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Using dynamic voltage restorers to improve power quality in the electrical distribution system: an overview

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ABSTRACT : ***This paper represents a review of the dynamic voltage restorer for power quality improvement in the electrical distribution system. Over the past 50 years, issues concerning power quality have steadily increased, to prevent the effect of the voltage disturbances, some of the devices are put as a solution to these problems such as distribution static compensator (D-STATCOM), solid-state transformer (SST), and uninterruptible power supply (UPS), dynamic voltage restorer (DVR). The DVR is one of the economic solutions to overcome the voltage disturbances like voltage sag/swell and harmonics. It is widely used to mitigate the voltage disturbances in the power distribution system, especially in the medium and low distribution networks. This paper aims to review the implementation of the DVR in the system integrated with renewable energy resources. This is important because the future of electricity business is moving towards renewable energy and also provides a thorough discussion of the typical components, controllers, compensation methods, and the application of DVR. The extensive review of the technology aims to ease and speed up the development and the advancement of the DVR in the near future.***

Keywords: Cyber-physical system Dynamic voltage restorer Power quality Technological review Voltage compensation Voltage sag/swell

INTRODUCTION

The significance of power quality is something that cannot be compromised between customers and power utility companies because it dictates the benefits in the ever-competitive trade arena. The quality of power delivered to the customer is an asset for the utility company. Voltage disturbance and various power quality issues may cause damage to electrical and electronic appliances. Thus, many efforts have been considered to ensure that the quality of the voltage magnitude and frequency are within the allowable tolerance to deliver a viable quality of power to the user [1].

There are various power quality issues that exist in the system, like voltage swelling, sagging, harmonic, and service interruption. Of all the voltage issues, voltage sag and swell are the critical kinds of disturbance because it affects the performance of the load in the system, especially the sensitive loads. In order to mitigate the impact of the voltage and power quality disturbance to the system, several methods have been proposed and utilized in practice. The method such as D-STATCOM, SST, UPS, and DVR are used to compensate for the voltage difference between normal and disturbed operating conditions. The DVR is considered as the better solution among all devices in mitigating the voltage sag and swell due to its high-performance as compared to others [2]. Moreover, DVR provides a cost-effective solution compared to other devices [3]. DVR is commonly installed between a network and a sensitive load through a transformer that provides the supplementary voltage supply to compensate voltage instabilities that may cause damages to appliances [4].

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THE DYNAMIC VOLTAGE RESTORER

This section discusses the typical construction of the DVR used in practice. The DVR is a custom power device used in practice to compensate for the voltage sagging, swelling, and harmonic in the distribution network [13]. It is very critical to the operation of the sensitive load [14]. The primary function of a DVR is to detect the voltage disturbance in the system and inject necessary voltage to recover the system voltage back to its normal operating level. injecting voltage to inconstant input to ensure voltage quality for appliances [15].

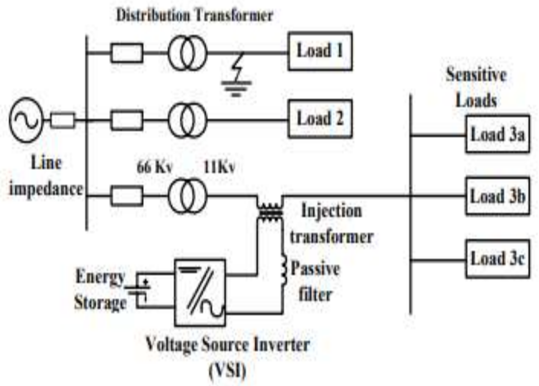

Figure 1. The typical power circuit of a DVR

Table 1. The descriptions of DVR's components

Component	Discussion
Energy storage	• To supply the required energy to compensate the voltage in the system (e.g., supercapacitors, batteries with superconducting magnetic energy storage, lead-acid, and flywheel. • Lead-acid batteries are the most popular types of energy storage considered for DVR due to it is highly responsive during the charging and discharging process [17].
VSI	• To convert the DC supply from the energy storage to the AC supply of the distribution network. • The invertal voltage needs to be balanced, pure sinusoidal; synchronized with the system voltage.
Filter circuit	• To filter out any harmonics generated by the VSI in order to maintain the quality of the compensated voltage [16]. • The VSI filter may be located either on the grid [18] or the converter side [19].
Bypass switch	• To prevent high current from passing through the DVR circuit in the event of a fault in the system. • Upon detecting an excessive current flow, the switch bypasses the current from the DVR circuit to protect it from the overcurrent.
Voltage injection transformer	• To increase the compensation voltage derived from the output of the VSI to meet the voltage level in the distribution network. • It also functions as isolation between the DVR and the distribution network.

THE DVR POWER CIRCUIT A DVR

power circuit comprises four essential aspects, namely, a voltage injection transformer, VSI, low-pass filters, and a device to store DC energy [16], as shown in Figure 1. The descriptions of each DVR components are tabulated in Table 1.

DVR COMPENSATION METHODS

For voltage injection, phase angle and magnitude are crucial aspects in controlling a DVR. The required voltage supply could be met by employing three methods of compensation. The basic approaches for control include in-phase, pre-sag, and minimal energy compensation techniques [20].

Compensation via Pre-Sag

Figure 2 illustrates the pre-sag compensation technique utilized for the DVR application. This method compensates the variance of sagging voltage with pre-sag voltage by restoring the magnitude and the phase of the voltage prior to the occurrence of the voltage sag [21]. In the figure, the voltage of the system prior to the disturbance are represented by $Vpre{-}sag$. Following the voltage disturbance, the voltage and the phase angle decreased to $Vsag$ and θsag, respectively. In order to compensate this sag, this method injects the voltage magnitude $VDVR$ and the phase angle θDVR to the system to compensate for the decrement of the $Vsag$ and θsag during the disturbance, respectively. This pre-sag compensation method requires a relatively higher magnitude of voltage injection as compared to other approaches. Hence, the active power requirement is relatively high at the occurrence of voltage sagging. Typically, this approach is applied to the appliances that are sensitive to the phase angle shift, e.g., thyristor-type converter.

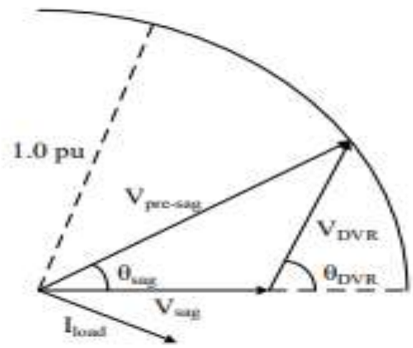

Figure 2. The pre-sag compensation technique

Compensation via In-phase

Figure 3 shows the in-phase voltage compensation method of a DVR. In this method, the DVR injects the voltage magnitude $VDVR$ without the phase angle compensation θDVR as in the previous approach. This approach compensates for the reduction of the voltage magnitude only. Therefore, it is suitable for the linear load that does not require any phase angle compensation [19]. When the magnitude of the voltage supply decreases due to the voltage disturbance, the approach provides the missing voltage magnitude $VDVR$ to the load

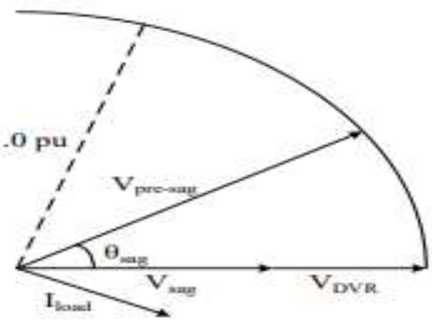

Figure 3. Compensation technique via in-phase

Minimum Energy Compensation

Figure 4 depicts the magnitude and angle representation of the minimal energy compensation method of a DVR. From the figure, the method injects the required voltage magnitude $VDVR$ with the phase angle of 90∘ to the load [16]. The system voltage Vpre−sag$\angle\theta pre{-}sag$ drops to the $Vsag\angle 0$ ° following a voltage disturbance in the system. Consequently, the DVR injects the necessary $VDVR\angle 90°$ to the system upon detection of the voltage disturbance and raises the voltage to $Vcomp$. Although the method does not require active power injection to the system, the injected voltage may require a higher rating transformer and inverter to compensate for the voltage disturbance in the system. As illustrated in the figure, $VDVR$ shown in Figure 4 is relatively higher as compared to the VDVR required for the pre-sag and in-phase compensation method shown in Figure 2 and 3, respectively.

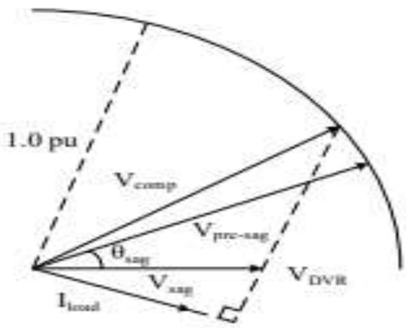

Figure 4. Minimum energy compensation

TYPES OF DVR CONTROL STRATEGIES

The operation of a DVR is highly depended on its strategies to control the active power and the reactive power in mitigating any power quality issues in the system [22]. As discussed in Section 2, the control strategies of the DVR are focused on the controlling of the VSI [23, 24]. Thus, the discussion in this section is focused on the control strategies of the VSI. There are over a myriad of the VSI control strategies reported in the literature. In this paper, the control strategies of the DVR are segregated into two main categories: linear and non-linear control. The consideration of the DVR control strategies depends on the nature and the sensitivity of the load in the system.

Conventional Control

The conventional control method can be divided into three different categories: feedforward, feedback, and hybrid. The feedforward control is the most common method used in DVR. The method mitigates the power quality issue by determining the difference between the pre-sage and the real-time voltage in the system through an open-loop system [25]. Although it is not as accurate as other control methods, the method is popular due to its simplicity, price, and fast. Thus, it is preferred to mitigate less sensitive and less critical load as compared to other more advanced methods. The feedback method adopts a closed-loop control strategy by comparing the load voltage with the reference voltage [26]. The method outperforms the feedforward method in terms of accuracy in power quality mitigation. However, the method is more complicated and has a time delay in providing the required control response. On the other hand, the hybrid control method combines both feedforward and feedback control strategies to utilize the advantages of both methods [27]. The composite control method provides better accuracy of power quality compensation at the expense of the simplicity and the cost of the controller.

Artificial Intelligence-based

Control In practice, it is known that the power system behavior is non-linear in practice. Therefore, the effectiveness of linear control is limited to only a certain operating range. Usually, a conventional controller has covered the application of DVR over a limited operating range. The performance of the linear control of DVR is not enough for the varying operating condition in a higher level of the distribution network. Therefore, the nonlinear control is considered to address this issue. Consequently, there are various nonlinear control methodologies for the DVR that utilized artificial neural network (ANN), fuzzy logic, and space vector pulse width modulation (SVPWM) are reported in the literature. Currently, ANN is being considered in any engineering topic to solve a complex engineering problem in practice. Its ability to replicate the decision-making capability of a human or a complex system is the main highlight of this method. There are several studies reported utilize ANN to provide the nonlinear control for the DVR application [21]. In the report, ANN is able to represent the non-linear correlation between the input and the output without knowing the complex mathematical functions representing the system. The performance of ANN varies with the number of training data and the structure of the neural network considered. Unlike the ANN, the fuzzy logic controller has proved itself in replacing the conventional controller in practice. The fuzzy logic controller allows definite decision-making process based on imprecise or ambiguous data. Researchers in [28] demonstrate the effectiveness of the fuzzy logic controller in the DVR application. In the paper, the fuzzy logic controller is able to decrease the transient overshoot of the VSI. In [29], SVPWM is utilized to eliminate the impact of the negative sequence component of the load voltage on the performance of the DVR. The report shows that the technique successfully mitigates the power quality issue, even the system is unbalanced.

ADVANCEMENT OF DVR

Conventional Sources

Using interline dynamic voltage restorer Although

the DVR is proven to mitigate the voltage disturbance in the system, the cost of replacing the energy storage system is undesirable in a certain situation. The interline DVR is reported in [30-32] to address this issue. Figure 5 shows the typical configuration of the interline DVR. From the figure, it shows that the two closely located DVR shares the same energy storage system to provide the voltage compensation to two different distribution lines. Due to its effectiveness, interline DVR has attracted power system researchers and engineers to conduct further investigation on its application. The study to come out with the optimized design is reported in [33], and the fast control scheme development is reported in [34].

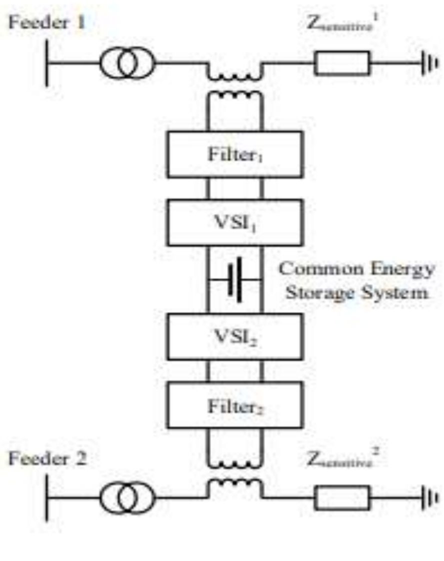

Figure 5. The typical configuration of an interline DVR

Development based on SOGI-PLL In [35],

a control algorithm to generate the reference voltage and current for the DVRapplication is reported. The method is based on the second-order generalized integrator (SOGI) applied on each phase in the distribution line. The DVR is combined with the D-STATCOM approach as the shunt and series active compensator to compensate the harmonics, sag, and swell in the system voltage and current, respectively. From the report, the SOGI-based algorithm is able to generate the required reference voltage and current from the distorted signals. Researchers in [36] focus on addressing the undesirable performance of the conventional DVR under unbalanced voltage sag condition. The method utilizes a dual SOGI (DSOGI) algorithm to extract the symmetrical components and eliminate the double frequency interference from the measured signal. The approach demonstrates promising performance in mitigating various power quality issues under various types of disturbance such as asymmetric, and symmetric voltage sag and harmonic. On the other hand, second-order - SOGI (SO-SOGI) is reported in [37]. The method aims to achieve fast power quality compensation with and without phase jump at harmonic conditions.

Other controllers Currently, the development of the DVR

is active in the literature. There are many advanced controllers have been proposed to address various power quality issues. In [38], a positive and negative sequence extractor (PNSE) is proposed to address the predicament of the conventional SRF-PLL in filtering our negative sequence voltage and harmonics in the power system. The method simplifies the process of the reference generation algorithm in order to restore the voltage following a disturbance in the system. On the contrary, the researchers in [39] report a soft-switching single-phase three-arm DVR to reduce the number of switching during voltage compensation process to improve the reliability of the DVR power circuit. Moving average filter (MAF) based DVR is reported in [33] to extract the positive sequence fundamental component from the distorted supply voltage. The method is proposed to address the performance issue of the conventional DVR in generating an accurate reference instantaneous injected voltage. In [40], a self-tuning filter (STF) is reported with the combination of the PQ control method to improve the performance of the DVR. The method significantly reduces the number of filters required in the DVR design.

Renewable Energy Integration

It is an inevitable trend for the researchers and engineers to consider renewable energy source in the development of technologies in power system studies. The consideration of the renewable energy source to the system possesses huge integration challenges to the power system community. The development of DVR is not excluded from this trend. The researchers in [41] utilize the feedforward vector control algorithm to generate the firing angle for the VSI for the voltage disturbance mitigation. The effectiveness of the proposed method is demonstrated on the actual wind farm measured data at Chinnaputhur substation, India, during the voltage sag and swell event. In [42], a PV-based DVR is reported to improve the power quality following a disturbance in the system. Here, PV plays a bifold role: supplying power to the load and supplying power to the DC-link of the DVR. A switching controller based on wavelet transform is proposed to detect any power quality event and transform the PV system's role into a DVR. A combination of feedforward and feedback control of the DVR is utilized to mitigate the voltage sag during unbalanced fault conditions is reported in [43]. The control of the DVR is vital for the fault ride-through (FRT) capability improvement in the doublyfed induction generator (DFIG) based wind turbine. The report shows that the proposed method is able to compensate for the variance in voltage under both balanced and unbalanced conditions.

CONCLUSION

The review of the DVR implementation in the electricity system is given as a conclusion. The power circuit's usual structure is displayed. The DVR is examined in depth, each part. As a result, the actual DVR compensation techniques are mentioned and discussed. This explains the pre-sag, in-phase, and minimum energy compensation methods in depth. Next, this study also discusses the variance of the control techniques. The functioning and critical evaluation of both the traditional controller and the artificial intelligence-based controller are included in the debate. After discussing DVR control options, it is also reviewed how far the technology has come with traditional energy sources. This article also reviews recent developments in renewable energy sources.

It is advised to continue the development of the DVR control circuit, especially for its functioning during imbalance voltage disturbance, according to the debate. Even though there has been a lot of study done to date to solve this problem, the performance and reaction time of the controller still have a lot of space for improvement. Additionally, one might work on the DVR's development while including renewable energy. Researchers need to pay immediate attention to a number of difficulties in this area, particularly the growth of the renewable energy system's dual function and the problems with power quality that have arisen as a result of the integration of renewable energy sources into the conventional power grid.

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