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Performance Evaluation of Dynamic Voltage Restorer for Voltage Sag Mitigation in Distribution Systems using MATLAB/Simulink

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ABSTRACT: One of the most common disturbances in electrical distribution systems is voltage sag and it can have a great impact on sensitive loads. Dynamic Voltage Restorer (DVR) is a custom power device that is series connected to load to compensate abnormal supply conditions. This paper discusses the modelling and performance analysis of a voltage sag mitigation system based on a DVR system implemented in MATLAB/Simulink. The proposed model studies how the distribution system responds when subjected to voltage sag and assesses the capability of the DVR in recovering the load voltage. When the source voltage drops, the reduction is detected by the DVR which can add an appropriate compensating voltage via a series injection transformer. The simulation results indicate that the DVR can successfully reduce the impact of voltage sag, improve the load voltage profile and further improve the power quality offered to the load. The results obtained show the effectiveness of the solution provided by DVR for the protection of sensitive loads from voltage disturbances in distribution networks.

KEYWORDS: Dynamic Voltage Restorer; Voltage Sag; Power Quality; Voltage Compensation; Distribution System; MATLAB/Simulink.

INTRODUCTION

The use of sensitive equipment, a growing number of power electronic devices, industrial drives, automation systems, and nonlinear loads are creating power quality concerns for today's electrical distribution systems. The reliable and stable voltage supply is necessary to get the correct working from such loads. An irregular supply voltage can lead the equipment to malfunction, interrupt processes, lose data or compromise system reliability. Hence it is vital to enhance the quality of power to ensure uninterrupted power supply and safeguard critical power users along distribution networks [1] [2].

The power quality disturbance which among all power quality disturbances is one of the most common and serious problem in the distribution system is voltage sag. Normally, voltage sag is defined as a brief decrease in voltage from its normal RMS level. May be caused by short circuits, load changes, energizing of transformers or starting of large motors. Voltage sag typically lasts a few seconds, but its impact on sensitive loads, such as those found in industries and commerce, can be profound [1], [3].

Various custom power devices have been designed to overcome disturbances of power quality in power distribution systems. The Dynamic Voltage Restorer (DVR) is considered as one of the most effective devices in the protection from voltage sags. DVR is a power electronic series connected device inserted in between source and load via an injection transformer. It primarily is used to compensate for a voltage during specific conditions of voltage disturbances in order to maintain the voltage of the load close to its value. [2] [3]

The operating mechanism of DVR is to sense the voltage drop and send the needed missing voltage component to the distribution line. The DVR only supplies a significant voltage when it is commanded to do so (by the Control Unit or other external control signal). As voltage sags, the controller senses the decrease in the voltage of the voltage source and produces the necessary control signal to be delivered to the voltage source inverter. The inverter then generates the compensating voltage which when added in series to the supply voltage will keep the load voltage in the desired limits [3,4].

The performance of DVR varies significantly based on the control strategy and voltage detection, inverter response, and DC-link energy support. While conventional control methods are simple and easy to implement they can sometimes be inadequate to deal with the performance requirements in the nonlinear and rapidly changing operating conditions. In fact, intelligent control techniques like fuzzy logic systems and adaptive neuro-fuzzy inference system (ANFIS) have enjoyed broad application to increase the dynamic response, decrease oscillations and increase the compensation capability of power electronic systems [4], [5]. For renewable energy supported DVR, PV source will be used to supplement the energy into the DC-link needed for voltage compensation. The output power of PV system varies with solar radiation and temperature so maximum PV power output should be obtained by the use of maximum power point tracking (MPPT). The use of ANFIS-based MPPT is an effective intelligent technique that combines learning ability of neural network with reasoning ability of fuzzy logic to enhance tracking performance and dynamic response under varying operating conditions [5], [6].

In this paper, modeling and performance evaluation of a PV-based Dynamic Voltage Restorer for voltage sag mitigation is presented by using the MATLAB/Simulink tool. A double line to ground fault is used to develop a voltage sag of the distribution line. The aim of this work is to show the effect of DVR and how this device will recover the load voltage using the necessary compensating voltage. By plotting the simulation results such as PV power, source voltage, RMS voltage, load voltage, and injected voltage the effectiveness of the DVR in improving the power quality and protecting the load from voltage sag is shown.

Dynamic Voltage Restorer Overview

Dynamic Voltage Restorer (DVR): A custom Power Series Device with a control mechanism employed to prevent damage to sensitive loads from voltage disturbances in the distribution system. It is most commonly used to boost and/or reduce the voltage to control voltage sag, voltage swell and voltage imbalance without interrupting the service and accomplishes this by injecting a controlled voltage in series with the supply voltage. A Series Injection Transformer (SIT) is normally connected between the load and the source hence, the compensating voltage can be added directly to the disturbed supply voltage [7] [8].

The primary purpose of the DVR is to deliver the normal voltage level at the load in normal supply conditions. If the voltage drops below the normal level because of a fault or disturbance, the DVR will be aware of the voltage drop and will add the proper component to make the voltage back to normal. The injected voltage makes up the gap between the source voltage and the desired load voltage. Therefore, in the presence of source side voltage sag [7, 9] the load voltage can be preserved within the nominal setting. The principle of voltage compensation of the basic DVR can be described as follows**:**

$$\mathbf{Vload = Vsource + Vinj}$$

VLoad is the compensated load voltage, Vsource is the source voltage when the system is working under normal and disturbed conditions, Vinj is the injected voltage of the DVR. This relation indicates that the DVR plays the role of series voltage supporting device. As an effect of voltage sag, the volume of voltage will boost to counter source voltage reduction, and during normal operation, the quantity of voltage is very small or close to zero [8] [9]. The capability for fast voltage compensation, protection of the load terminals makes DVR an effective solution for power quality improvement. The series connection of the DVR can more directly control the voltage to the load than shunt compensation device. For this reason, DVR can be used in sensitive applications like industrial drives, drive-offloaders, automation systems, medical equipment, process control loads, and data centers [8, 10].

.The components of a typical DVR systems comprise of a voltage source inverter, a DC-link energy source, an injection transformer, passive filter, a control unit, and a voltage measurement system. The voltage source inverter (VSI) takes the DC-link voltage and transforms it into a controllable AC voltage. Through the injection transformer this voltage is passed on to the distribution line. To minimize switching harmonics created by the inverter, the passive filter was included and the required injected voltage phase angle and magnitude was determined by the control unit [7] [10]

The DC-link is a significant component of the DC-to-DVR (direct voltage regulator) as it supplies energy to voltage inject them during compensation. Capacitors, batteries, supercapacitors, or renewable energy generation (e.g., PV) could all be used to support the DC-link. The stability of the DC-link voltage is directly related to the capability of the DVR to compensate the DC-link voltage during disturbance event, since the generated injected voltage by the inverter could be lessened during the sag event when the energy stored in the DC-link is not enough [9, 11]. The source and load voltages are continuously measured by the control system, and are compared with the reference voltage. If the voltage measured is less than the required voltage, the controller will sense the voltage sag and will generate the switching signals for the inverter. The compensating voltage is then generated by the inverter so that the output voltage of the controller. This process can make the DVR react fast upon voltage disturbances and transmit the correct voltage value to the load [10], [12]. The DVR can be primarily used in two functions: standby and compensation. During the "STANDBY" mode, the supply voltage will remain normal, and the DVR will not supply a significant voltage. When the voltage sag is detected in compensation mode, a suitable voltage of the DVR is added in series with the supply line. The voltage injected into the sagged source voltage, enables the load voltage to be nominally held near to its nominal value. This working principle allows to isolate sensitive loads from the disturbances from the supply side [7] and consequently to make the DVR effective.

Proposed MATLAB/Simulink Model

Finally, the proposed PV supported DVR system was modeled and simulated in MATLAB/Simulink to study its performance against voltage sag situations. The circuit diagram of the model is shown in figure 1. Figure 1 consists of three phase voltage source, three phase transformer, distribution line, double-line-to-ground fault block, Dynamic Voltage Restorer, a three phase breaker and three phase parallel RLC load. DVR connects in-series between the source and load to deliver the correct compensating voltage in response to voltage perturbations.

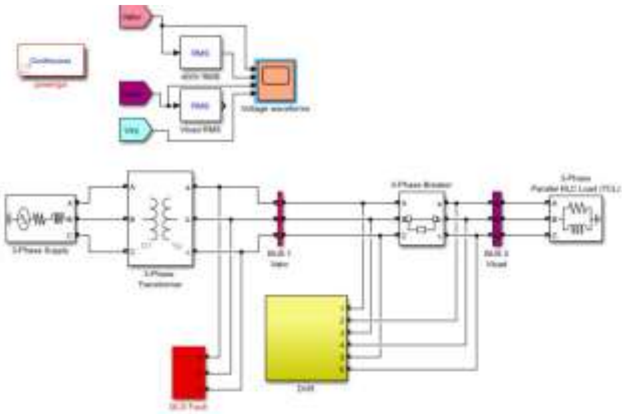

Fig. 1. The developed PV-supported DVR model in MATLAB/Simulink software.

In this model, the voltage sag occurs when a double-line-to-ground fault is simulated in the distribution system. This fault results in a source voltage loss and disturbance. This voltage drop is detected by the DVR which then adds an appropriate voltage to the power line in series. The injected voltage is used to boost de-sagged source voltage in an effort to bring load voltage near to its nominal value. In the proposed system, there is a PV system, along with an ANFIS controller for maximization of Power from PV system. The PV system is adopted to serve the DC-link of the DVR as its energy source. The ANFIS-MPPT controller enhances the performance of the PV system by maximizing the available PV system power and assists in the voltage compensation process during a voltage drop (sag). The main purpose of the simulation model is to study the behavior of the distribution system before and after DVR compensation. The source voltage waveform is used to illustrate voltage sag condition and the DVR injected voltage waveform illustrates the compensation action. The most important parameter used to assess the effectiveness of the DVR is the load voltage waveform. If the power side voltage keeps constant during the power sag period, then the DVR is able to reduce the voltage disturbance and enhance the power quality at the load side.

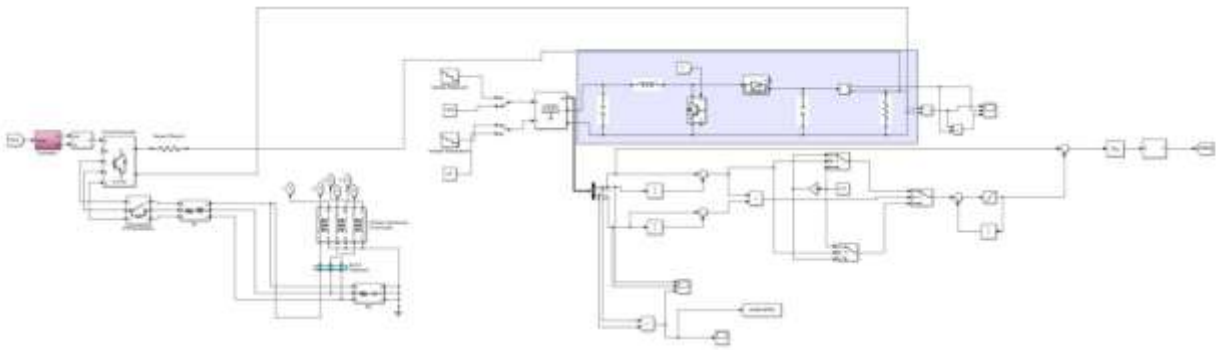

Fig. 2. PV system with ANFIS-MPPT integrated with the DVR.

The proposed model uses the Dynamic Voltage Restorer as the primary compensation device to safeguard the load against the voltage sag due to fault. The DVR is placed in series between the source and load and thus can add a compensating voltage directly to the distribution line. Such a series connection allows the DVR to compensate for a reduced voltage at the source caused by a disturbance by restoring the load voltage.

The source voltage is disrupted when the double-line-to-ground fault occurs and its RMS value drops. This reduction will be directly passed to the load terminals without compensation from the DVR and can impact the operation of the connected load if there is no DVR compensation. When Fig. 2 shows the detailed structure of the PV-supported DVR system with ANFIS-based MPPT. The PV array is connected to a DC-DC converter, and the ANFIS-MPPT controller is used to extract the maximum available power from the PV system under the given irradiation and temperature conditions. The extracted PV power supports the DC-link of the DVR, which provides the required energy for voltage injection during sag compensation. This configuration improves the ability of the DVR to generate the required compensating voltage and restore the load voltage during voltage disturbance conditions.

Role of DVR in the Proposed Model:

shows that DVR is effective in mitigating the voltage sag effect and boosting the power quality at load side.

In addition, the PV system with ANFIS-MPPT supports the DVR by providing energy to the DC-link. This support helps the DVR generate the required injected voltage during compensation. As a result, the proposed PV-supported DVR system improves voltage stability, protects the load during fault conditions, and enhances the overall performance of the distribution system.

RESULTS AND DISCUSSION

MATLAB/Simulink has been used to simulate performance of the proposed PV supported DVR system under voltage sag condition. The main results include the PV output power using ANFIS-MPPT, source voltage, RMS voltage, load voltage, and DVR injected voltage. These results can be used to test the capability of the DVR to compensate voltage sag and enhance the voltage profile at the load side.

the DVR is connected, however, it senses the voltage drop, and adds the missing voltage component. This injected voltage is applied to the sagged voltage of the source to hold the voltage of the load close to its nominal value. In the proposed model, the function of the DVR is represented by:

Vload = Vsource + Vinj

The compensated load voltage, Vload, the sagged source voltage, Vsource, and the voltage injected by the DVR, Vinj, are all indicated. In the sag period, the DVR will boost injected voltage based on the amount of sag voltage. Once the fault has been cleared and the source voltage is heading back towards normal, the compensation voltage is reduced due to less compensation needed.

The role of the DVR is easily seen on the simulation waveforms. The source voltage waveform displays the disturbance created by the fault; the injected voltage waveform displays the compensation action taken by the DVR; and the load voltage waveform displays the voltage supplied to the load. Hence, the improvement in load voltage

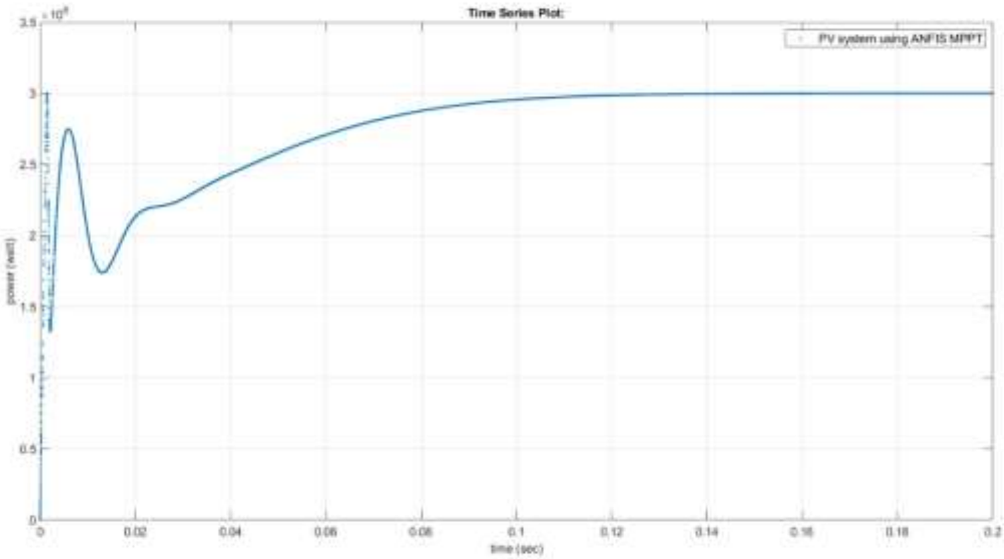

Fig. 3. Power response of PV array with ANFIS-MPPT.

Using ANFIS-MPPT controller, the PV output power response is shown in Fig.3. The PV power has some transient fluctuations in the initial conditions of the simulation because of the dynamic response of the PV system and MPPT controller. The output power slowly ramps up and levels off to a stable value following the transient. The result shows that the ANFIS-MPPT controller is able to track the maximum

available power from the PV system and provide power support to the DVR DC-link.

The stable PV power is critical in the operation of the DVR due to the fact that the operation of the DVR needs enough energy at its DC-link for voltage sag compensation. Thus, the PV system with ANFIS-MPPT enhances the energy provision of the DVR and aids to ensure a proper compensation over the disturbance period.

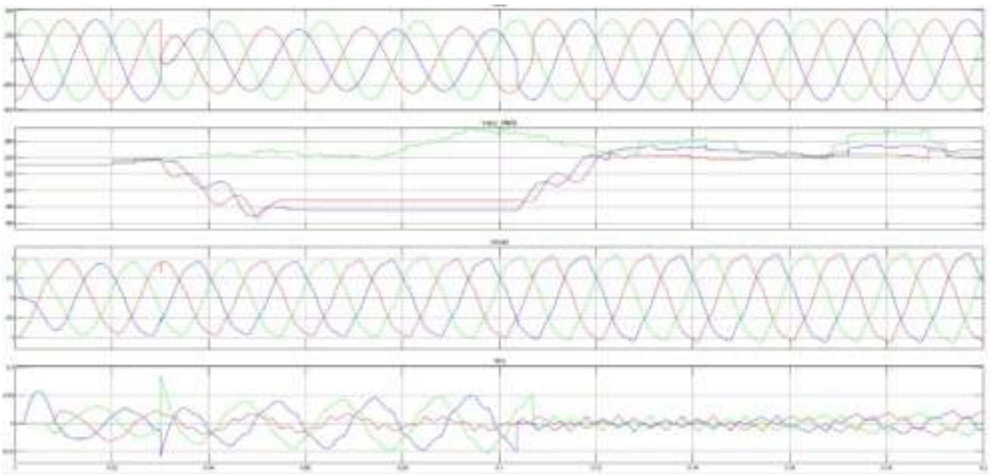

Fig. 4. Simulation waveforms of source voltage, RMS voltage, load voltage and DVR injected voltage.

The source voltage, RMS voltage, load voltage and DVR injected voltage waveforms are shown in Fig. 4. The source voltage wave form reveals a voltage sag during the period of the fault. This sag is due to the fault (double-line to ground) that was applied to the distribution system. The reduction and distortion in the source voltage will verify that the system is operating under abnormal voltage circumstances.

A better representation of the voltage sag comes from the RMS voltage waveform. The RMS value falls below the normal operating value during the fault time, thus proving the voltage sag. This reduction is the voltage sag which the DVR has to handle to ensure the load is protected.

The DVR injected voltage waveform shows the compensation action of the DVR. During the voltage sag, the DVR will produce an injected voltage to make up for the lost voltage component. The injected voltage is seen while the disturbance is occurring, and gets smaller when the source voltage returns to normal conditions. This behaviour proves that the voltage disturbance is being read by the DVR and a compensating voltage is only being injected as required.

The load voltage waveform clearly shows that the DVR has reduced the voltage sag. The source voltage is influenced by the fault, while the load voltage is more stable thanks to the compensating voltage that is added to the voltage source by the DVR. The effect of the disturbance from the source side is thus suppressed by the DVR and the voltage at the load terminals is restored.

In general, the results of the simulation show that the proposed system is successful in getting better voltage profile during the sag condition. The first voltage waveform is the source voltage which shows the disturbance, the second voltage waveform is the injected voltage which shows the DVR compensation process, and the third voltage waveform is the load voltage which shows the improvement after compensation. So, the DVR effectively protects the load, and improves the power quality of the distribution system.

Result	Observation	Interpretation
PV output power	Power reaches a stable value after the transient period	ANFIS-MPPT provides stable power support for the DVR
Source voltage	Voltage sag and distortion appear during the fault period	The DLG fault creates a disturbance in the distribution system
RMS voltage	RMS value decreases during the sag period	The system experiences a voltage sag condition
DVR injected voltage	Injected voltage appears during the disturbance	DVR injects the missing voltage component
Load voltage	Load voltage remains more stable than the source voltage	DVR restores the load voltage and protects the load

CONCLUSION

The paper proposed the modelling and performance evaluation of the PV supported DVR to mitigate voltage sag in distribution system by using MATLAB/Simulink. A double line to ground fault was used to implement a voltage sag and test the compensation performance of the DVR. Since the main function of the DVR in the proposed model is to sense the voltage drop, it can deliver the compensation voltage in series with the supply line. The simulation results demonstrated that during the fault period the source voltage varied, and during the normal period it seemed that the DVR injected voltage compensated for the missing voltage component. This meant that the load voltage was more stable than when the source voltage was disturbed. The RMS voltage response also showed that the DVR brought better voltage profile at the load side during the sag condition. Besides, the PV system with ANFIS-MPPT also supplied power support to the DC-link of the DVR. The PV output power became stable after the transient period, showing the capability of ANFIS-MPPT controller in providing sufficient energy demands of the DVR. The results obtained overall validate the effectiveness of the proposed voltage sag elimination system that is based on PV for the distribution voltage system by reducing the effect of voltage sag, restoring the voltage of the load and enhancing the power quality.

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