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Fuzzy Based Dynamic Voltage Restorer for Sag Mitigation to Improve Electric Power Quality

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***Abstract*—This paper presents a fuzzy logic based Dynamic Voltage Restorer (DVR) which operates in voltage sag and swell conditions of the electrical power system. As now-a-days the all consumers of electrical energy are facing efficiency problems in the power system with the magnitude fluctuations in the voltage. In this paper we use fuzzy logic to operate the DVR in voltage sag and swell periods of the system, in order to improve the quality of electric power by reducing the harmonics, distortions and voltage ripples in the time of DVR on and off states.**

Keywords— Fuzzy Logic, DVR, Electric Power Quality

I. INTRODUCTION

Power quality in the present-day distributed systems are addressed in the literature [1]-[6] due to increased use of sensitive and critical equipment pieces such as communication network, process industries and precise manufacturing processes. Power quality problems such as transients, sags, swells and other distortions to the sinusoidal waveform of the supply voltage affect the performance of these equipment pieces. Voltage sags can occur at any instant of time, with amplitudes ranging from 10 - 90% and a duration lasting for half a cycle to one minute. Further, they could be either balanced or unbalanced, depending on the type of fault and they could have unpredictable magnitudes, depending on factors such as distance from the fault and the transformer connections. Voltage sag can cause sensitive equipment (such as found in semiconductor or chemical plants) to fail, or shutdown, as well as create a large current unbalance that could blow fuses or trip breakers. These effects can be very expensive for the customer, ranging from minor quality variations to production downtime and equipment damage [3]. There are many different methods to mitigate voltage sags, but the use of a DVR is considered to be the most cost efficient method [3].

The most common choice for the control of the DVR is the so called PI controller since it has a simple structure and it can offer relatively a satisfactory performance over a wide range of operation.

II. DYNAMIC VOLTAGE RESTORER(DVR)

Dynamic Voltage Restorer (DVR) is a series connected device capable of regulating the load side voltage in a distribution network. The DVR provides a three phase independently controlled voltage source utilizing power electronic components, whose voltage vector (magnitude and angle) is added to the source voltage to restore the load voltage to a prescribed level [7]. The main function of DVR is the protection of sensitive loads from voltage sags/swells arising from the distribution network. Thus it is generally installed in a distribution system between the supply and the sensitive load feeders [8]. In addition to voltage sags and swells compensation, DVR can also be used for line voltage harmonics compensation, voltage transients reductions and fault current limitations. Various circuit topologies and control schemes are available that can be used to implement a DVR.

III. CONFIGURATION OF DVR

The general configuration of the DVR consists of an Injection transformer, a Harmonic filter, a Voltage Source Converter (VSC), Energy Storage Unit and a Control and Protection unit. Energy Storage Unit in DVR can be external batteries or capacitors charged from the supply line feeder through a rectifier. Generally the energy storage unit of a DVR can be divided into two parts (i.e. Storage devices and DC Charging Circuit). The purpose of energy storage devices is to supply the necessary energy to the VSC via a dc link for the generation of injected voltages. Supply DC Link Load Energy Storage Unit Voltage Source Inverter Control Unit Fig 3: Schematic Diagram of DVR Configuration The different kinds of energy storage devices are superconductive magnetic energy storage (SMES) [9], batteries, and capacitors [10, 11]. In fact, the capacity of the stored energy directly determines the duration of the sag which can be mitigating by the DVR. Batteries are the common choice and can be highly effective if a high voltage battery configuration is used [12]. However, batteries in general have a short lifetime and often require some type of battery management system, which can be quite costly [13]. An interesting alternative to batteries is the use of super capacitors, which have a wider voltage range than batteries and can be directly paralleled across the input bus. Super capacitors have a specific energy density less than that of a battery, but a specific power greater than a battery, making them ideal for short (up to several seconds) pulses of power. Certain super capacitors can hold charge over extended periods of time, so as to act like a battery. However, unlike batteries, these super capacitors have a short charging time and much longer lifetime [10, 11]. The purpose of the DC Charging Circuit is to charge the energy storage devices after the compensation of a voltage sag/swell event as well as maintain a nominal dc link voltage. The charging circuit can be an external power supply or a rectifier fed from the supply mains of the distribution network. A Voltage Source Converter is a power electronic system capable of generating a sinusoidal voltage at any required frequency, magnitude, and phase angle. DVR configurations use the VSC to generate the voltage required to compensate for the voltage sag/swell events [14, 15]. Since the majority of the voltage sags/swells observed on distribution systems are unbalanced, the VSC will often be required to operate with unbalanced switching functions for the three phases and must therefore be able to treat each phase independently. Moreover, sag on one phase may result in swell on another phase, so the VSC must be capable of handling both sags and swells simultaneously. The output voltage of the inverter is varied by using different PWM schemes available. Given to the nonlinear nature of the semiconductor devices Voltage waveform distortion associated with the high frequency harmonics at the output of the inverter circuit is a common phenomenon. A harmonic filter unit is generally used at the output of the inverter circuit to keep the harmonic distortions at a permissible level. Although the filter unit keeps the harmonic distortion minimum and improves the quality of the generated voltage, it can also introduce voltage drop and phase shift in the fundamental component of the inverter output and needs to be accounted for in the generated compensation voltage [16]. Injection transformers are responsible for connecting the DVR to the sensitive loads in the distribution network via the high tension windings and transforming and coupling of the injected compensating voltages generated by the voltage source converters to the incoming supply voltage. In addition, the Injection transformer also serves the purpose of isolating the load from the system (VSC and control mechanism). Generally three single-phase transformers are used as injection transformers for injecting the compensating voltages to the system at the load bus. Proper integration of the injection transformer into the DVR, the MVA rating, the primary winding voltage and current ratings, the turn-ratio and the short-circuit impedance values of transformers are required. The existence of the transformers allow for the design of the DVR in a lower voltage level, depending upon the stepping up ratio. In such case, the limiting factor will be the ability of the inverter switches to withstand higher currents [17]. The control unit of DVR is solely responsible for controlling the compensating voltage generation by controlling the PWM pulses to the gates of semiconductor switches of the VSC. To maximize dynamic performance of DVR, efficient control architecture capable of achieving fast compensation is necessary [18, 19]. The protection unit of DVR generally consists of Bypass switches, breakers, measuring and protection relays etc. Depending upon the operating conditions, the control and protection unit maximizes the system performance and minimizes the losses associated with the operation of DVR.

Voltage Injection Transformer: The basic function of this transformer is to connect the DVR to the distribution network via the HV-windings and couples the injected compensating voltages generated by the voltage source converters to the incoming supply voltage. The design of this transformer is very crucial because, it faces saturation, overrating, overheating, cost and performance. The injected voltage may consist of fundamental, desired harmonics, switching harmonics and dc voltage components. If the transformer is not designed properly, the injected voltage may saturate the transformer and result in improper operation of the DVR [20].

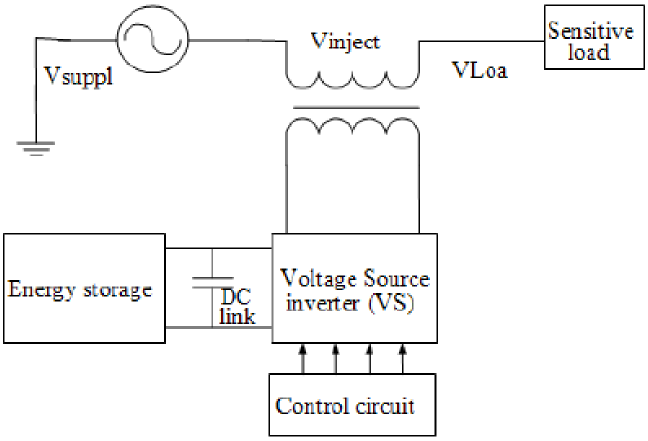

Figure 1. DVR general configuration

Output Filter: The main task of the output filter is to keep the harmonic voltage content generated by the voltage source inverter to the permissible level (i.e. eliminate high frequency switching harmonics).It has a small rating approximately 2% of the load VA [16].
Voltage Source Inverter: A VSI is a power electronic system consists of switching devices (IGCTs, IGBTs, GTOs), which can generate a sinusoidal voltage at any required frequency, magnitude, and phase angle. In the DVR application, the VSI is used to temporarily replace the supply voltage or to generate the part of the supply voltage which is missing [1].
DC Energy Storage Device: The DC energy storage device provides the real power requirement of the DVR during compensation. Various storage technologies have been proposed including flywheel energy storage [21], super-conducting magnetic energy storage (SMES) [22] and Super capacitors [10, 11]. These have the advantage of fast response. An alternative is the use of lead-acid battery [23, 12]. Batteries were until now considered of limited suitability for DVR applications since it takes considerable time to remove energy from them [13]. Finally, conventional capacitors also can be used [24, 25].
Control System: The aim of the control system is to maintain constant voltage magnitude at the point. Where a sensitive load is connected, under system disturbances. The control system of the general configuration typically consists of a voltage correction method which determines the reference voltage that should be injected by DVR and the VSI control which is in this work consists of PWM with PI controller. The controller input is an error signal obtained from the reference voltage and the value of the injected voltage. Such error is processed by a PI controller then the output is provided to the PWM signal generator that controls the DVR inverter to generate the required injected voltage.

IV. FUZZY LOGIC CONTROLLER

Fuzzy logic theory is considered as a mathematical approach combining multi-valued logic, probability theory, and artificial intelligence to replicate the human approach in reaching the solution of a specific problem by using approximate reasoning to relate different data sets and to make decisions. The performance of Fuzzy Logic Controllers is well documented in the field of control theory since it provides robustness to dynamic system parameter variations as well as improved

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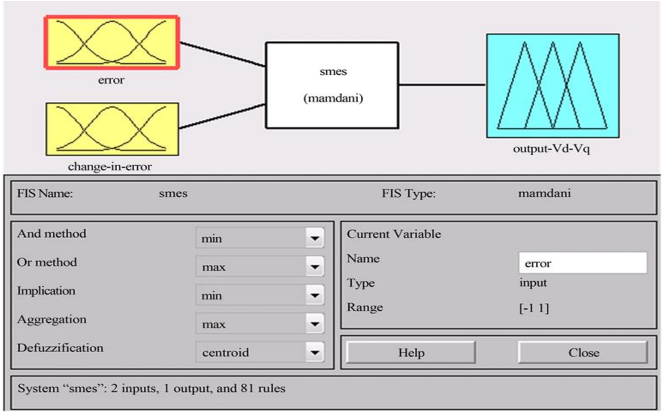
transient and steady state performances. In this study, a fuzzy logic based feedback controller is employed for controlling the voltage injection of the proposed Dynamic Voltage Restorer (DVR).

Fuzzy logic controller is preferred over the conventional PI and PID controller because of its robustness to system



parameter variations during operation and its simplicity of implementation. Since the proposed DVR uses energy storage system consisting of capacitors charged directly from the supply lines through rectifier and the output of the inverter depends upon the energy stored in the dc link capacitors. But as the amount of energy stored varies with the voltage sag/swell events, the conventional PI and PID controllers are susceptible to these parameter variations of the energy storage system; hence the control of voltage injection becomes difficult. The proposed FLC scheme exploits the simplicity of the Mamdani type fuzzy systems that are used in the design of the controller and adaptation mechanism. Fig. Schematic representation of Fuzzy Logic Controller. The fuzzy logic based control scheme can be divided into four main functional blocks namely Knowledge base, Fuzzification, Inference mechanism and Defuzzification. The knowledge base is composed of data base and rule base. Data base consists of input and output membership functions and provides information for appropriate fuzzification and defuzzification operations. The rule-base consists of a set of linguistic rules relating the fuzzified input variables to the desired control actions. Fuzzification converts a crisp input signals, error (e), and change in error (ce) into fuzzified signals that can be identified by level of memberships in the fuzzy sets. The inference mechanism uses the collection of linguistic rules to convert the input conditions to fuzzified output. Finally, the defuzzification converts the fuzzified outputs to crisp control signals using the output membership function, which in the system acts as the changes in the control input (u). The output generated by fuzzy logic controller must be crisp which is used to control the PWM generation unit and thus accomplished by the defuzzification block. Many defuzzification strategies are available, such as, the weighted average criterion, the mean-max membership, and center-of-area (centroid) method. The defuzzification technique used here is based upon centroid method.

V. MATLAB SIMULATION RESULTS

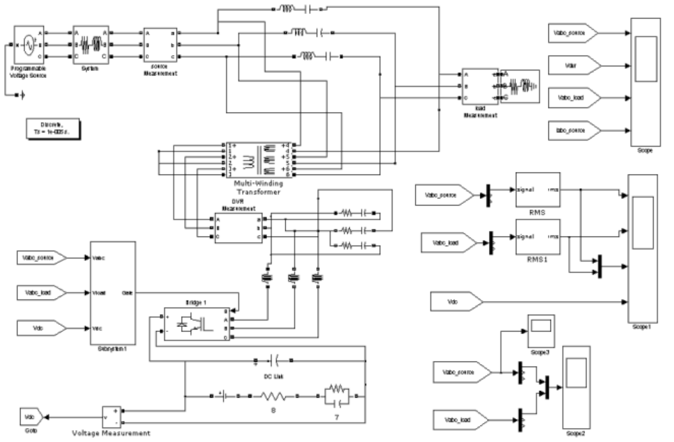


Figure 2. MATLAB SIMULINK diagram

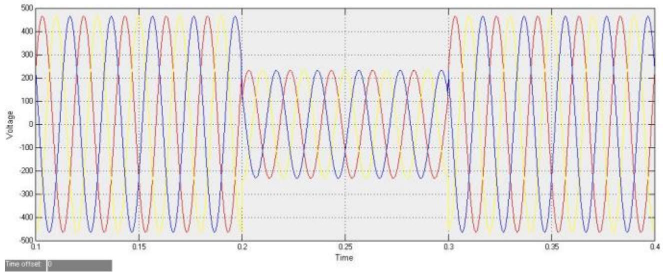


Figure 3. Supply side voltage with sag.

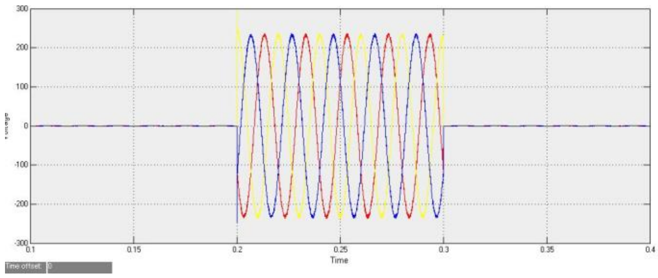


Figure 4. Voltage across DVR during sag time

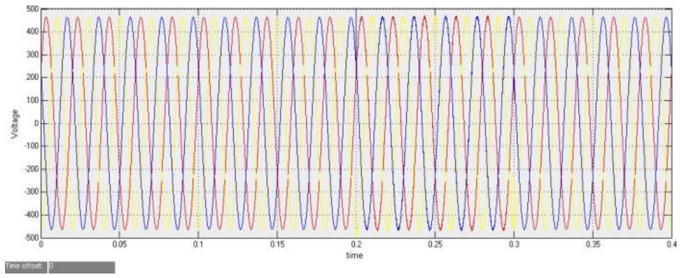


Figure 5. Load side voltage (mitigated sag voltage)

CONCLUSION

DVRs are effective custom power devices for voltage sags and swells mitigation. They inject the appropriate voltage component to correct rapidly any anomaly in the supply voltage to keep the load voltage balanced and constant at the nominal value. In the present paper a reliable controller with high performance for dynamic voltage restorers was proposed. The proposed controller is generated by ANFIS training according to a given input output data. Compared to the traditional fuzzy controller, the proposed one is the simplest (9 rules only) and the most cost efficient controller. In addition this controller has no gains to adjust and solve the problem of traditional fuzzy controller gains tuning.

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