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BALANCED VOLTAGE SAG CORRECTION WITH THE HELP OF ENERGY STORAGE SYSTEM

Dr.Y. S. Bais, HOD Electrical Engg. Dept, Nagarjuna Institute of Engineering, Technology and Management, Nagpur, Maharashtra, India.
Prof. V. V. Jais, Prof. N. S. Moghe, Prof. P. A. Bhange, Assistant Professor, Electrical Engg. Dept, Govindrao Wanjari College of Engineering& Technology, Nagpur.

Abstract
Voltage sag is one of the major power quality problem which results in a failure or a mis-operation of end use equipments. Sensitive industrial loads and Utility distribution networks all suffer from various types of outages and service interruptions which can cost significant financial 1oss per incident. The aim therefore, is to recommend measures that can improve voltage sag. In this paper a method of determining the exact amount of voltage injection required to systematically correct voltage sag with active power injection with the help of energy storage system (ESS) is described. This paper presents the Dynamic Voltage Restorer (DVR) with ESS based PI Controller method to compensate balanced voltage sag. Simulation results show that this proposed method can compensate balanced voltage sag effectively**.**

Keywords: Power quality, voltage sag, Custom power Devices, DVR, Energy Storage System, pulse width modulation.

Introduction
Voltage sag is a momentary decrease in the *rms* voltage magnitude lasting between half a cycle and several seconds [1]. Two important parameters of voltage sag are magnitude and time duration. However, the sag magnitude is not constant, due to the induction motor load [2]. Fig. 1 shows 50% voltage sag for 300ms. Voltage sag due to faults have become one of the most important power quality problems facing industrial customers. Any disturbances to voltage waveform can result in problems related with the operation of electrical and electronic devices. Users need constant sine wave shape, constant frequency and symmetrical voltage with a constant rms value to continue the production. This increasing interest to improve overall efficiency and eliminate variations in the industry have resulted more complex instruments that are sensitive to voltage disturbances [3]. Static Series Synchronous Compensator (SSSC), commercially known as Dynamic Voltage Restorer (DVR) injects a voltage in series with the system voltage provides the most cost effective solution to mitigate voltage sags by improving power quality level that is required by customer [4]. When a fault happens in a distribution network, sudden voltage sag will appear on adjacent loads. DVR installed on a sensitive load, restores the line voltage to its nominal value in few milliseconds.

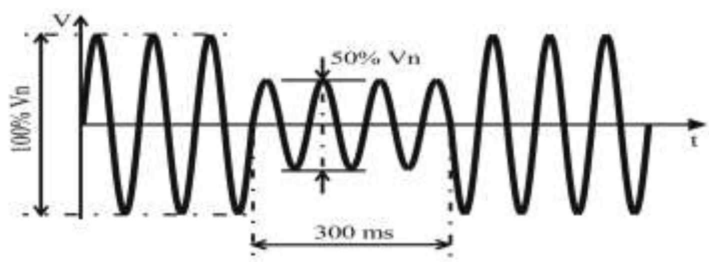

Fig. 1 Voltage Sag

power injection into the system [5]. When the injected voltage leads the supply voltage, however, the same correction can be made with a lower value of active power injection [5]. This is possible at an expense of higher voltage injection. Such an operation requires careful determination of injected voltage magnitude and angle.

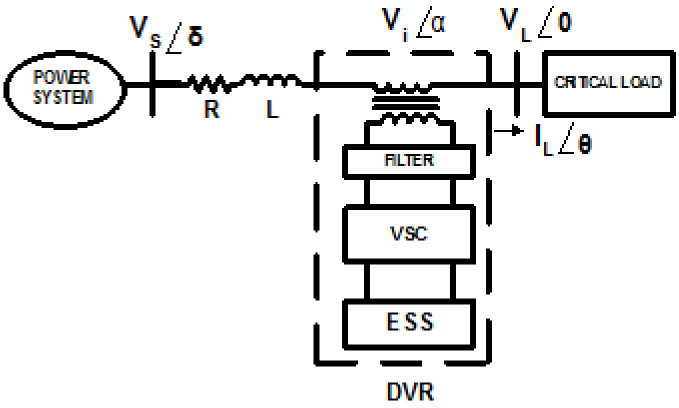

Fig. 2 Dynamic voltage restorer

In general, the active and reactive power flows are controlled by the angle between the voltage that is injected in series with the line and the line current as shown in fig. 3. For example, if the voltage is in phase with the current, only active power is changing with the line. Otherwise, if the voltage is in quadrature with the current, nothing more than reactive power, will change with the line, also minimum active power injection will be required if the power factor of supply is unity [6].

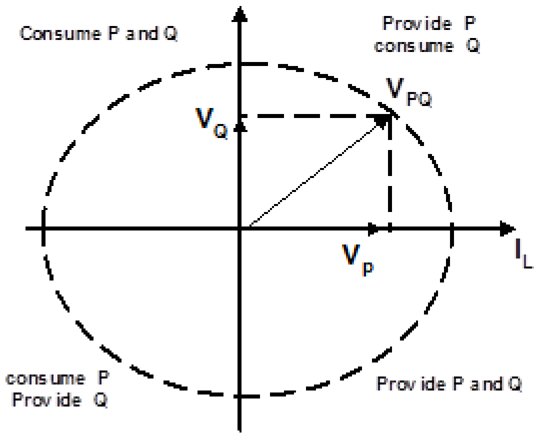

Fig. 3

Without energy storage system, the DVR can only inject voltages in quadrature with the load current and hence a larger voltage injection is required to mitigate the voltage sag. In addition, reactive power compensation is only effective for small voltage sag. Energy storage system gives the flexibility to inject voltage at any phase angle and compensate for deeper voltage sags, voltage sags with phase jumps and longer duration voltage sag.

As From fig 2 , the equation governing the system without series compensation is:

$$V_S = V_L + I_L Z \qquad (1)$$

where: V_L is the load voltage (reference phasor), **δ** is the power (or torque) angle, I_L is the line current and V_S is the supply voltage. A disturbance or fault in the system may reduce the supply voltage magnitude V_S to a new value $V_{S\text{-}new}$. The supply voltage can be maintained by the injection of V_i .

The equation for the compensated system is:

$$V_{S\text{-}new} = V_L + I_L Z - V_i \qquad (2)$$

where: V_i is the injected voltage
α is the phase angle of V_i.
The rating of the ESS is: $S_i = 3V_i I_L$ (3)
where the above the current represents the complex conjugate

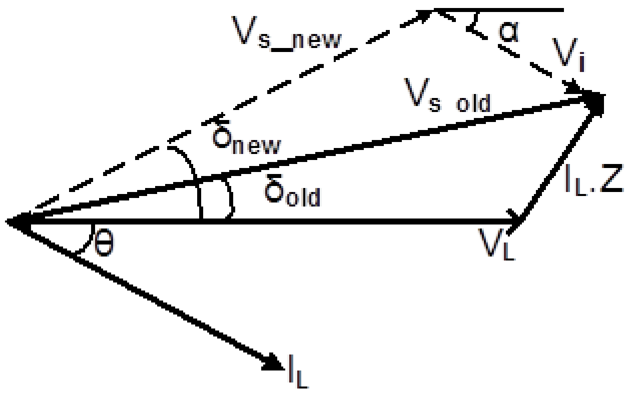

Fig. 4 Vector Diagram of Compensated System

Fig. 4 shows the vector diagram of the compensated system. The direction of the vector ($I_L Z$**)** depends on the power factor of the load (in this case a lagging power factor) and the impedance of the line. For distribution feeders, the ratio of reactance to resistance is less than for transmission lines, which implies that the impedance angle will be less than 90 degree.
Fig. 4 illustrates that the injection of an arbitrary voltage V_i can maintain the load voltage constant when the supply voltage dips. However, the injected complex power depends on the amplitude and phase angle of V_i. Visual observation of Fig. 4 suggests that S_i will be minimum when **α = δ** . This is shown in Fig. 5

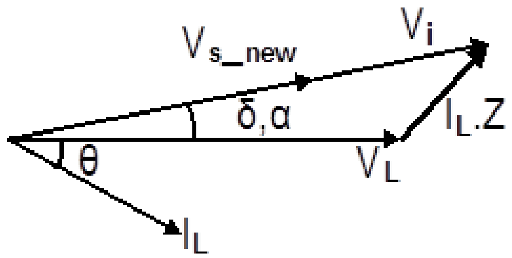

Fig. 5

The effectiveness of the series compensation can be obtained by the determination of injected power as a function of system parameters. Therefore, minimization of injected kVA from the ESS should be used as the criteria.
Solving for V_i in (2) and substituting into (3) yields:
$V_{S\text{-}new}=3.(V_L+I_L Z - V_{S\text{-}new}).I_L$ (4)
$V_{S\text{-}new}$**,** the new source voltage, is simply a function of the transient voltage dip (V_d**)** in the line from the original source voltage **(**V_S**):**
$V_{S\text{-}new} = (1- V_d). V_S$ (5)
Note that V_d is a phasor quantity since both V_S and $V_{S\text{-}new}$ are phasor quantities. Substitution of (5) and (1) into (4) yields after simplification:
$Si = 3[|V_d| I.|V_S|.e^{j(\delta+\phi)}]$ (6)
where: ϕ is the phase angle of V_d
The voltage deviation (VD) of the system which is referred to as voltage regulation in the utility industry is found from:
$VD = |V_S|-|V_L|/|V_L|$ (7)

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Since V_L is the reference vector, the absolute value marks can be removed from it. Solving for the absolute value of the supply voltage and substituting into (6) yields the amount of KVA injected by ESS of DVR:

$$|Si| = 3[|V_d|.\ |I|.V_L.(1+VD)] \quad (8)$$

Equation (8) is the calculation of the injected KVA of the ESS of DVR as a function of the system parameters.

III.MODELING OF DVR

The system under consideration consists of simple radial system with a source, a bus, and two parallel loads as shown in fig 6. When a three phase fault occurs in the system, the critical load experiences balanced voltage sag. Fig.6 also shows the basic model layout of DVR with ESS. ESS can be used to protect sensitive production equipments from shutdowns caused by voltage sags. These are usually DC storage systems such as

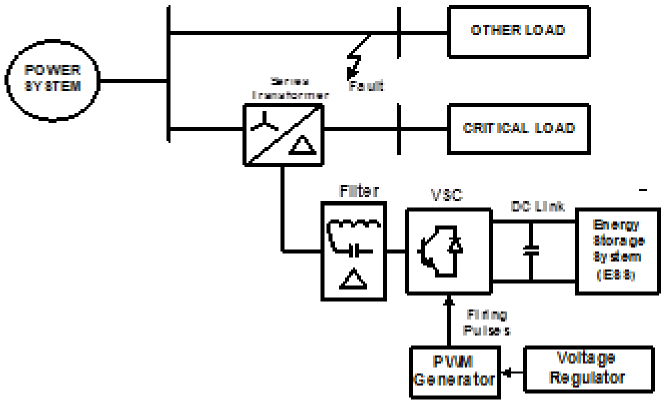

Fig. 6 SYSTEM and DVR model layout

The outer control system consists of a sag detector, sag corrector and energy control system as shown in Fig. 7(a),7(b).

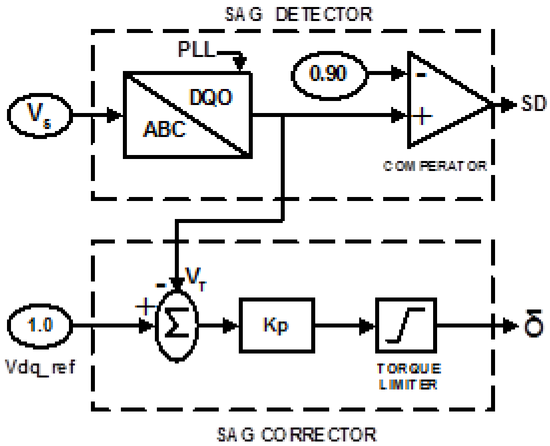

Fig. 7(a) Sag detector and sag corrector

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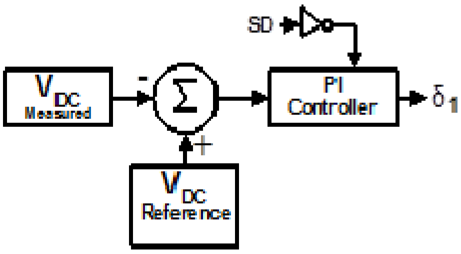

Fig. 7(b) Energy control system

The sag detector detects the voltage sag and activates the control system for sag correction. The output of it is a pulse with duration equal to the duration of voltage sag. The inputs are the voltages measured on the supply side. The measured voltages are converted to d-q space vector in p.u. in synchronously rotating reference frame. The magnitude of the space vector is compared to a reference value (1.0pu). The detector can give accurate result only for balanced voltage sags.

B. Sag corrector

In sag corrector, the controller input is an error signal obtained from the reference voltage and the p.u. rms value of the terminal voltage measured. Such error is processed by a PI controller and the output is the angle δ, which is provided to the PWM signal generator. The PWM generator then generates the pulse signals to the IGBT gates of voltage source converter.

C. PWM Scheme

The inverter is the core component of the DVR, and its control will directly affect the performance of the DVR. In the proposed DVR, a discrete PWM scheme will be used. The inverter used in this study is a six-pulse inverter. The carrier waveform is a triangular wave with high frequency (3000 Hz). The modulating index will vary according to the input error signal. The basic idea of PWM is to compare a sinusoidal control signal of normal 60 Hz frequency with a modulating (or carrier) triangular pulses of higher frequency. When the control signal is greater than the carrier signal, three switches of the six are turned on, and their counter switches are turned off. As the control signal is the error signal, therefore, the output of the inverter will represent the required compensation voltage.

D. Energy Control System

A proportional integral feedback control is used for controlling DC bus voltage. If the sag detector detects sag SD goes low. The DC bus voltage controllers during sag improve the response time.

V. SIMULATION RESULTS

The ESS performance is analyzed by creating a three phase fault at the location shown in Fig. 6. The fault results in a balanced voltage sag of 60% on the supply side of the series transformer. Distance of the fault from the bus decides the depth of the voltage sag. The first simulation contains no DVR and second simulation contains DVR. Using the facilities available in MATLAB [7], the DVR is simulated to be in operation only for the duration of the fault, as it is expected to be the case in a practical situation.

Extensive simulation is done by considering super capacitor and battery as ESS. The results shown in fig. 8 indicates that the variable SD is one until the fault is detected and then goes to logic zero when the supply voltage is out of tolerance. The output Vdqs is the per unit magnitude of supply side voltage space vector, and Vdql is the per unit magnitude of load side compensated voltage space vector. Note that the space vector voltage magnitude changes much more quickly since it is based on instantaneous quantities, and not averaged over a cycle as the RMS voltages are. Therefore, a RMS voltage reference based sag detector will react more slowly, and hurt the response of the system. The space vector based d-q voltage is used to provide faster, more accurate detection of the voltage sag in the system described in this paper.

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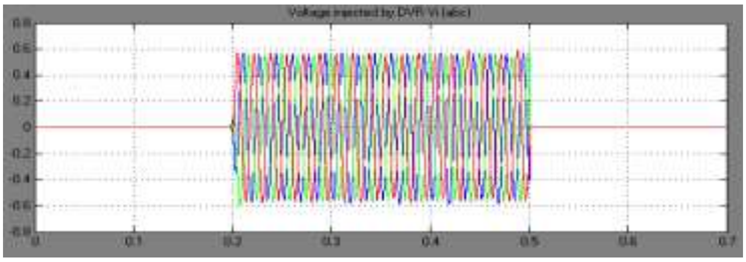
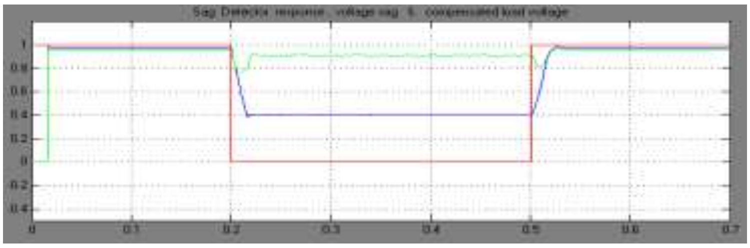
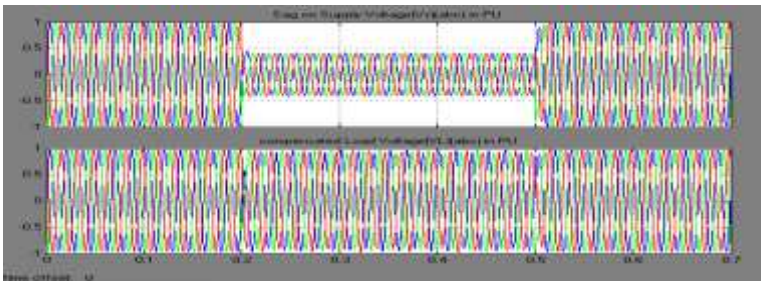


When SD goes low as shown in Fig. 7(a), the sag corrector is activated. The DC bus controllers are bypassed when SD is one. The ESS was in standby mode until SD goes low. Fig.9 shows the per-unit phase to phase RMS voltages on the supply side and critical load side. Figure 10 and 11 shows the voltage injected by DVR in abc & dqo system.

Figures 12 show the pu line voltage of phase A on the supply side and critical load side respectively. The ESS responded



within 2 cycles to keep the critical load voltage within the 10% tolerance (i.e. the sag is corrected to 0.90 per unit, not 1.0 per unit).



The sag correction can be done for 0% tolerance but it will result in over voltages at the end of the sag, with the potential to cause insulation damage. Figure 13 and 14 shows the active power on load side with and without DVR. Figure 15 shows the state of charge of the battery. In this case, the critical load voltage was regulated below 10% of the nominal.

Fig. 8 Sag detector response, balanced voltage sag, compensated critical load voltage in pu in dqo system

Fig.9 Balanced Voltage sag & compensated critical load voltage in pu in abc system

Fig. 10 Voltage injected by DVR in abc system

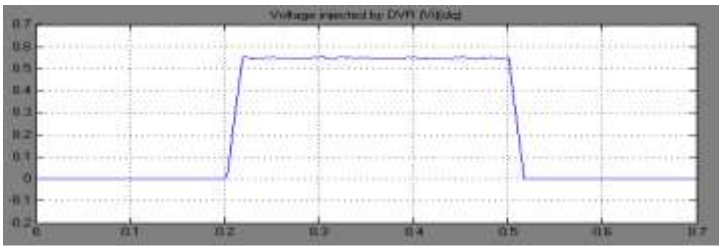


Fig. 11 Voltage injected by DVR in dqo system

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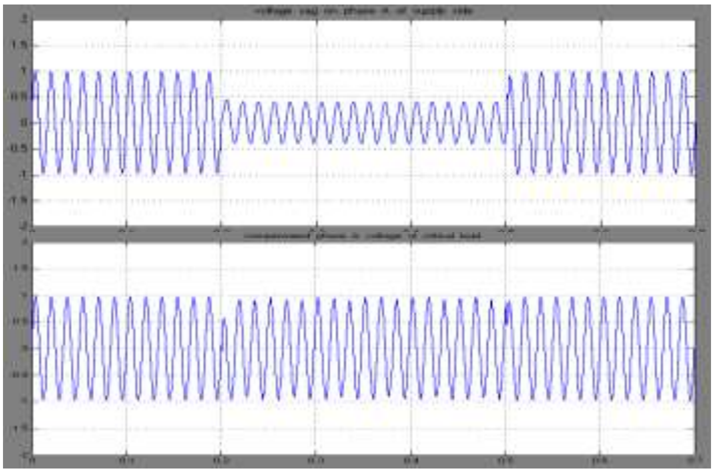

Fig. 12 Per unit line voltage of phase A on the supply side and critical load side

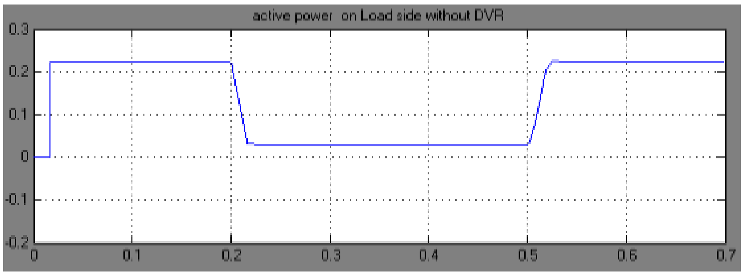

Fig. 13 Active power on load side without DVR

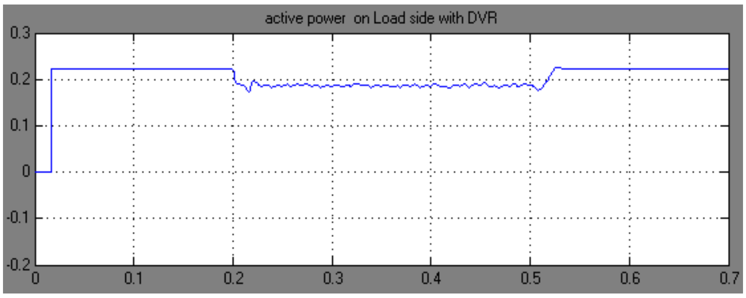

Fig. 14 Active power on load side with DVR

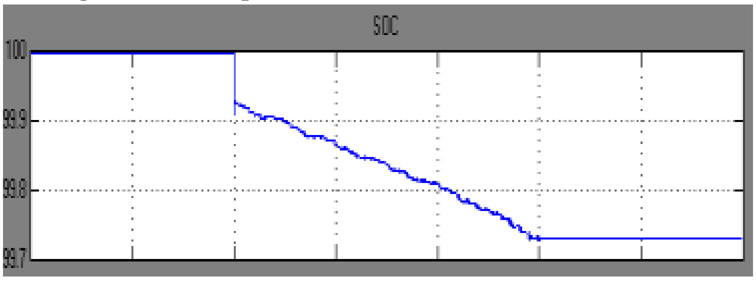

Fig15. State of charge of Battery

Conclusion

In this paper, a simple, fast, and cost effective Dynamic Voltage Restorer (DVR) is proposed for mitigating the problem of voltage sags in industrial distribution systems, with a large portion of its load consisting of induction motors. Calculation of the compensating voltage is done with reference to voltage only, since induction motors are not sensitive to changes in phase angle. A controller based on feed foreword technique is used which utilizes the error signal (difference between the reference voltage and actual measured voltage) to trigger the switches of an inverter using a Pulse Width

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Modulation (PWM) scheme. A new PWM-based control scheme has been implemented to control the electronic valves in the two –level VSC used in the DVR. The proposed DVR utilizes energy drawn from the ESS during abnormal condition and stored in capacitors, and which is converted to an adjustable three phase ac voltage suitable for mitigation of voltage sags. An energy control system that regulates the DC bus voltage charges the ESS has been proposed. The advantages of a d-q based sag detector over rms voltage have been shown.

The simulation shows that the capacity of power compensation and voltage regulation depends mainly on the rating of ESS of DVR.

Power System	3ph,480V,60Hz,50KVA
Series Transformer	480/480V,50KVA,10%
LC Filters	10mH,20μP
Critical Load	Passive,3ph-Resistive Load,10Ω
Other Loads	Passive,3ph-RL Load,5Ω,10mH
Line Impedance to both Loads	0.2Ω,1mH
DC Link	2000μF
PWM Switching Frequency	3000Hz
Nominal voltage of battery	160V
Maximum Capacity	1Ah

Table 1 System Data

TABLE 1 provides a list of system data used in this paper.

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