Review of Voltage Sag/Swell Mitigation Techniques with Dynamic Voltage Restorer in a Grid Integrated Distribution System

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***Abstract*—Voltage disturbances in power distribution systems caused by the integration of renewable energy sources can be efficiently minimized with the use of the Dynamic voltage restorer (DVR). DVR is an efficient custom power device that is used in power systems to mitigate voltage disturbances. The DVR's performance is determined by its maximum voltage injection capability and the amount of energy stored in the restorer. Enhancement in the control technique of this non-linear device (DVR) is required to improve its efficiency. To efficiently regulate DVR, Synchronous reference frame Theory (SRF), Artificial Neural Networks (ANN), Integrated Sliding Mode Controller (ISMC), Fuzzy logic, and a variety of other control approaches have been developed. This paper gives a comprehensive review of voltage quality challenges, as well as the different DVR-based control strategies used in reducing voltage sag and swell in power networks along with their advantages and disadvantages.**

***Keywords*— DVR, Solar PV, SRF, ANN.**

I. INTRODUCTION

The dependence of the world on non-renewable resources for production of energy has already started to prove itself as in-economical (costly), non-environmental friendly and above all its likelihood of sustainability for a long time is unachievable. Thus, world has changed its view on production of energy towards renewable resources. Conventional types for energy production like nuclear power plants, hydroelectric power plants, wind farms are effected by shortage in fossil fuels but are still not completely extinct. Thus, life span of these production units can be stretched and taken to high efficiency in usage with the help of technique, Distributed generation. Major production of these clean energies in DG comes through PV and Wind mills. In figure 1(intro reference),it can be seen that 52.4% of its total energy production in 2015 came from renewable resources, so in Europe and North America with 34.2% and 27.7% respectively. Aspects such as clean energy, availability in different sizes and power has led to large scale of production and R&D in the field of production of renewable resources, especially the PV-grid integrated systems [1]. Despite all these advantages, there are major drawbacks to PV systems. PV systems majorly depend on irradiance and ambient temperature, these give the power production in PV systems a lot of undesirable power quality issues and makes its integration with grid less efficient. Thus, the study of these power quality issues responsible for the serious damages by PV systems is essential in order to enhance the power quality and its reliability to sustain.

Several techniques to generate power from renewable resources have been discovered and several power quality problems arise with them. Conventional devices for solving voltage sag/swell problems including DVR, UPQC are used. Rising technology mainly introduces modern methods of artificial intelligence techniques like Artificial Neural Network (ANN) into conventional power quality mitigation devices to improvise their efficiency. In [2], a DVR structure is proposed where it is used to mitigate voltage sag at the load terminals due to fault occurrence at bus as well as along the line of a distribution system. The ability of the DVR through steady-state analysis is demonstrated in this paper. Different methodologies are discussed to mitigate deep and long duration voltage sag. The harmonic activity was described and the mathematical model was tested and made to best suit for the Indian power quality issues scenarios. Many topologies and control methods have been presented for DVRs in the literature. The presented topologies are categorized into two main groups. The first group of the presented topologies uses AC/DC/AC conversion i.e., first rectifier, then capacitor and inverter. The second group of presented topology is DC/AC conversion i.e., inverter operation. The second group of topologies is rarely used, because for large voltage sag, only capacitor bank is not capable of supply the required reactive power at the instant of very deep voltage sag i.e., <0.5 pu. To mitigate the problems of power quality, distributed generation can also be a solution. In [6] , discussion on distributed generation as a solution to power quality issues concludes with a model of DG behaviour for networks with synchronous and asynchronous generator. The behaviour of converter-based DG, synchronous generators, and asynchronous generators during voltage dips was verified. In opposition to the reported effects of synchronous and asynchronous generators on voltage dips in high to medium voltage networks, their influence on voltage dips in low voltage networks was rather minimal. Converter-based DG was found to have a similar effect on voltage dips in low voltage networks, in opposition to high-voltage networks.

Different topologies with arrangements of DVR and ANN based DVRs for power quality improvements is discussed in [2]. A DVR with ANN controller and with the help of PWM controller are made in series with the voltage bus and faults are avoided from damaging the other parts of the network. Voltage sag/swell is rectified with Fourier mathematical techniques used in building the ANN model. This paper concludes with the fact that an excellent total harmonic distortion (THD) mitigation is achieved with 13.5% when compared with other algorithms like Fuzzy logic and PID with 24.4% and 19.7% respectively. Thus, performance of the of the ANN based DVR proves to be excellent.

In [20] , two theories , Synchronous Reference Frame (SRF) theory controlled DVR and Novel control theory which is proposed are being compared. Novel theory proposes a mathematical model wherein error signal from each phase is taken, fed to a common bus and PWM gives out appropriate Vsc. The Total Harmonic Distortion (THD) at the supply voltage and the load voltage are measured by the Fast Fourier Transform (FFT) analysis tool of the Simulink model at different conditions of single phase, two phases, three phase sag and swell conditions. Each condition's THD results are shown and examined under each case.

Thus, mitigation of power quality issues like sag/swell using conventional custom power devices are improvised with recent technologies like Artificial Intelligence and with advanced mathematical models using fast Fourier transforms and other algorithms. Discussion and comparison of various methods to adopt a particular method is essential and with that the prevention of the power quality issues that arise with them need to be mitigated with such adaptive solutions.

II. POWER QUALITY

Good power quality is concurred with several parameters which bunch up to good results. Consumers receiving a steady supply voltage, frequency that stays within the prescribed range and smooth voltage curve waveform resembling a sine wave makes it up to a good power quality supply (G). Thus, Power quality can be defined as measure of the standard of power delivered. When power with low quality is delivered, it affects the utilities at consumer side, malfunctioning in the operation of protective systems at home, stations and others. PV systems as DG when supplied to grid makes a significant contribution to the grid and any disturbance with PV systems would adversely affect the power quality. Major issues to be addressed based on their severity are voltage fluctuation, Flickering, Harmonics, Voltage Sag, Swell etc.

Fluctuation in voltage occurs when the output power is unstable. Fluctuations in power being considered as a potential threat at PV systems is mainly due to its dependence on the surrounding environmental conditions i.e., temperature and irradiance. Irradiance is mainly dependent on the moving clouds which are often at high speeds during noon time which are experimentally proven in [7],[8],[9] and blocks the solar radiation onto the PV systems. From this it is clear that size and topology of PV system arrangement also has its significance in power fluctuation (concentrated collectors). Since, a PV system with low capacity is relatively small and hence shaded area is vast. (PREPA standards mentionable). Thus, in PV systems, significant drops in power happen during power fluctuation phenomena.

Voltage flicker is also one of the noticeable problems at the PV grid – Tied system. Voltage fluctuations are a major cause for voltage flickers. Since irradiation in PV systems are highly dependent on cloud transient, it varies the voltage level and as a result output power fluctuates. Thus, variations in voltage levels cause voltage flickers which can cause damage to equipments at load side. The other fluctuation issue is frequency fluctuation which occurs due to imbalance in the supply and demand of the power system. Irradiance has a significant role here too. Fluctuations in irradiance lead to frequency fluctuation often and worsen when high penetration of PV systems is in use, since they create a significant amount of drop in power.

Another power quality issue is to deal with is harmonics. Harmonics are usually introduced by the power electronic devices used in renewable energy generation (xiaondong) or converters, inverters for integration of PV systems to grid. Since output of a PV system is DC, a inverter at high switching frequency helps in converting a DC Voltage and thus injects more harmonics [8,10-12]. Harmonics are also caused by disturbance in irradiation and also due to non-linear loads on the consumer side. Some researches shows that irradiation is inversely proportional to Total Harmonic Distortion (TDHI)[8,12-13] and thus irradiation magnifies the TDHI. This is because, during fluctuations in irradiation, voltage levels drop down and its major effect is seen significantly on the fundamental component of the harmonic rather than its multiples. Maintaining a good power factor needs loads that are linear and efficient. If customer loads are non-linear and consume non-sinusoidal voltage from sinusoidal voltage source, harmonics are caused. Harmonic currents, generated by non-linear loads interact with the power system impedance to give rise to harmonic voltage distortion. If this distortion exceeds the recommended limit it can cause severe damage to equipments, computers may exhibit data error or loss of data and electronic process control may operate out of sequence on the load side.

In [14,15] , it clearly shows that 80% of the power quality complaints reported is of Voltage Sag. Voltage Sag or Voltage Dip (IEC term) is defined by the IEEE 1159 as the decrease in the RMS voltage level to 10% - 90% (1% - 90% for EN 50160) of nominal, at the power frequency for durations of ½ cycle to one (1) minute. Also, voltage sag is classified as a short duration voltage variation phenomena, which is one of the general categories of power quality problems. This common power quality problem is usually caused by weather and utility equipment problems, which normally lead to system faults on the transmission or distribution system. For example, a fault on a parallel feeder circuit will result in a voltage drop at the substation bus that affects all the other feeders until the fault is cleared. The same concept would apply for a fault somewhere on the transmission system. Most of the faults on the utility transmission and distribution system are single-line-to-ground (SLG) faults [16]. An improvement in voltage profile of distributed systems can improved with PV grid-tied systems even with low penetration systems as observed in [17].

Along with voltage sag, voltage swell occurs in PV grid-tied systems. As per IEEE standards voltage swell is an increase to between 1.1 pu and 1.8 pu in rms voltage or current at the power frequency durations from 0.5 to 1 minute [18]. Voltage swell and over-voltages are the phenomenon which occurs when large load switching or power line switching occurs. If these swells have high peaks then the insulation (protection mechanism) would not be quick enough to withstand voltage swells or sags.

III. DYNAMIC VOLTAGE RESTORER

Dynamic voltage regulator (DVR) are static devices used to provide series compensation to mitigate voltage dip and restore the appropriate amplitude of voltage in the stable system by injecting or removing required power. Symmetrical component estimation (calculation) at point of common coupling is done and voltage sag is mitigated by DVR. Power quality issues and hence voltage dips can be calculated as shown in the equation (1),

$$\text{Voltage}_{sag/swell} = V_s (Z_f / Z_f + Z_S) \quad (1)$$

Where,

Zs = The source impedance including the transformer impedance,

Z f =The impedance between the PCC and the fault including fault and line impedances.

This method of estimation ensures correction in dip and protects the sensitive loads during sag/swell.

Fig. 1 shows the block diagram of the DVR with injection transformer which is coupled with the system to inject power. There are mainly 2 types of DVR, one with storage unit and without storage unit. The DVR’s without storage unit compensate by drawing power from voltage supply and the other uses the storage to compensate the dip. Thus, DVR’s only supply the part of waveform that is faulty (Sag or Swell) and not the entire waveform. This is major difference between an UPS and DVR. As Fig (1) shows, DVR consists of a injection transformer coupled with the transmission system, a filter circuit, a voltage source converter and a control system for fast response and efficiency. DVR integrated in series with distributed generation and transmission system. Another key aspect of DVR systems is that they can be used for harmonic mitigation, fault current limiting, power factor correction and reduction of transients, in addition to voltage sag mitigation [19].

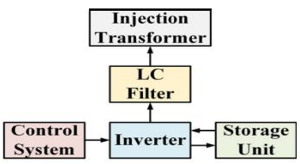

Fig. 1: Block diagram of Dynamic Voltage Restorer (DVR)

A. *Grid integrated solar PV system with Dynamic voltage restorer*

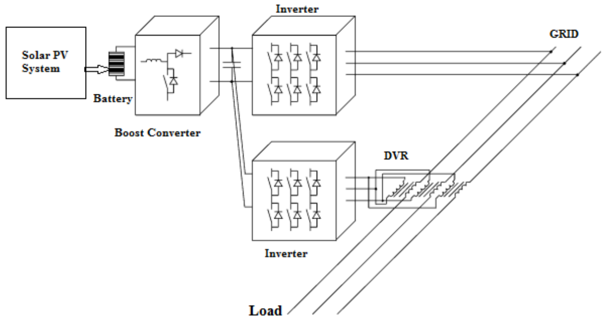

Fig. 2: Grid Integrated Solar PV System with DVR

Grid integrated solar PV system with DVR is shown in Fig 2. Power generated at solar PV system is stored in a battery as DC voltage. A boost converter is used in order to boost the battery voltage up to required average DC grid voltage. Later this DC voltage is inverted to AC for Grid Voltage levels. At Point of common coupling (PCC) power generated at the Solar PV distributed generation is integrated with Grid.

Any disturbance in the grid like voltage sag/swell is later taken care by DVR which is placed along the grid. DVR with storage units try to inject real power into grid in case of voltage sag and draw reactive power in case of voltage swell. These voltages come and go through inverters to battery storage units where power from distributed generation gets stored.

IV. CONTROL TECHNIQUES

There are mainly three voltage sag compensation techniques that are used by dynamic voltage restorer in order to cater the power quality problems: pre-sag compensation, in-phase compensation, and phase advanced compensation technique [19].

Use of power electronics devices into a network makes the whole system non-linear. DVR proves to be a pure non-linear device due to the presence of power electronics switches in the inverter. Non-linear controllers used are ANN, Fuzzy logic, Space Vector Pulse Width Modulation (SVPWM). ANN control method has adaptive and self-organization capacity. It also has inherent learning capability that can provide improved precision by interpolation. Because of these reasons, ANN is chosen in the proposed system to overcome the shortcomings of linear PID method [19].

A. *Artificial Neural Networks*

ANN model proposed has an algorithmic procedure wherein it takes the data of the power quality i.e, it analyses the issues with the power quality, randomizes the data, normalization of the data around a chosen point, assigns particular weights and biases by back propagation. Iterates through its neural network with suitable parameters. With the output values it calculates the Mean Squared Error (MSE) and checks whether its below the desired or agreeable error value. MSE is greater than the agreeable error then it stops iteration and updates the weights and biases and moves to the next layer of the ANN, else it continues to iterate until MSE is less than desirable error value. With these steps in the algorithm, ANN model is accurately able to calculate the sag/swell by iterating up to appropriate number of iterations and calculate the error with which the sag/swell occurs in comparison with the normal voltage level (voltage of the sine wave). This ensures that the ANN based DVR maintains a stable network by injecting or removing the power from the line that has the power quality issue.

This algorithm when compare with other non-linear methods such as Fuzzy Logic or SVPWM gives a more accurate results and reduced level of THD(Total Harmonic Distortion). The mathematical model and the MATLAB Simulink model output matches precisely and have been discussed thoroughly in [19].

This algorithm also overcomes the drawbacks of the PID control wherein it applies only to linear networks.

B. *Integrated Sliding Mode Control (ISMC)*

For controlling the DVR there are different methods as discussed above, another method which can be employed is Integrated Sliding Mode control, ISMC-DVR control strategy. In [20] they have implemented in-phase compensation method. The DVR operation modes can be subdivided in 2 modes:

Protection mode: to protect the DVR from the over current in the load side due to large inrush currents and short circuit on load it is first isolated from the system whenever system parameters exceed the predetermined limits primarily current on load side. So that control system detects faults and manages bypass switches to remove DVR from system.

Injection mode: As it is known that the primary function of DVR is compensating voltage disturbances on distribution system hence to achieve these three single phase ac voltages are injected in series with desired magnitude, phase and wave shape. Among the different methods of DVR voltage injection, namely, Pre- sag compensation method, In-phase compensation method and In-phase advanced compensation method, ISMC uses In-phase compensation method as mentioned before.

Sliding mode controller (SMC):

In this control method the system has to change its state to get the desired results. The main part in this method is to define the sliding line so that states of the system easily slide on these lines to attain stability at one point.

$$\boldsymbol{x = -1\beta x}$$

The above equation defines a sliding line. Another requirement is that since it is a two-stage process it is required to converge the sliding line and also stay on a sliding line hence this gives an exponential convergence with time constant$\boldsymbol{\beta}$.

The overall system that is employing SMC with DVR includes a reference voltage calculator, SMC, inverter, filters and injecting transformers. The output of filter has to be connected to the system via an injection transformer, the function of DVR is to inject a reference voltage which is calculated by subtracting reference source voltage and actual source voltage. This generated reference voltage is subtracted from actual injected DVR voltage the error obtained is processed by sliding mode controller. Hence the output obtained from SMC is given to the inverter for switching purposes.

C. *Synchronous Reference Frame*

Another method for controlling the DVR is using Synchronous reference frame (SRF) theory. This theory involves numerous mathematical and arithmetic operations to generate the reference current signals. In this theory, first the current signals are transformed into rotating coordinates that is from a-b-c frame to d-q frame which is referred to as Park transform and hence the loss component can be calculated from the PI controller and thus the d-q frame is transformed back to a-b-c frame using inverse Park transform. Now the obtained a-b-c coordinate system is considered as generated reference current signals and are compared with 3-phase actual current waveform which is used to setup signals to power the switches of Dynamic Voltage Restorer [20]. It is also necessary to use filters particularly low pass filters to remove the higher order components and also DC link capacitors are used to control the DC link voltages. [20].

D. *Improvised Synchronous Reference Frame (Novel Theory)*

Since controlling using SRF method is complex due to the mathematical equations involved, [20] proposes a novel control methodology the transformation blocks are not utilized because the line voltage of the system is split into different phases and accordingly their error signals, also which can be given to PWM generator hence the trigonometric functions also reduce. By using simple mathematical operations like squaring each phase voltage later adding a delay and by applying a square root to the obtained resultant signal which is considered to be maximum value is then compared to a base value such as 1 p.u. The resultant signal after processing it in a phase locked loop is the reference for first phase which was divided. Similarly, for the other two phases this was repeated at a phase difference of 120° between any two phases. Thereafter the three phase error signals are fed through PWM generator which generates gate signal thereby controlling the power switches of DVR.

E. *Comparison of SRF and Novel control theory for voltage sag*

Table I. gives the comparison between SRF and Novel control theory approach with regard to voltage sag.

TABLE I. COMPARISON OF SRF AND NOVEL CONTROL THEORY FOR VOLTAGE SAG

Methods / Number of phases	SRF control method	Novel control theory	Observations
One phase	Analysis carried out considering sag in one phase. The THD results for source voltage is 26.27% and for load voltage is 4.52%.	The total harmonic distortion in source voltage and load voltage is 22.51% and 1.08% respectively.	It is observed that using novel control method the reduction in load voltage is around 3.44%.
Two phase	Considering the voltage across the load with sags in any two phases of supply voltage, the total harmonic distortion in supply voltage is 11.08%,	Similarly, the harmonic distortion in source voltage is 11.08% while in load voltage it is 3.01%.	There is a change in THD in load voltage for sag in two phases by decrease in 1.51%.

	whereas load voltage is 4.53%.		
Three phase	When there is voltage sag in 3 phases of the supply voltage the source voltage in this method has harmonic distortion of 11.01% while the load voltage is distorted by 4.15%	Whereas, in this method the distortion in source voltage is around 11.08% and load voltage has around 2.20% distortion	THD in load voltage for sag in three phases using novel control theory is 1.95% lesser than SRF method.

F. *Camparison of SRF and Novel control theory of Voltage swell*

Table II. gives the comparison between SRF and Novel control theory approach with regard to voltage swell.

TABLE II. COMPARISON OF SRF AND NOVEL CONTROL THEORY OF VOLTAGE SWELL

Methods / Number of phases	SRF control method	Novel control theory	Observations
One phase	In case of swell in one phase of supply voltage crossing the limit p.u unit, by this method after compensating signals are injected by DVR the voltage magnitude across the load remains constant. The distortion in source voltage is around 14.79% and that in load voltage is 4.57%.	Similarly, after injecting compensating signals by DVR using this method, the total harmonic distortion in supply voltage and load voltage are 11.25% and 4.44% respectively.	THD in load voltage for swell in one phase using novel control theory is 0.13% less than that of SRF method.
Two phase	If there is swell in two phases of supply voltage following the DVR controller using SRF method the total harmonic distortion in source voltage and load voltage is 14.79% and 4.28% respectively.	Whereas, in DVR controller using novel control technique, the total harmonic distortion in supply voltage and load voltage are 11.67% and 3.09% respectively.	The THD in load voltage for swell in two phases using the novel control theory is 1.09% lesser than SRF method.
Three phase	When there is voltage swell in 3 phases of the supply voltage the source voltage in this method has harmonic distortion of 14.79% while the load voltage is distorted by 4.17%load voltage is distorted by 4.15%	The total harmonic distortion for voltage swells in source voltage and load voltage is 11.67% and 2.03% respectively.	It is observed that THD in load voltage for swell in three phases using the novel control theory is 2.14% lesser than SRF control method.

From the research findings it is observed that both conventional and intelligent control techniques have been proposed for the DVR to mitigate voltage sag and swell issues. In comparison with intelligent techniques, Conventional control techniques are not reliable and fail to give efficient results in compensation with fast response, efficiency in mitigation of harmonics (THD) and increased energy consumption for voltage sag/swell compensation. It is proved that conventional method fails to mitigate the voltage issues within short period compared with their proposed method.

Hence, Table summarizes the different control techniques adapted with DVR along with their merits and de-merits.

TABLE III. CONTROL TECHNIQUES ADAPTED WITH DVR

Control strategy	Merits and Demerits	Remarks
PID	Conventional method used with DVR to compensate voltage in linear networks. Cannot be applied to non-linear networks.	Load voltage restoration and THD mitigation capability is acceptable.
Fuzzy logic	Easy to apply without any complications. Compensating performance of a transformer-less DVR is enhanced. THD mitigation is around 10.22% which is not acceptable when compared to other control techniques.	Results show that fuzzy logic DVR control is very effective in damping system oscillations and improving the compensating performance compared to the traditional PI controller.
Integrated sliding mode controller (ISMC)	SMC is robust and has good dynamic response with stable condition for supply and load variations. Obtaining the convergence angle for sliding line and staying on this sliding line is difficult.	Load voltage restoration and THD mitigation capability is moderate.
Synchronous reference frame theory (SRF) and improved SRF method(novel)	Compared to previous control strategies it efficiently mitigates balanced and imbalanced sag to protect sensitive loads in power distribution line. In novel control method the limitation of using transformation blocks in SRF theory is eliminated.	Use of ANN controller with the PWM increases its THD mitigation capability.

Artificial neural network (ANN)	It uses a technique of back propagation increasing the value of every node with its weights thus providing accurate results with increase in iterations. Algorithm is fast and efficient in terms of normalizing the data. Involves complex mathematical models.	Has the highest capability in THD mitigation. Widely used technique because of its accuracy.

CONCLUSION

An overview of voltage quality challenges, like voltage sag and swell is discussed in this paper. Comparison of the different non-linear techniques employed with DVR for the mitigation of voltage sag and swell along with their pro's and cons is presented. Based on the findings, it is concluded that reduced THD of 2.83% is obtained using ANN [21] compared to other techniques. Fuzzy logic can provide with acceptable limits of THD and hence can also be considered. ANN is proven to be efficient in terms of fast response, reduced energy consumption. Training an AI model necessitates a large quantity of data and takes time, but with faster and dedicated GPUs, the ANN's drawbacks can be overcome. With this consideration ANN can be a used as a better choice with DVR in the power system to forsee and mitigate a power quality issue before its occurrence.

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