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RESEARCH ARTICLE OPEN ACCESS

Mitigation of Voltage Sag and Swell using Dynamic Voltage Restorer and its Simulation and Configuration using MATLAB

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Abstract:
This paper focusses on the study and MATLAB Simulation of Dynamic voltage restorer. DVR is a custom power device used to alleviate common power quality problems: Sag and Swells. At the first, DVR structure and its important elements are discussed followed by topologies used to configure a DVR and its classification is presented. In phase and pre-sag compensation techniques are described along with their applications. The center of focus remains on the Simulink model of DVR. A 400-volt line is used with 3 different loads, one of which is constantly connected in the system while another two are used with Normally open &Normally closed circuit breakers in order to produce sag and swells. Under different test conditions, performance of DVR is logged to estimate its efficacy and efficiency under abnormal fault conditions. In this study, DVR is designed using SRF theory, Hysteresis controller, Voltage Source inverter, Phase locked Loop and a storage unit. After simulation it is found that DVR works fine under sag as well as swell conditions and efficiently trouble shoots both the faults. It is noteworthy to iterate that DVR is an economical solution as compared with other Facts devices.

Keywords: Dynamic Voltage Restorer, In-Phase Compensation, Pre-sag compensation,Voltage Source Inverter, Synchronous Reference Frame, Hysteresis Controller.

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I. INTRODUCTION:

Amongst Power Quality Engineers, supplying distortion free voltage to end users is of prime importance. From past few decades, industrialization has emerged with sensitive loads which demand power with absolutely no fluctuations. This includes a completely balanced voltage, not only in terms of magnitude but also in terms of phasor angle. Furthermore, voltage must be free from frequently occurring disturbances, for instance noise, flicker, interruption, harmonics etc. These transients, sometimes when hit to the sensitive loads, ends up causing a huge financial loss to the companies [1,2]. In general, these power quality distorting problems occur due to the switching in or out the heavy loads which further leads to distortion in voltage profile causing voltage flicker, spikes, Voltage sag or Voltage Swell. To deal with these problems, a number of approaches has been invented by different researchers which mainly suggest the use of FACTS or Custom Power Devices. One of which is the use of Dynamic Voltage Restorer (DVR).

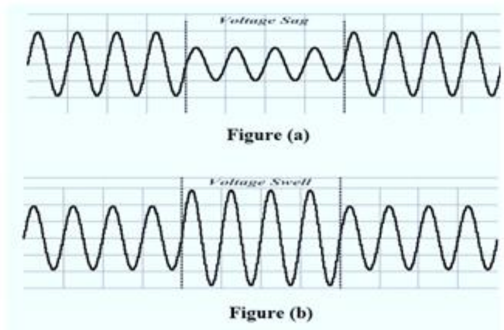

Figure 1: Voltage Sag and Swell

A DVR addresses the voltage magnitude issues, specifically in alleviating the effects of Voltage Sag and Swell. This Custom Power Device (CPD) senses the dip or swell in voltage magnitude and injects or draws the extra amount of compensating voltage into the line. According to the definitions, Voltage Sag is a short-term reduction in Root Mean Square (rms) value of the voltage. It might range from 90% to 10% of its default value. The span of time of this particular fault is from 0.01 seconds to a few seconds (i.e from a half cycle to few cycles), as indicated in figure 1(a). Voltage Swell, on the other hand, is a rise in voltage rms value for no longer than 2 minutes as shown in figure 1(b). If a swell exceeds this timeline, it would be considered as overvoltage [3].

This paper addresses the specific issues of Voltage Sag & Swell and its mitigating methodology using Dynamic Voltage Restorer, its structure, working and Simulink configuration using MATLAB vR2017a.

II. STRUCTURE OF DVR:

DVR is a custom power device connected always in series with the line. It contains a controllable voltage Source which connects a common coupling point (PCC) in between the primary voltage source of the grid and sensitive loads at the consumer end. As per the FACTS criteria, to trouble shoot voltage disturbances, a device should be connected in series with the line in order the inject the required compensating voltage [4]. During a severe sag, DVR also prevents the load from tripping OFF. The indispensable elements of DVR are an Energy storage, VSC (Voltage source converter), series injection transformer, filters and DC-link condensers as depicted in figure 2.

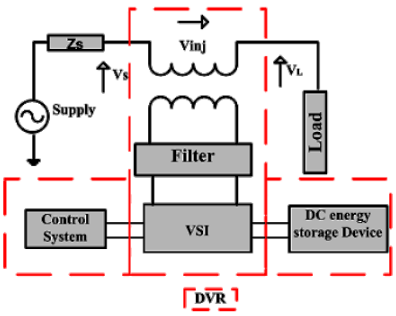

Figure 2: Structure of DVR

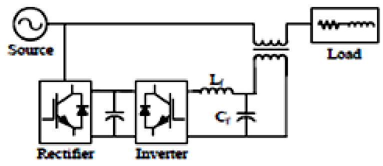

Figure 3: Back to Back connected converters.

2.1 Energy Storage:

If a voltage sag appears into the line, according to DVR topology, it has to inject the voltage in series with the line at PCC to restorer the default voltage magnitude. To inject this amount of voltage, DVR needs a source of energy which is fulfilled by Energy Storge Unit [5]. There are two different proposed configurations, either to employ Batteries or using back to back (B2B) connected Power Electronic Converters as shown in figure 3.

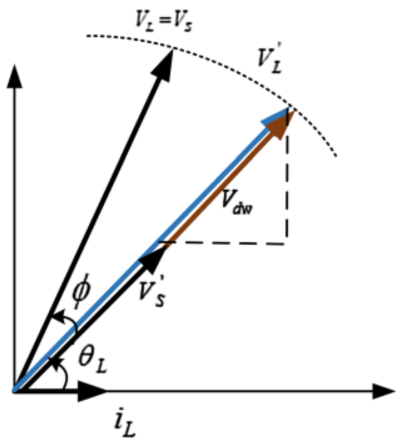

Figure:4. Phasor Diagram of In-phase compensation

2.2 Voltage Source Inverters:

A VSI or voltage source converter is used to convert DC voltage into controllable 3-ph AC voltage. This converter employs the Sinusoidal Pulse Width Modulation technique to (SPWM) to modulate its o/p. A VSI is configured to operate even in unbalanced voltage condition and hence it utilizes an independent control structure. Moreover, sometimes sag on one phase causes to produce Swell on another phase and therefore, a DVR is designed to mitigate sag and swell simultaneously. Another suggested DVR topology is to use a Multi-level cascaded Converter. This structure is also known as Transformer less design of DVR as it excludes the use of Injection Transformer. [6].

2.4 Filters:

At the output side of converter, higher order harmonics distorts the voltage waves created due to the non-liner characteristics of the load. To resolve this problem filters are used in between VSI and Injection Transformers [7].

2.5 Injection Transformer:

An injection transformer is used to inject or draw the compensation voltage in case of sag and swell respectively. The injection or drawing the voltage occurs at the point of common coupling (PCC). For proper integration of injection transformer into the DVR circuit, some important parameters have to be estimated which includes impedances of HV and LV windings, turns ratio and more importantly, the MVA rating of transformer. The output voltage rating of Dynamic voltage restorer is substantially reduced if the turns ratio is higher (i.e. the ratio of stepping up the voltage [8].

III. DVR TOPOLOGIES:

When designing a DVR circuit, some important factors to be taken into account are: Quick response, precision, modulation and finally, economy. Another important factors which classify the DVR are *(i)* Constant dc link voltage and *(ii)* variable dc link voltage [9]. However, this paper focusses on the study of constant dc link voltage DVR topology.

IV. DVR COMPENSATION TECHNIQUES:

For keeping the constant load voltage at the utility end, the compensation voltage injected or drawn from the line on the occurrence of sag or swell. This compensation method is opted owing to the type of load as it might be sensitive to voltage magnitude or the phase angle or both. An analysis is carried out on load before choosing the DVR compensation methodology. Two voltage injection techniques are discussed below.

4.1 In phase compensation:

This methodology is suitable for loads susceptible to deviating voltage magnitude. Independent of the preadult condition, this technique balances the load voltage by injection of missing voltage in phase with the line voltage [10]. Therefore, this technique is also recognized by Voltage Magnitude Optimization Control (VMOC) Technique. Corresponding phasor diag. is shown in the below figure (4).

Let,

V_{grid}, I_{grid}, and V_{load} be the pre-sag represents grid voltage, current and load voltage respectively.
V'_{grid}, I'_{grid} and V'_{load}. be the same quantities under sag condition.
Let,

V'_{dvr} = DVR injected voltage
Φ = Phasor variation between load voltage and load current
δ = Corresponding angle to the phase jump of the grid voltage (during sag)
k = Any phasor*a,b, or c*

During sag, power and voltages are….

$$P_{DVR} = P_{Grid} - P_{load} \quad \ldots\ldots..(1)$$

$$P_{DVR} = V_l I_l \cos\varphi - V_g' I_l \cos(\varphi - \delta) \quad \ldots\ldots..(2)$$

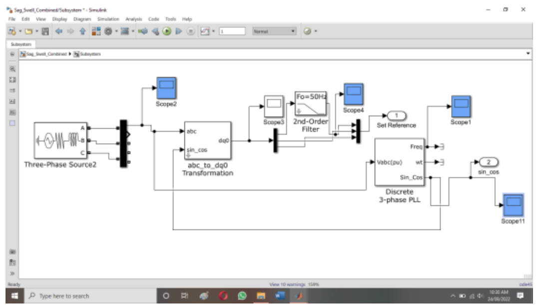

Fig:6 Simulink Model of PLL and dq0 Transformation

DVR Injection Voltage….

$$V_{DVR} = \sqrt{2}\sqrt{\{V_l^2 + V_s'^2 - 2V_l V_s' \cos\delta\}} \quad \ldots\ldots..(3)$$

Phase angle of Voltage of DVR ….

$$\angle V_{DVR} = \tan^{-1}\left[\frac{V_l \sin\varphi - V_s' \sin(\varphi - \delta)}{V_l \cos\varphi - V_s' \cos(\varphi - \delta)}\right] \quad \ldots\ldots..(4)$$

4.2 Pre-sag Compensation:

When Voltage magnitude and phase angles are simultaneously be compensated, pre-sag compensation technique is employed. To minimize the differences between pre-sag and post sag condition, this technique injects with the same profile of voltage with identical magnitude, harmonics, & waveshapes [11]. Therefore, voltage at the utility end completely matches with the voltage at the sending end. Hence, this method is suitable for uneven sags either with or without phase jumps. Although this technique have a high range of voltage injection, a storage unit of large capacity is required to supply active and reactive power injected by Voltage source inverters (VSI) [12]. Fig 5 shows the phasor diag. of pre-sag compensation and following equations gives the magnitude & phase angles of voltage to be injected.

$$V'_{DVR,k} = \sqrt{2}\sqrt{\left[V_{load}^2 + V_{grid}^2 - 2V_{load}\,V'_{grid}\,\cos\delta_k\right]} \,..(5)$$

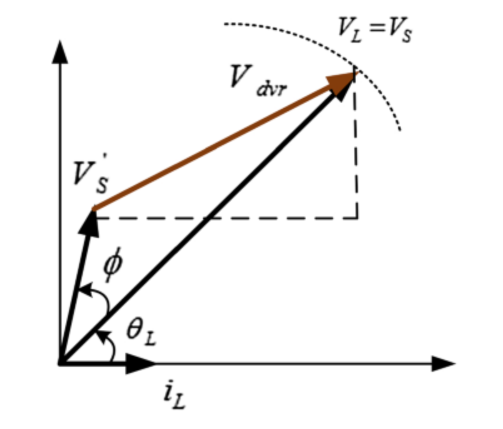

Figure:5. Phasor Diagram of pre-sag compensation

$$\angle V'_{DVR,k} = arctan\left\{\frac{V_{load}\,\sin(\varphi) - V'_{grid,k}\,\sin(\varphi-\delta_k)}{V_{load}\,\cos(\varphi) - V'_{grid,k}\,\cos(\varphi-\delta_k)}\right\}$$

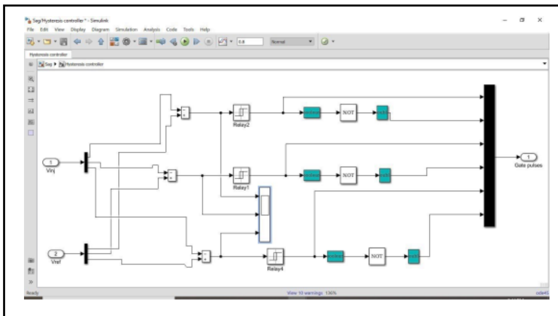

Fig:8 Simulink Model of Hysteresis Controller

V. METHODOLOGY:

5.1 SRF Theory:

To mitigate a sag or swell, the generation of reference voltage requires the transformation equations. Here, SRF (Synchronous reference Frame) theory is used to convert *abc* into *dq0* reference frame as these signals are much easier to process [12].

(a) Clarke's Transformation:

In Clarke's transformation, *abc* reference phasors are converted into $\alpha\beta$ reference frame using the following equations.

$$\begin{bmatrix} V_\propto \\ V_\beta \end{bmatrix} = \sqrt{(2/3)}\begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix}\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad \ldots\ldots..(7)$$

(b) Park's Transformation: To convert signals into rotating dq0 frame, equation is used (8)…

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} cos\theta & sin\theta \\ -sin\theta & cos\theta \end{bmatrix}\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} \quad \ldots\ldots..(8)$$

For this transformation, Phase Lock loop (PLL), indicated in figure :6 is used to extract angle θ. As V_d&V_q, still contain some ac components which are further filtered out via low pass filter (LPF). Further, inverse park (eq:9) and Clarke's transformation (eq:10) equations are used to obtain default *abc* co-ordinates.

$$\begin{bmatrix} V_\alpha^* \\ V_\beta^* \end{bmatrix} = \begin{bmatrix} cos\theta & -sin\theta \\ sin\theta & cos\theta \end{bmatrix}\begin{bmatrix} V_{ddc} \\ 0 \end{bmatrix} \quad \ldots\ldots..(9)$$

$$\begin{bmatrix} V_a^* \\ V_b^* \\ V_c^* \end{bmatrix} = \sqrt{2/3}\begin{bmatrix} 1/\sqrt{2} & 1 & 0 \\ 1/\sqrt{2} & -1/2 & \sqrt{3}/2 \\ 1/\sqrt{2} & -1/2 & -\sqrt{3}/2 \end{bmatrix}\begin{bmatrix} V_0^* \\ V_\alpha^* \\ V_\beta^* \end{bmatrix} \quad \ldots\ldots.(10)$$

5.3 Hysteresis Controller:

Hysteresis controller, as compared to PWM is much easier to design. Fundamentally, it uses error signal obtained while differentiating the injection voltage with reference voltage. It then leads to produce the proper firing sequence of the Thyristors of VSI[13,14]. Eventually, the injection voltage produced by VSI is penetrated via PCC into the line via Injection Transformer as…

$$V_L = V_s + V_{inj} \quad \ldots\ldots..(14)$$

Working principal of hysteresis controller to produce firing sequence is depicted in fig7. Whereas, fig.8 shows it's Simulink model using MATLAB.

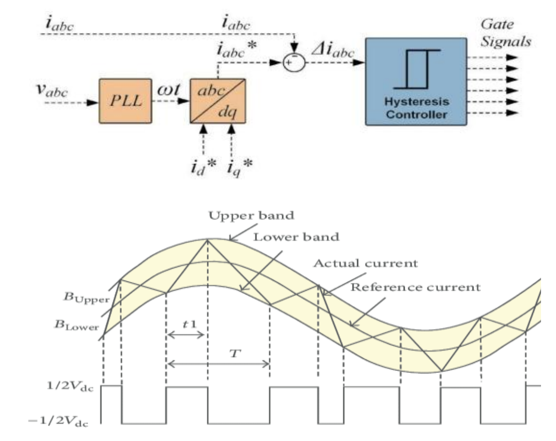

Fig:7Hysteresis Controller and its gate signal output

The dotted line showed in the figure denotes the highest and lowest limit of triangular waves*viz* +1

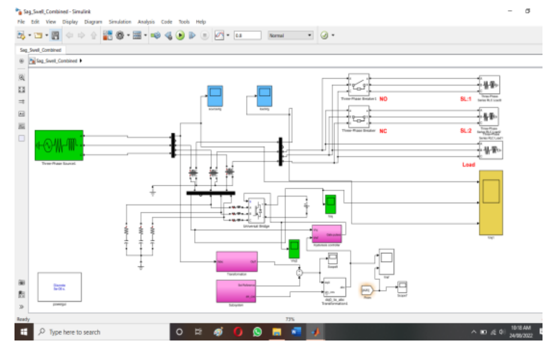

Fig:9Simulink Model of Complete DVR Circuit

& -1 respectively. At position +1 the switch gets ON and remains until the signal reaches to its lower -1 value [15]. This sequence repeats itself and produces a firing sequence for the Power Electronic switches of IGBT.

VI. SIMULATION AND RESULTS:

6.1 Simulation of DVR under Sag and Swell.

Using MATLAB Simulink, simulation of Working of Dynamic voltage restorer carried out under different loading circumstances. The voltage sag and swell on the line was deliberately created via switching of heavy loads *viz* Shunt Loads (SL-1 and SL-2). To create sag, SL-1 with the rating of *S=15e3+j150* was switched on via Normally Open (NO) switched timed to be in circuitry for the duration between 0.25 to 0.3 *i.e* for 5 milli seconds. For this duration a sag is produced and for the same duration DVR produces injection voltage as discussed above. This is further depicted in figure: 10 and 11.

To produce a swell, we are switching a normally closed (NC) breaker which is cutting off the SL:2 Load of capacity *S=26e10+j110*. The breaker now operates at *t=0.6 to t=0.7i.e.* for 0.1 seconds. Evidently, in contrast to the sag situation, we are actually removing a heavy load which, for a short duration of time, rises the voltage hence creating a swell (Fig:10). Again, DVR circuitry comes into the operation and the surplus voltage created during certain time is now gets drawn to Energy storage unit via VSI and Injection transformer& compensation voltage is produced which is shown in Fig:12. This trouble shoots the fault condition and reduces the voltage to its steady state rated value. The final Diagram of restored waves are shown in Fig:13.

6.2 Simulation Parameters:

Sr. No	Equipment	Description	Rating
1	Injection Transformer	Step Up	320/400 V,
2	SL:1	Inductive	*S=15e3+j150*
3	SL:2	Inductive	*S=26e10+j110*
4	CB:1	Normally Open	*t=0.25 to t=0.3*
5	CB:2	Normally Closed	*t=0.6 to t=0.7*
6	L-filters	Series Connected	*3.5e-3 H*
7	Source	Star Grounded	*400v,50Hz*
8	Load	Star Grounded	*10e3+j100*

Fig:11 Reference generated to measure depth of sag and height of swell

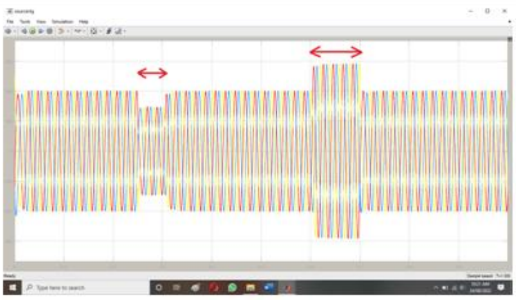

Fig:10 Sag and Swell produced due to switching of SL:1 & SL:2

Fig:12 Compensation voltage generated

Final compensated voltage is given in Figure 13.

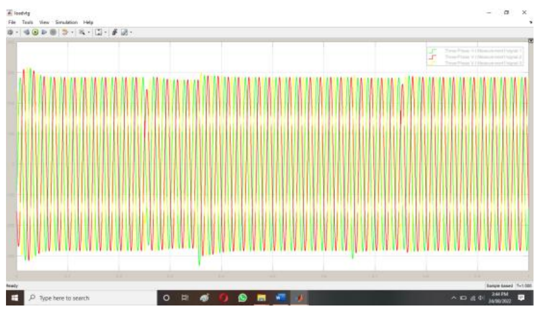

Fig:13 Final Restored Voltage Waves

VII. Results and Discussion:

From the graphs, it is apparent that during the sag, DVR is producing exact amount of Voltage magnitude with the reference phase angle to be injected at PCC to compensate the line voltage and restore it to normal steady state value. The duration of sag is from t=0.25 to t=0.30 seconds. The injection voltage produced is injected during the same period of time. In contrast to the Sag situation, swell is produced by cutting off the heavy load during t=0.6 to t=0.7 at Simulink time. The swelled voltage is drawn from the line through injection transformer via DVR and the response time observed from the graph in both situation is less than a half cycle i.e. 0 .1 seconds.

VIII. CONCLUSION:

This paper narrates the construction, working and MATLAB design of a Dynamic voltage restorer for mitigation of Sag and Swell. Simulation of DVR is completed into MATLAB Simulink environment using version R2017a. During the simulation, DVR circuit was subjected to Different test conditions, for instance, varying switching times of the breaker and increasing/decreasing the load capacity. In each iteration, DVR o/p sufficed to compensate the line voltage either by injecting or drawing into the DVR. Hence, we can conclude that DVR can be a potential custom power decide and can be installed at sensitive loads to keep voltage profile balanced, supplying electricity with power quality.

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