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Simulation Analysis of DVR Performance for Voltage Sag Mitigation

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Abstract— **Voltage sag is literally one of power quality problem and it become severe to industrial customers. Voltage sag can cause miss operation to several sensitive electronic equipments. That problem can be mitigating with voltage injection method using custom power device, Dynamic Voltage Restorer (DVR). This paper presents modeling and analysis of a DVR with pulse width modulation (PWM) based controller using Matlab/Simulink. The performance of the DVR depends on the efficiency of the control technique involved in switching the inverter. This paper proposed two control techniques which is PI Controller (PI) and Fuzzy Logic Controller (FL). Comprehensive results are presented to assess the performance of each controller as the best power quality solution. Other factors that also can affect the performance and capability of DVR are presented as well.**

Keywords- Voltage sag; Dynamic Voltage Restore; Pulse Width Modulation (PWM); PI Controller; Fuzzy Logic Controller

I. INTRODUCTION

Recently, power quality problems become a major concern of industries due to massive loss in terms of time and money. Hence, there are always demands for good power quality, which positively resulting in reduction of power quality problems like voltage sag, harmonic and flicker [1]. Voltage sag is always considered as one of the major power quality problems because the frequency of occasion is so high. Moreover, according to the data recorded by Tenaga Nasional Berhad (TNB), 80% of power quality complaints by consumers in Malaysia were outlined to be associated with voltage sag [2]. The common causes of voltage sag are faults or short circuit in the system, starting of large loads and faulty wiring [3]. This will lead to increase in both production and financial loss for industries. Therefore, it is vital to mitigate voltage sag.

Two main characteristics that explain the voltage sag are depth/magnitude and duration of voltage sag itself. The depth/magnitude and duration of voltage drop that said to be voltage sag is between 0.1 to 0.9 pu with time interval, t about 0.5 cycles to 1 minute [4]. This classification is based on IEEE standard 1159-1995.

There are various types of voltage sag mitigation equipment that available nowadays such as Uninterrupted Power Supply (UPS), flywheel, and the flexible ac technology (FACTS) devices which have been widely used in the power system due to the reliability to maintain power quality control [5]. One of the most FACTS devices that have been created in improvement the performance of power quality is Dynamic Voltage Restorer (DVR) also known as custom power devices. In this paper, DVR which consists of the injection transformer, filter unit, PWM inverter, energy storage and control system is used to mitigate the voltage sag in the power distribution system.

Control unit is the heart of the DVR where it main function is to detect the presence of voltage sags in the system, calculating the required compensating voltage for the DVR and generate the reference voltage for PWM generator to trigger on the PWM inverter. The components of control system unit are the dq0-transformation, Phase-lock-loop (PLL) and the PI or FL Controller. PI Controller is a feedback controller which drives the plant to be controlled with a weighted sum of the error (difference between output and and desired set-point) and the integral of that value.

II. METHODOLOGY

A. Mathematical Calculation

When voltage drop occurred at load, DVR will inject a series voltage through transformer so that load voltage can be maintained at nominal value as shown in Fig.1. Thus,

$$V_{DVR} = V_L + Z_{th} I_L - V_{th} \tag{1}$$

$$I_L = \left[\frac{P_L + jQ_L}{V_L} \right]^* \tag{2}$$

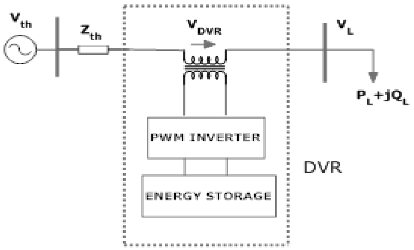


Figure 1. Calculation for DVR voltage injection

If V_L is considered as a reference ;

$$V_{DVR}\angle\alpha = V_L\angle 0^\circ + Z_{th} I_L \angle(\beta-\theta) - V_{th}\angle\delta \tag{3}$$

Here α, β, and δ are the angle of V_{DVR}, Z_{th} and V_{th}, respectively and θ is the load power factor angle with

$$\theta = \tan^{-1}\left(\frac{Q_L}{P_L}\right) \tag{4}$$

Thus, the power injection of the DVR can be written as

$$S_{DVR} = V_{DVR} I_L \tag{5}$$

B. Principal of Operation

The basic function of DVR is to inject dynamically voltage required, V_{DVR} to compensate sagging occurrence. Generally, the operation of DVR can be categorized into two modes; standby mode and injection mode [6]. In standby mode, DVR either in short circuited operation or inject small voltage to cover voltage drop due to transformer reactance losses. The DVR is turn into injection mode as soon as sagging is detected. V_{DVR} is injected in series with load with required magnitude and phase for compensation.

C. Modelling of DVR

Fig. 2 shows the flow chart of basic concept of the DVR operation. Typical DVR is built in Matlab/Simulink program as depicted in Fig. 3. The study considered the standard voltage used in Malaysia, supplied by Tenaga Nasional Berhad (TNB). The source is 11kV fed from TNB distribution substation (PPU). 11kV is then cabled to step down transformer, convert the 11kV voltage to 415V before deliver it to consumer's load. In this study, we applied two example of load, Load 1 and Load 2. Load 2 represents the non-sensitive equipment which means that the equipment can tolerate the sagging condition. Meanwhile, Load 1 represents the sensitive equipment like ASDs and PLCs where voltage regulation is crucial. Thus, DVR will be inserted in series with Load 1 to help improving the supply voltage before to be fed by Load 1.

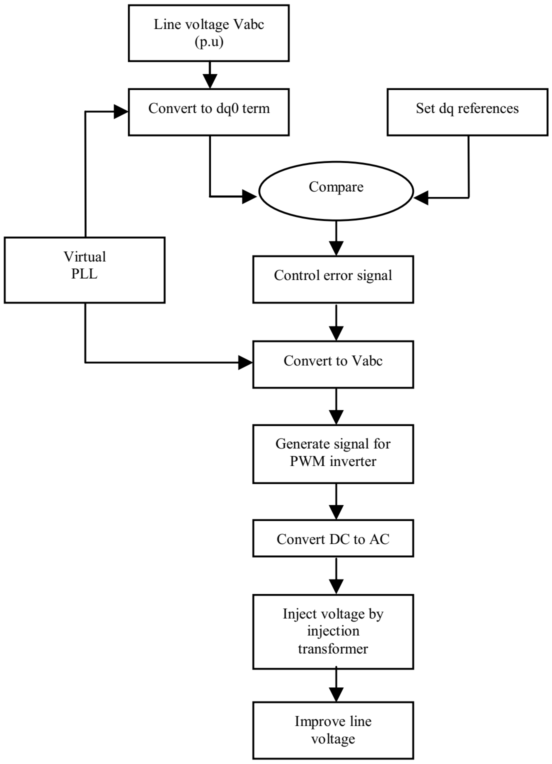


Figure 2. Flow chart of DVR operation

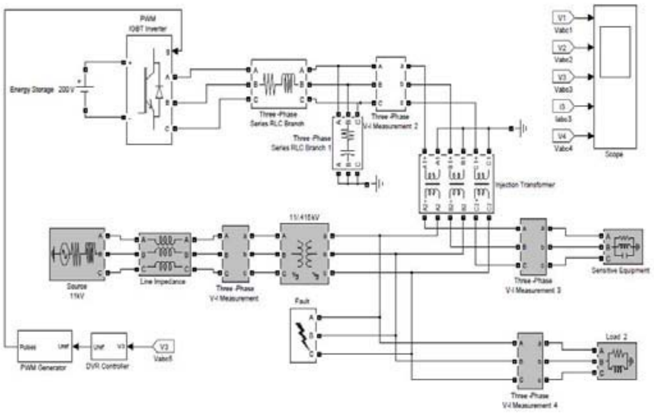


Figure34. DVR Modelling using Matlab/Simulink

Three legs PWM inverter is used to convert DC source to AC voltage and then injected into the line by injection transformer. The inverter model consists of self-commutating IGBT switches with parallel diodes. The sinusoidal pulse width modulation technique (PWM) forms the control strategy. The control block generates the firing signals for each switch with controllable amplitude, phase and frequency whenever sag is detected. The filter unit is applied to output of the inverter as it is closer to harmonic source.

D. DVR Control Techniques

The fundamental roles of a controller in a DVR are to detect the voltage sag occurrences in the system; calculate the compensating voltage, to generate trigger pulses of PWM inverter and stop triggering pulses when the occurrence has passed. Using RMS value calculation of the voltage to analyze the sags does not give fast result. In this study, the dq0 transformation or Park's transformation is used in voltage calculation. The dq0 transformation is a transformation of coordinates from the three-phase stationary coordinate system to the dq rotating coordinate system [7]. This dq0 method gives the information of the depth (d) and phase shift (q) of voltage sag with start and end time.

$$V_0 = \frac{1}{3}\left(V_a + V_b + V_c\right) = 0 \tag{6}$$

$$V_d = \frac{2}{3}\left[V_a \sin\omega t + V_b \sin\left(\omega t - \frac{2\pi}{3}\right) + V_c \sin\left(\omega t + \frac{2\pi}{3}\right)\right] \tag{7}$$

$$V_q = \frac{2}{3}\left[V_a \cos\omega t + V_b \cos\left(\omega t - \frac{2\pi}{3}\right) + V_c \cos\left(\omega t + \frac{2\pi}{3}\right)\right] \tag{8}$$

After conversion, the three-phase voltage Va, Vb and Vc become two constant voltages Vd and Vq and now, they are easily controlled. In this paper, two control techniques have been proposed which are proportional integral (PI) controller and fuzzy logic (FL) controller. Comprehensive results are presented to assess the performance of each controller as the best power quality solution.

1) Proportional-Integral (PI) Controller

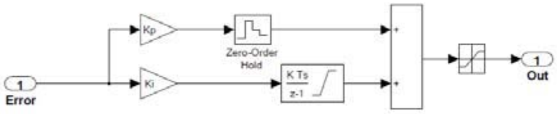


Figure 4 Discrete PI controller

PI Controller shown in Fig. 4 is a feedback controller which drives the plant to be controlled with a weighted sum of the error and the integral of that value [8]. The proportional response can be adjusted by multiplying the error by constant K_P, called proportional gain. The contribution from integral term is proportional to both the magnitude of error and duration of error. The error is first multiplied by the integral gain, K_i and then was integrated to give an accumulated offset that have been corrected previously [8].

Fig. 5 shows the control circuit designed in Matlab/Simulink. The input of the controller come from the output voltage, V3 measured by three-phase V-I measurement at Load 1 in pu. V3 is then transformed in dq term (expressed as instantaneous space vector). The voltage sag is detected by measuring the error between the dq-voltage and the reference values. The d-reference is set to rated voltage whilst q-reference is set to zero. The dq components of load voltage are compared with the reference values and the error signal is then entering to PI controller. Two PI controller block are used for error signal-d and error signal-q separately. For error signal-d, K_P is set to 40 and K_i is set to 154 whilst for error signal-q, K_P and K_i is set to 25 and 260 respectively. All the gains selected use to tune up the error signal d and q so that the signal is stable and well responses to system disturbances. The outputs of the PI controller then are transformed back into Vabc before forwarded to PWM generator.

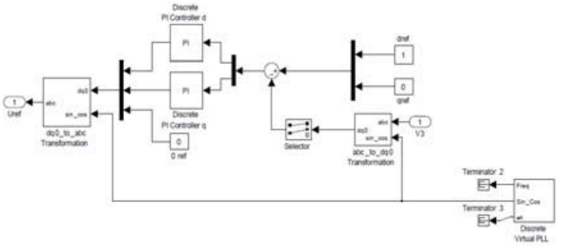


Figure 5. Control circuit using PI controller

2) Fuzzy Logic Controller

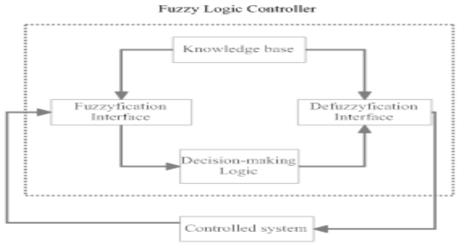


Figure 6. Basic configuration of FL controller

Unlike Boolean logic, fuzzy logic allows states (membership values) between 0 or 1. Its major features are the use of linguistic variables rather than numerical variables. *Linguistic variables*, defined as variables whose values are sentences in a natural language (such as *small* and *big*), may be represented by *fuzzy sets* [9]. The general structure of an FLC is represented in Fig. 6 and comprises four principal components:

- a *fuzzyfication interface* which converts input data into suitable linguistic values;
- a *knowledge base* which consists of a data base with the necessary linguistic definitions and control rule set;
- a *decisionmaking logic* which, simulating a human decision process, infers the fuzzy control action from the knowledge of the control rules and the linguistic variable definitions; and
- a *defuzzyfication interface* which yields a nonfuzzy control action from an inferred fuzzy control action.

In this paper, two FL controller block are used for error signal-d and error signal-q as shown in Fig. 7. The process also same as before except the controller now is Fuzzy Logic. For both blocks (error signal-d and q) the FL controller consists of 8 linguistic variables from input which is; Negative (N), Zero (Z), Positive Small (PS), Positive Fair Small (PFS), Positive Average (PA), Positive Fair Big (PFB), Positive Big

(PB), and Positive Very Big (PVB). Each parameter from linguistic variables for error signal is shown in Fig. 8. For delta error, there are two linguistic variables, Negative (N) and Positive (P). Both variables can be depicted as in Fig. 9.

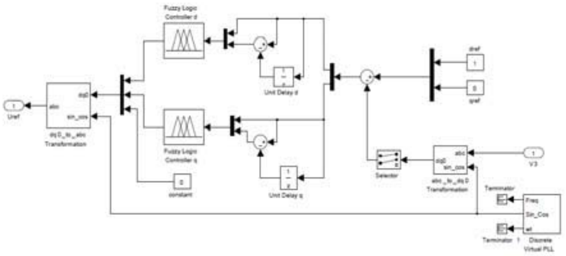


Figure 7. Control circuit using FL controller

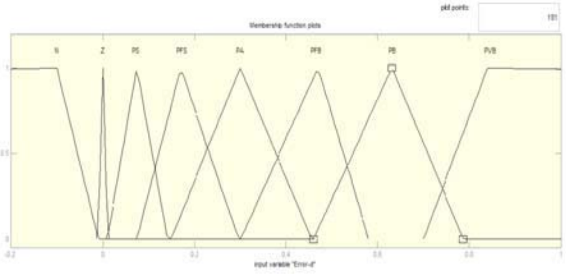


Figure 8. Linguistic variables from input

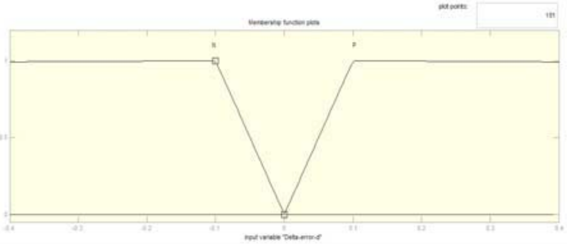


Figure 9. Linguistic variables from delta error

In defuzzyfication process, there are 13 linguistic variables which are Negative (N), Zero (Z), Positive Small 1 (PS1), Positive Small 2 (PS2), Positive Fair Small 1 (PFS1), Positive Fair Small 2 (PFS2), Positive Average 1 (PA1), Positive Average 2 (PA2), Positive Fair Big 1 (PFB1), Positive Fair Big 2 (PFB2), Positive Big 1 (PB1), Positive Big 2 (PB2) and Positive Very Big (PVB). Fig. 10 shows each parameter for output signal.

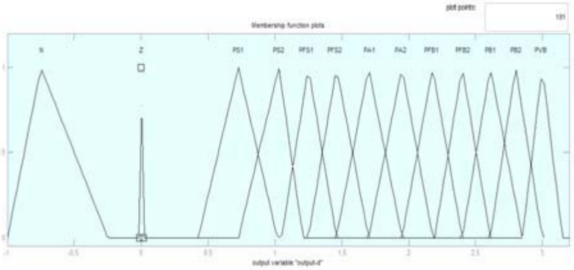


Figure 10. Linguistic variables from output signal

TABLE I. RULE BASE

E / DE	N	Z	PS	PFS	PA	PFB	PB	PVB
N	N	Z	PS1	PFS1	PA1	PFB1	PB1	PVB
P	N	Z	PS2	PFS2	PA2	PFB2	PB2	PVB

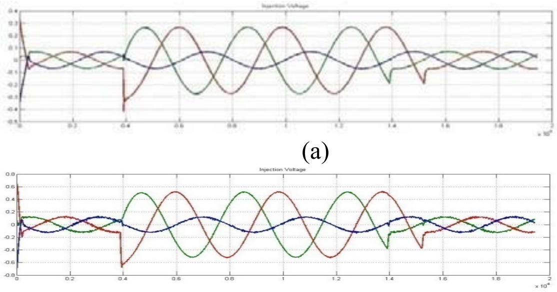
In the decision-making process, there is rule base that linking between input (error signal) and output signal. Table 1 show the rule base used in this FL controller.

III. RESULTS AND DISCUSSIONS

A. Fault Analysis

Simulation of voltage sag disturbance on the industrial electricity system is done by generating fault using 3-phase fault generator at load 2 until load 1 (sensitive equipment) are affected too by sag phenomenon. DVR are inserted to industrial electricity system, load 1. Two types of fault generated at load 2 to produce sag phenomenon which is double-line-to-ground fault (unbalanced) and balanced three phase fault. There are four levels of voltage generated to load 1 for every fault (0.02 to 0.07 seconds duration) which are 30%, 50%, 80% and 90% voltage sags. Both PI and FL Controller are simulated and performance of DVR is analyzed to determine how it deals with all type of fault and which controller gives better efficiency.

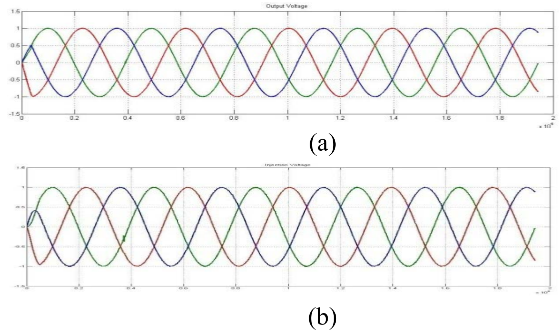
1) Double-line-to-ground fault with 50% sagging



(a)

(b)

Figure 11. (a) Injection voltage from DVR controlled by PI ; (b) injection voltage controlled by FL

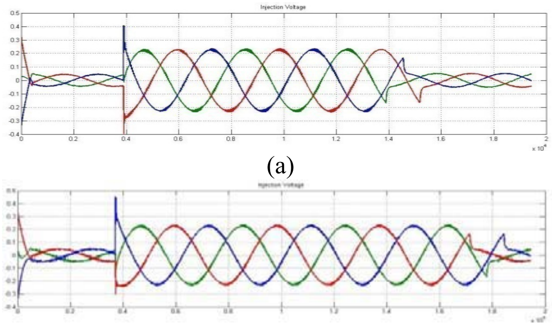


(a)

(b)

Figure 12. (a) Output voltage at load 1 after injection voltage from DVR controlled by PI; (b) Output voltage at load 1after injection voltage controlled by FL.

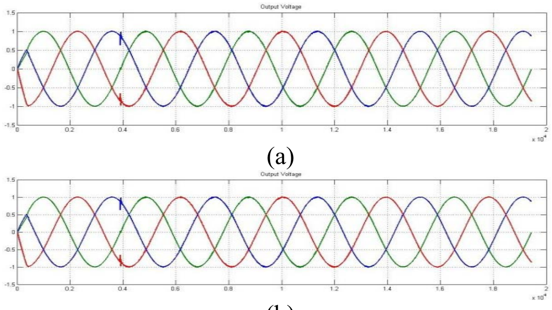
2) *Balanced three-phase fault with 50% sagging*



(a)

(b)

Figure 13. (a) Injection voltage from DVR controlled by PI; (b) injection voltage controlled by FL.



(a)

(b)

Figure 14. (a) Output voltage at load 1 after injection voltage from DVR controlled by PI; (b) Output voltage at load 1after injection voltage controlled by FL.

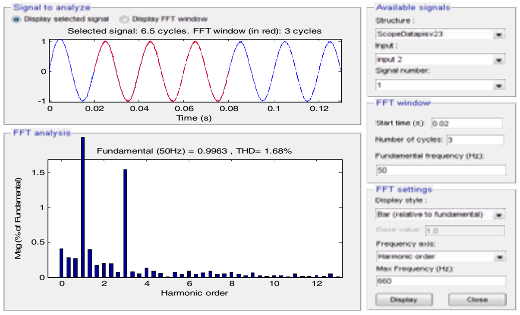
Fig. 11 to 14, shows that, the moment where fault occurred at load 2, resultant in sag happened at load 1 as dip as 50% voltage drop. Table II and Table III show the comparison of the output voltage as a result due to voltage injection from DVR controlled by PI and FL for each phase in four levels of voltage sag. It can be seen that both controllers gave an optimum performance and have the ability to improve the source voltage back to 1 p.u before deliver it to the load in balanced and unbalanced fault condition. Even for worst case, balanced three phase fault with 0.1 p.u voltage sag, DVR controlled by PI and FL still can work successfully. However, PI Controller generates higher total harmonic distortion (THD), 1.68% as compared to FL Controller, 0.64% as shown in Fig. 15 and 16.

TABLE II. DOUBLE-LINE-TO-GROUND FAULT

Sag (%)	Before Injection (%)			Injection DVR PI Controller (%)			Injection DVR FL Controller (%)		
	A	B	C	A	B	C	A	B	C
30%	70.65	70.45	100	99.41	99.41	100	100.3	100.1	100
50%	51.5	51.08	100	99.29	99.82	100	100.2	99.98	100
80%	20.66	20.44	100	100	100.3	100	100.4	100.4	100
90%	10	10.1	100	99.98	100.1	100	99.98	100.2	100

TABLE III. BALANCED THREE PHASE FAULT

Sag (%)	Before Injection (%)			Injection DVR PI Controller (%)			Injection DVR FL Controller (%)		
	A	B	C	A	B	C	A	B	C
30%	70.64	70.59	70.65	99.83	100.3	100.2	100.1	100.2	100.1
50%	51.02	50.97	50.94	99.74	99.82	99.72	100.2	100.1	100.2
80%	20.13	19.76	19.66	99.56	99.55	99.63	100	100.2	100.4
90%	10	9.98	10.1	100.2	100.4	100.1	100	100.1	100.1



● Display selected signal ○ Display FFT window

Selected signal: 6.5 cycles. FFT window (in red): 3 cycles

Fundamental (50Hz) = 0.9963 , THD= 1.68%

Structure : ScopeDatapisv23

Input : input 2

Signal number: 1

Start time (s): 0.02

Number of cycles: 3

Fundamental frequency (Hz): 50

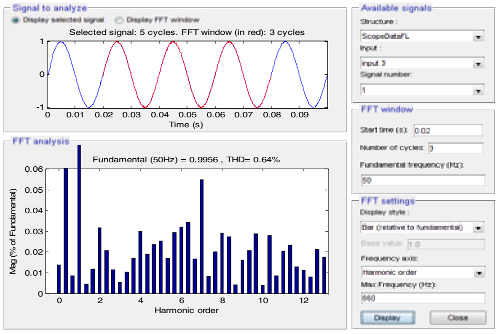
Display style : Bar (relative to fundamental)

Base value: 1.0

Frequency axis: Harmonic order

Max Frequency (Hz): 660

Figure 15. THD generated when PI controller is applied



● Display selected signal ○ Display FFT window

Selected signal: 5 cycles. FFT window (in red): 3 cycles

Fundamental (50Hz) = 0.9956 , THD= 0.64%

Structure : ScopeDataFL

Input : input 3

Signal number: 1

Start time (s): 0.02

Number of cycles: 3

Fundamental frequency (Hz): 50

Display style : Bar (relative to fundamental)

Base value: 1.0

Frequency axis: Harmonic order

Max Frequency (Hz): 660

Figure 16. THD generated when FL controller is applied.

B. *Effect of Energy Storage Capacities*

The ability of DVR to compensate voltage sag depends on the capacity of energy storage. Table IV shows the improvement of capability of DVR to mitigate voltage sag with respect to variation of energy storage capacities. At 100 Vdc energy storage, the DVR is no longer capable to mitigate sag and only able to improve voltage 0.0632 p.u higher. And it is clearly show that 110 Vdc is the least voltage that capable to compensate voltage drop above 0.9 p.u.

C. *Effect of Transformer Ratings*

Table V shows the differences of THD generated before and after DVR mitigation with respect to changing of kVA ratings of injection transformer. The tabulated result shows that with higher kVA rating used, the THD generated will be less. DVR improve 46.55% in term of THD with 5kVA rating used compared to 1.5kVA rating. However, higher rating means that transformer is more expensive.

TABLE IV. CAPABILITY OF DVR TO MITIGATE SAG

Energy Storage (Vdc)	VL Before Mitigation (p.u)	VL After Mitigation (p.u)
200	0.803	1.003
180	0.8036	1.003
150	0.803	0.9989
120	0.8026	0.9545
110	0.8026	0.9036
100	0.8027	0.8659

TABLE V. EFFECTS OF TOTAL HARMONIC DISTORTION WITH DIFFERENT KVA RATING

kVA	THD Before Mitigation %	THD After Mitigation %
1.5	0.8	0.64
2	0.7	0.55
3	0.56	0.4
4	0.56	0.35
5	0.55	0.31

IV. CONCLUSIONS

In this study, the modeling and simulation of DVR controlled by PI and FL Controller has been developed using Matlab/Simulink. For both controller, the simulation result shows that the DVR compensates the sag quickly (70µs) and provides excellent voltage regulation. DVR handles all types, balanced and unbalanced fault without any difficulties and injects the appropriate voltage component to correct any fault situation occurred in the supply voltage to keep the load voltage balanced and constant at the nominal value. Both controllers show an excellent performance and generate low THD (<5%). However, it can be seen that FL Controller gives better performance with THD generated with only 0.64% whilst PI generated 1.68% THD. However, other several factors that can affect the performance of DVR need to be addressed for enhancement of the output voltage. These factors are the energy storage capacity and transformer rating. From the simulation, it clearly shows the importance of these two factors and how they affect the performance of DVR. Therefore, when it comes to implementation, it is crucial to consider these factors, so that the performance of DVR is optimized.

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