	Voltage sag
25 kV	0.86	14%
27kV	0.91	9%
29kV	0.91	3%
30 kV	1	0%

Fig.24 shows that voltage sag of 84% in 40 kV transmission line is fully compensated with the DC energy storage voltage of 30 kV.

Case V: In this case a 60 kV transformer feeds the load. a voltage sag of 93%. DVR system is operating to maintain rated voltage (16 kV) at load terminals. Simulations are carried out to investigate the performance of energy storage device with capacities of 40, 44, 47 and 48 kV. Waveforms illustrating the sag compensation are shown in Fig.25 to Fig.28.

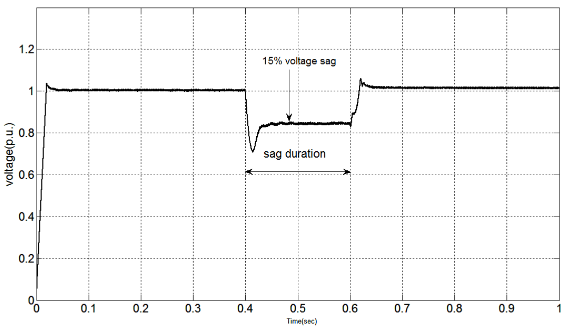


Fig.25. Voltage p.u. at the Load Point: with DVR Energy Storage of 40 kV.

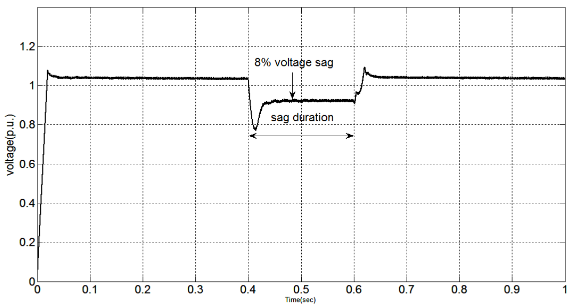


Fig.26. Voltage p.u. at the Load Point: with DVR Energy Storage of 44kV

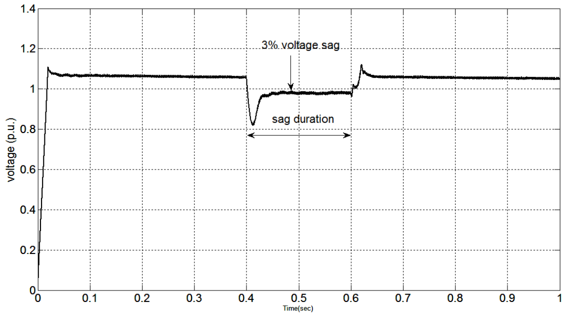


Fig.27. Voltage p.u. at the Load Point: with DVR Energy Storage of 47 kV.

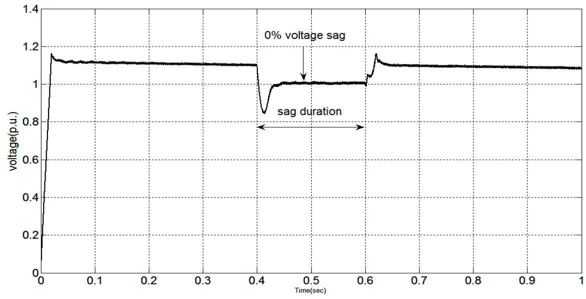


Fig.28. Voltage p.u. at the Load Point: with DVR Energy Storage of 48kV

Table 6: Voltage Required 60kv at Load Terminal

DC Voltage Supply	Voltage p.u.	Voltage sag
40 kV	0.85	15%
44kV	0.92	8%
47kV	0.97	3%
48 kV	1	0%

Fig.28 shows that voltage sag of 93% in 60 kV transmission line is fully compensated with the DC energy storage capacity of 48 kV.

VII. DC Storage Calculations

Results indicating requirements of DC battery storage capacities for maintaining various transmission voltages at load terminals during sags of different degrees are given in Table 7.

Table 7

Voltage at load terminal (V_{Load})	Required DC Storage voltage (V_{DCs})	Required DC Storage voltage (% age of V_{Load})
11kV	5 kV	45.45
16kV	8.5 kV	53.12
25kV	16 kV	64
40kV	30 kV	75
60kV	48 kV	80

For load terminal voltage sag compensation, required DC storage voltage which is supplied to as an input inverter, can be estimated for from equation 11, 12 and 13 as shown below.

$V_{DCs} = -5.55+0.89\ V_{Load}$ (11)

$V_{DCs} = -4.2+0.79\ V_{Load} +0.0014\ V^2_{Load}$ (12)

$V_{DCs} = -0.83 +0.38\ V_{Load} +0.015\ V^2_{Load} + 0.00013\ V^3_{Load}$ (13)

Where

V_{Load} is Voltage at load terminal.

V_{DCs} is DC Storage voltage required for sag compensation.

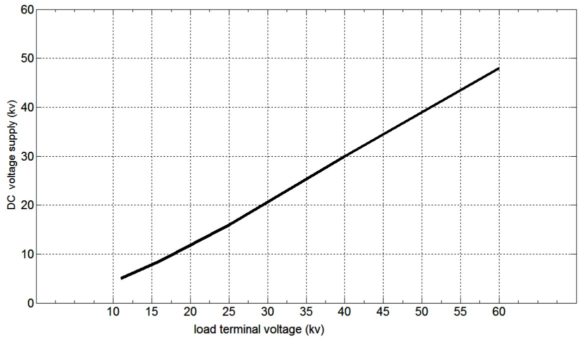


Fig.34. Load Terminal Voltage Verses DC Battery Voltage

Fig.34. shows approximate linear relationship between the DC storage voltage supplies and load terminal voltage.

VIII. Conclusion

Based on analysis of test system, it is suggested that percentage sag and operating voltage are major factors in estimating the requirement of DC storage capacity. The effectiveness of a DVR system mainly depends upon the amount and stiffness of DC energy storage device. Investigations were carried out for various cases of voltage sags at different transmission voltage levels. Result show that any increase in transmission voltage and voltage sag demands sufficient increase in DC storage capacity. An expression is developed to estimate the required DC storage voltage for specified transmission voltage and percentage sag. This can be used as a basis for future research in this area.

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