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Design of Voltage Sag Compensator with Transformer Inrush Current Mitigation Technique

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Abstract-**The power system survey results recommend that, voltage sag is the chief contributor in about 92% of manufacturing industries. Voltage sag results in decrease in competence of the systems which affect the manufacturers in terms of losses related to money and reliability. The transformer-coupled arrangement associated voltage-source inverter, called voltage sag compensator is among the most savvy arrangement against voltage sags. Transformers are mostly installed in front of critical loads for electrical separation purposes. When voltage dip occurs, the transformers are presented to the improper voltages and a dc offset occurs in its flux linkage. The flux linkage will be reach to the level of magnetic saturation at the time of compensator restores the load voltage and this cause's serious inrush current. The compensator may be interrupted because of its own over current protection, hence, the compensation gets failed, and the critical loads are interrupted by the voltage sag. This paper brings together a method for inrush current relief for voltage dip compensator with fuzzy logic controller. Voltage sag compensator along with additional parts of the distribution system is simulated using Matlab/ Simulink.**

Keywords- ***Flux linkage, Fuzzy Logic, Inrush currents, Transformer, Voltage Dip, Voltage Sag Compensator***

I. INTRODUCTION

In current years, utilities have been encountered with growing amount of objections about the quality of power due to voltage dips and disruptions. There is large increase in load demand as the improvement of technology is varying day by day. With the change in load condition the issues related to power quality must also be taken into consideration. Because of the abrupt change in the condition of load i.e., sudden increase of load the magnitude of the current in the distribution system is increased rapidly which leads to fall in the voltage of the line creating voltage sag.

Various transformer inrush current decreasing techniques are available, such as controlling power-on angle [1-5], actively controlling the transformer current [6-8] and controlling the voltage magnitude. These methods are not proper for voltage dip compensators as they could modify the waveforms of output voltage the converter.

Hence, load transformer is presented to the improper voltages before the restoration and magnetic flux abnormality may be developed within the load transformers. Saturation of the transformer core leads to substantial inrush current. The compensator may be interrupted because of its own over current protection, therefore, the compensation gets failed, and the critical loads are interrupted by the voltage sag.

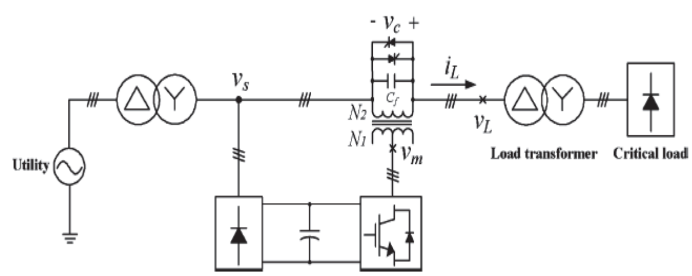

Fig.1 single-line drawing of the offline series voltage sag compensator.

There are 3 adverse side effects of inrush currents: 1) Misoperation of protective devices for overloads and internal faults may and disconnect the transformer. 2) The mechanical stresses experienced by the winding can damage the transformer; and 3) Power-quality problems may occurs and voltage sags.

In this paper, an inrush moderation technique is presented using fuzzy logic [10]. This control can successfully compensate voltage sag and also decrease inrush of load transformers.

II. SYSTEM DESCRIPTION

The voltage sag compensator comprises a coupler transformer for sequential connection and 3-phase voltage-source inverter (VSI) as shown in fig.1. At the normal condition of distribution system, the compensator is bypassed by the thyristors to get higher operating efficiency. When voltage sags occur, the voltage sag compensator adds the required compensation voltage with the help of coupling transformer to protect sensitive loads from being interrupted by sags. Though, certain detection time (about 4.0 ms) is required by the sag compensator controller to recognize the sag phenomena and the load transformer is exposed to the distorted voltage upto the moment when the compensator restores the load voltage.

Even though its small interval, magnetic flux deviation occurs inside the load transformer due to distorted voltage, and therefore the magnetic saturation can simply occur when the compensator restores the load voltage, and thus, results in the inrush current. The overcurrent protection of the compensator can be triggered due to this inrush and causes compensation failure.

The simplified circuit of the phase *a* and *b* winding of the delta/wye three-phase load transformer installed in downstream of the voltage dip compensator is shown in fig.2. The flux linkages of transformer windings can also be derived. Assuming that the deformed grid voltage forced upon the load transformer is,

$$v_{Lab}(t) = \hat{V}^{*}_{Lab}(1-u)\sin(\omega t + \Phi^{*}_{Lab} + \theta_{Lab})$$

$$\text{for} \quad t_{\text{sag}} \leq t \leq t_{\text{action}}$$

Where u $(0 \leq u \leq 1.0)$ is depth of voltage dip and θ_Lab is the phase shift during the fault incident.

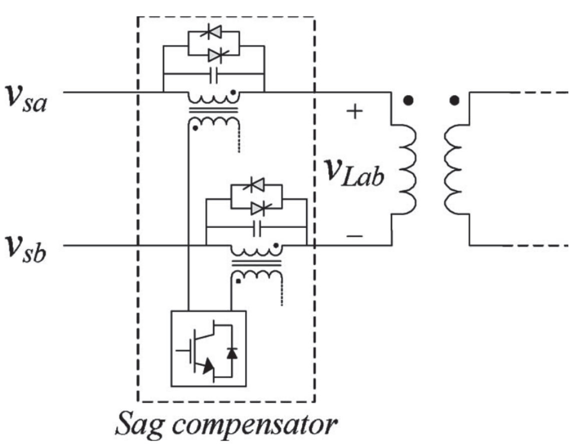

Fig.2 Connection diagram of the proposed system with delta/wye load transformer.

III. FUZZY LOGIC CONTROL OF COMPENSATOR

Now days, to implement different types of applications of fuzzy logic and the number of fuzzy logic applications are have increased considerably. In Fuzzy logic control, a basic control action through a set of linguistic rules to finding by the system, as the calculated modeling of system variables is not essential in FLC and mathematical variables are transformed into linguistic variables. To control the inverter action fuzzy logic control is proposed. The fuzzy logic controller has two real time inputs measured at each sample time, known as error rate and error also one output which is actuating signal. The membership function is made after the input signals are fuzzified and then represented in fuzzy set notations. The defined, If---Then--- rules create output i.e. actuating signal and to compare with a carrier signal for controlling PWM inverter the actuating signals are defuzzified to analog control signals.

The fuzzy logic based control scheme can be divided into 4 main parts viz. Knowledge base, Fuzzification, Inference mechanism and De-fuzzification. Various defuzzification schemes are available, like, weighted average criterion, the mean-max membership, and centroid method. The technique used here is based upon centroid method.

TABLE 1. Fuzzy Rules

CE(Change in error)	Error						
	NL	NM	NS	Z	PS	PM	PL
NL	PL	PL	PL	PM	PM	PS	Z
NM	PL	PL	PM	PM	PS	Z	NS
NS	PL	PM	PS	PS	Z	NS	NM
Z	PL	PM	PS	Z	NS	NM	NL
PS	PM	PS	Z	NS	NM	NL	NL
PM	PS	Z	NS	NM	NL	NL	NL
PL	Z	NS	NM	NM	NL	NL	NL

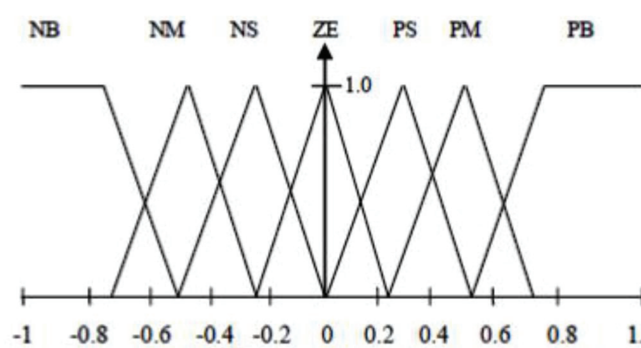

Fig. Error, 'e'.

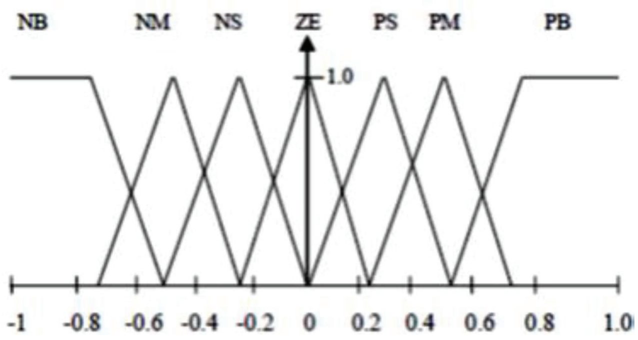

Fig. Input Variable Change in Error, 'ce'.

Fig.3 Membership Function for Input Variable.

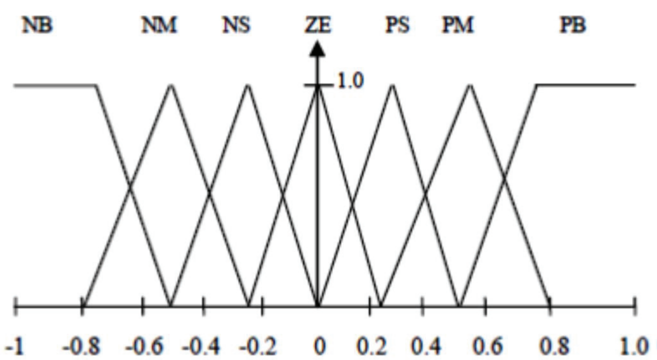

Fig.4. Membership Function for Output Variable Change in Control Signal, 'u'.

The set of fuzzy control linguistic rules can be taken from Table 1. The output is produced by the fuzzy logic operations by estimating all the rules and fuzzy sets. The input variables error rate and error are defined by linguistic variables like Negative Medium(NM), Negative Big (NB), and
Positive Big (PB) described by triangular membership functions, Zero (Z) Negative small (NM), Positive Small (PS), Positive Medium (PM).These functions have been chosen to fulfill the output requirements of the fuzzy controller. The output is also defined by seven linguistic variables such as Negative Medium (NM),Negative Big (NB), Negative Small (NS), zero (Z), Positive Small (PS), and Positive Big (PB) and Positive Medium (PM) described by membership functions given in fig. 3 & 4.

In practice, the fuzzy rule sets generally have several previous circumstances that are combined using Fuzzy operators, such as AND, OR and NOT, though again the definitions tend to vary. AND, in one popular definition, simply uses the maximum weight of all the previous circumstances, while OR uses the maximum value. There is a NOT operator that subtracts a membership function from 1 to give the "complementary" function.

There are Forty-Nine rules for fuzzy controller. The output membership function for each rule is given by the Min operator. To get combined fuzzy output from the set of outputs of Min operator, the Max operator is used .The output is produced by the fuzzy logic and fuzzy sets operations by estimating all the rules.

An if-then rule is defined as follows:

For error, Z and error rate, Z the output is, Z".

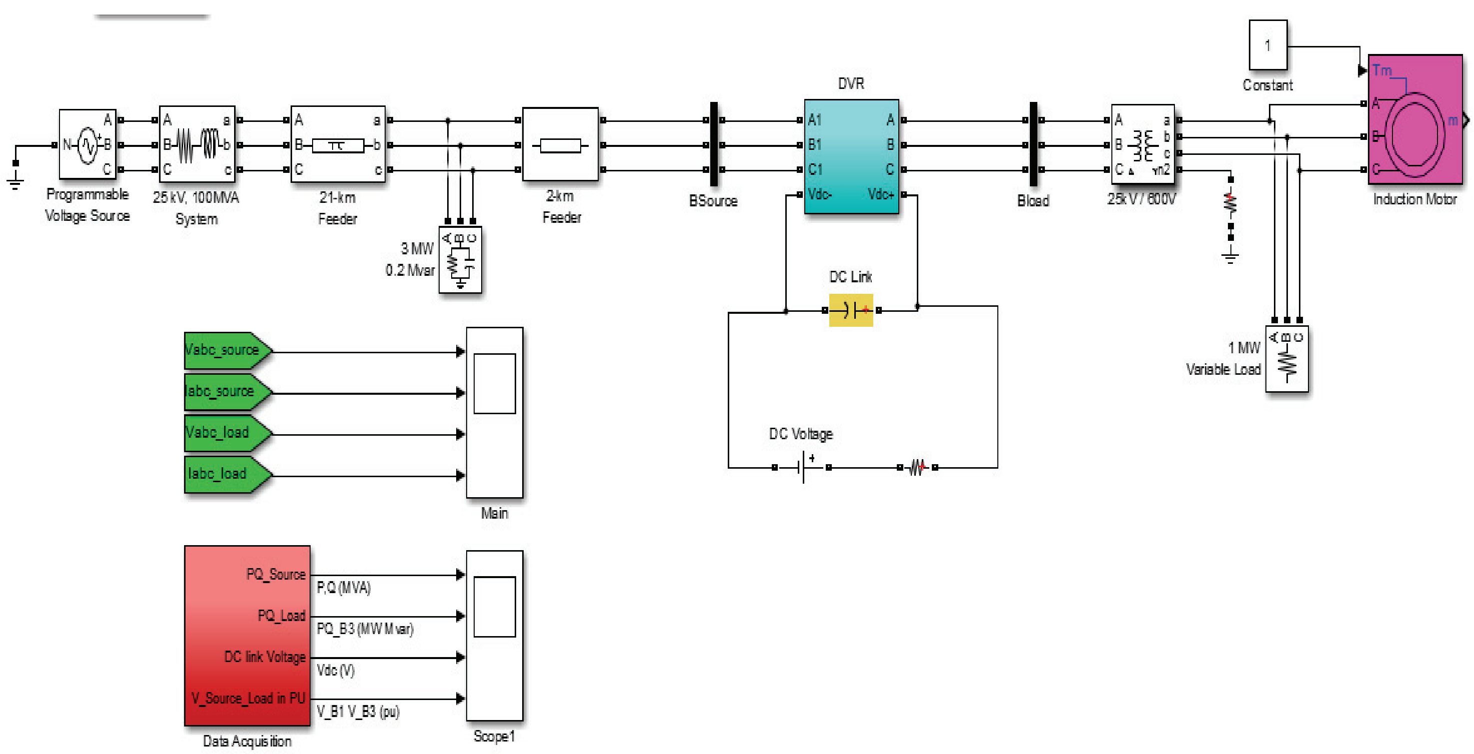

Fig 5. Simulink diagram of proposed system connected to a distribution system

IV. RESULTS

The system factors of the testbench and the corresponding controller are as follows:
1) source: 220 V, 60 Hz;
2) loads: a commercially available diode rectifier rated at 1600 V with load resistor R = 93.3 Ω, dc choke L =2.0 mH, and dc filter capacitor C = 3300 μF;
3) voltage sag compensator: a conventional three-phase inverter switching at 10 kHz, the leakage inductance of the coupling transformer Lf = 0.32 mH, and filter capacitor Cf = 4.0 μF;
4) load transformer: 5.0 kVA, 220 V/127 V (Δ/Y connection).

The scope connected to the V-I measurements at supply side and also the load side gives the simulations of supply voltage having sag with the voltage across load. If there is variation in the load then voltage sag occurs and the fuzzy controlled PWM inverter produces the required lost voltage so that the voltage dip does not disturb the sensitive load. The controller inputs are determined by comparing reference signals and measured source data signals. The fuzzy controller output signals are the inputs to the PWM module to produce the required missing voltages. The controller outputs are compared with triangle wave signals to generate the proper switching pulses. Control unit provides the reference voltage for tracing of source voltage. It controls the inverter to produce pure sinusoidal voltage at the same frequency for the system as shown in simulations. The output of the controller can be shown from the fig.6.

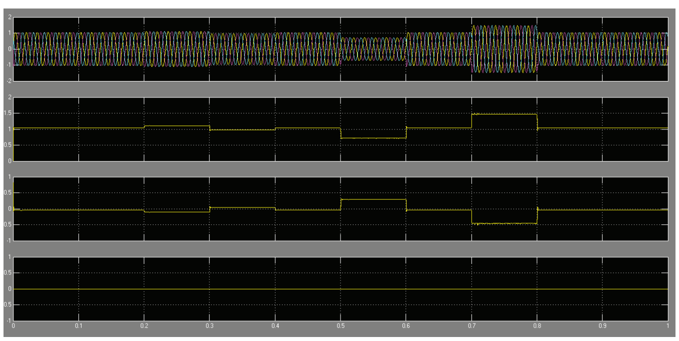

Fig.6 output signal of controller

The fuzzy controller operates only for the interval the voltage dip is detected as shown in fig.7.The sag compensator adds voltage through injection transformer to the load and thus restores the critical load voltage and the load voltage is nearly pure sinusoidal.

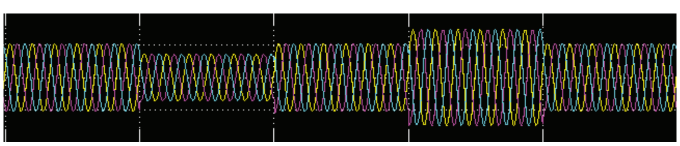

Fig.7 supply voltage having voltage sag & swell

The primary task of sag compensator is providing the high quality voltage to the critical loads. In case the measured phase voltages of source are different from the reference values fuzzy controllers quickly start working. The fuzzy controllers used for sag compensator support the proposed system for providing a good power and voltage quality to the critical load. The controller output signals stabilize when all the phase voltages of the load attain the desired value. Sag compensator gives high performance in injecting the more in-phase voltage with proper polarity and phase angle. The simulation in Fig. 6 shows the voltage across load side having no sag because of efficient working of sag compensator and Fig.8 shows load side current after sag compensation.

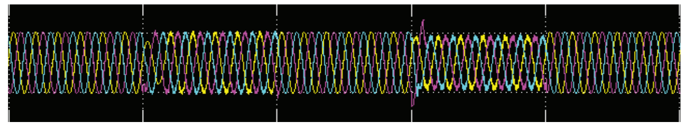

Fig.8 voltage across sensitive load after voltage injection

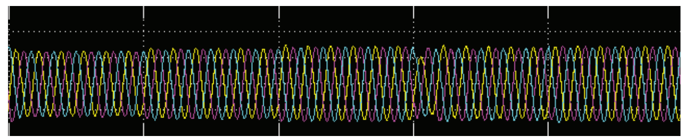

Fig.7 load current

From all the simulation results of the three-phase voltage waveforms, it is observed that the new control scheme of voltage sag compensator is instantly responds to sudden changes and a great quality load voltage waveforms are achieved. This ability confirms the results of proposed sag compensator control technique for the moderation of voltage sags.

IV.CONCLUSION

The recommended voltage sag compensator used for the distribution line has been assumed to be located in medium voltage distribution network level and it can mitigate three-phase sag. Pulse width modulation technique with switching specific frequency has been used in VSI. The compensator has been designed with special importance at the control of PWM inverter i.e fuzzy logic control.
The fuzzy logic control has been developed in the paper to response quickly and obtains a good dynamic performance. The control scheme does not necessitate a difficult computer algorithm. The removal of transformations, multiplications and divisions makes the control system simple and more reliable. The proposed sag compensator has shown the capability to diminish the voltage sag. The voltage sags have been generated by disturbed load in the system. The switching devices have correctly been triggered to make the it on-line or off-line and protect the compensator from the voltage drop. It is concluded that the proposed sag compensator has successfully mitigated the long extent voltage sags and perfectly restored the critical load voltage to nearly 1 pu. The designed system has provided a regulated and sinusoidal voltage across the complex load and thus increased efficiency of the system. The nearly perfect sinusoidal output voltages have resulted in improvements in the current and power quality of the sensitive load. The IGBT based VSI technology and dynamic performance capability of fuzzy control of DVR have improved the quality of critical load quantities by preventing the sags. Thus, the voltage can be

restored in a supply system by controlling the Dynamic Voltage Restorer using Fuzzy logic.

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