# Simulation Analysis of DVR Performance for Voltage Sag Mitigation

Mohd Saad Abdul Rahim
Faculty of Electrical Engineering
Universiti Teknologi MARA, Malaysia
40450, Shah Alam, Selangor, Malaysia
Email: saad.abdrahim@gmail.com

*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 by using the 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 Restorer, 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]. The equipments that normally cannot withstand with occurrence of voltage sag are sensitive devices like Adjustable Speed Drives (ASDs) and Programmable Logic Controllers (PLCs) and forced them to malfunction [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 regarding 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 equipments that available nowadays such as Uninterrupted Power Supply (UPS), flywheel, and the flexible ac technology (FACTS) devices which have been widely uses 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 the Dynamic Voltage Restorer (DVR) will be use to mitigate the voltage sag in the power distribution system.

## II. DYNAMIC VOLTAGE RESTORER (DVR)

### *A. System Configuration*

DVR is the series voltage controller connected in series with the load as shown in Figure 1 and normally the connection is made by a transformer. The basic components of DVR are:

- an injection transformer
- a filter unit,
- a PWM inverter,
- an energy storage and
- a control system

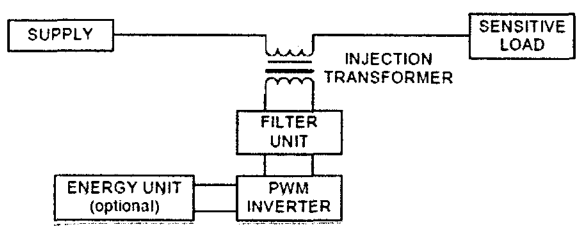



Figure 1. Typical application of DVR

*B. Mathematical Calculation*

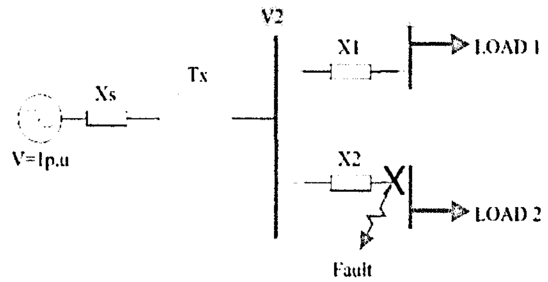



Figure 2. Equivalent circuit

Consider Figure 2, at normal condition, where no fault occurred, current from source equally flow through load 1 and load 2. When fault occur at point X somewhere on line feeder 2, high current (short circuit current) will flow towards point X. As a result, current flow to feeder 1 will decrease thus, the voltage also will decrease. This condition is referred as voltage sag occurrence.

Consider load 1 consist of sensitive equipment, in that case DVR is essential to improve supply voltage deliver to the load. Consider schematic diagram shown in Figure 3,

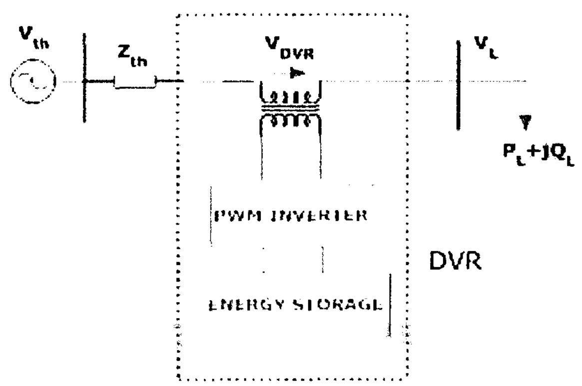



Figure 3. Calculation for DVR voltage injection

$$V_{DVR} + V_{th} = V_L + Z_{th} I_L \qquad (1)$$

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

$$V_{DVR} = V_L + Z_{th} I_L - V_{th} \qquad (2)$$

$$I_L = \left[ \frac{P_L + jQ_L}{V_L} \right]^* \qquad (3)$$

When $V_L$ is considered as a reference, therefore;

$$V_{DVR} \angle \alpha = V_L \angle 0^\circ + Z_{th} I_L \angle(\beta - \theta) - V_{th} \angle \delta \qquad (4)$$

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

$$\theta = \tan^{-1}\left( \frac{Q_L}{P_L} \right) \qquad (5)$$

The power injection of the DVR can be written as

$$S_{DVR} = V_{DVR} I_L \qquad (6)$$

*C. 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 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.

*D. Modeling of DVR*

To get a good picture how to modeling the DVR, it is the best way to start with sketching the flow of work chart. Figure 4 shows the flow chart of basic concept of the DVR operation. Then, the typical DVR is build in Matlab/Simulink program as depicted in Figure 5. The study considered the standard voltage use in Malaysia, supply 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.

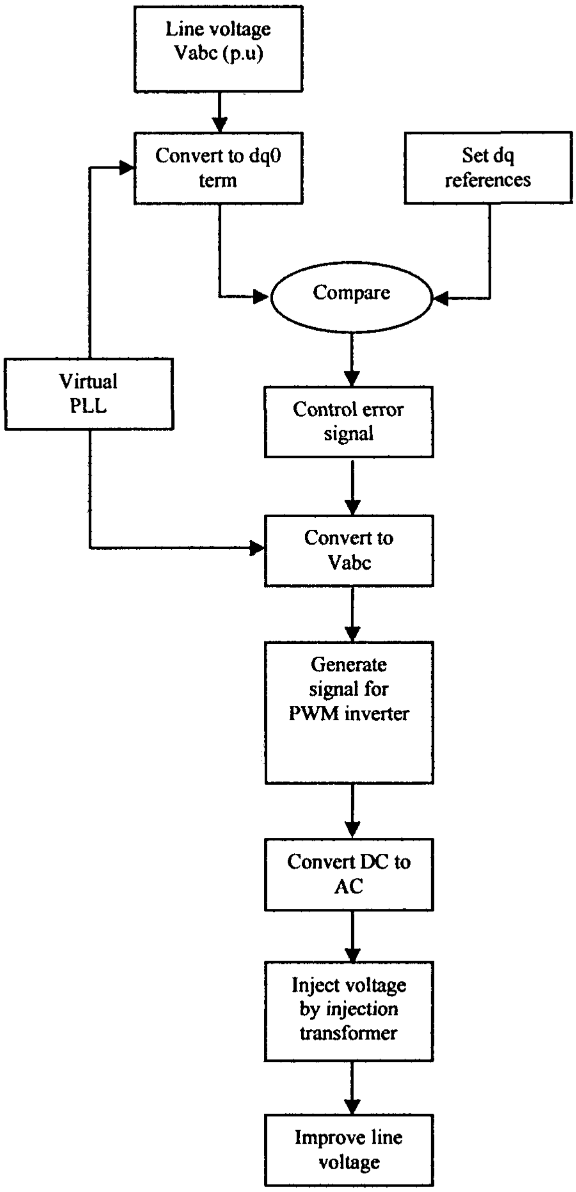



Figure 4. Flow chart of DVR operation

As mentioned before in system configuration section, DVR consists of an injection transformer, a filter unit, a PWM inverter, an energy storage and control system. Three legs PWM inverter is use to convert DC source to AC voltage and then injected in to 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.

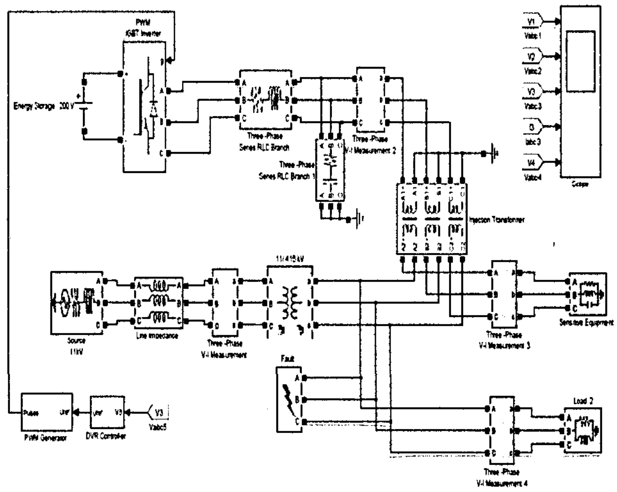


Figure 5. DVR modeling using Matlab/Simulink (refer to Appendix )

*E. 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.

$$V_0 = \frac{1}{3}(V_a + V_b + V_c) = 0 \tag{7}$$

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

$$V_q = \frac{2}{3}\left[V_a \cos\omega t + V_b \cos\left(\omega t - \frac{2\pi}{3}\right) + V_c \cos\left(\omega t + \frac{2\pi}{3}\right)\right] \tag{9}$$

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*

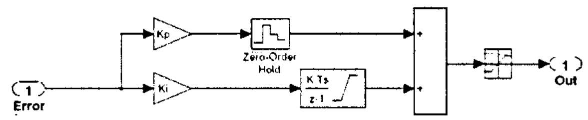



Figure 6 Discrete PI controller

PI Controller is a feedback controller which drives the plant to be controlled with a weighted sum of the error (difference between the output and desired set-point) and the integral of that value [8]. In PI controller, the derivative (D) of the error is not used. Proportional term (sometimes called *gain*) makes a change to the output that is proportional to the current error value. The proportional response can be adjusted by multiplying the error by constant $K_P$, called proportional gain. The contribution from integral term (sometimes called *reset*) 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]. The basic circuit of PI controller is shown in Figure 6, but in Matlab/Simulink, the circuit was compressed into one block.

Figure 7 show 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. The voltage is in the term of per unit (p.u). V3 is then was 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.

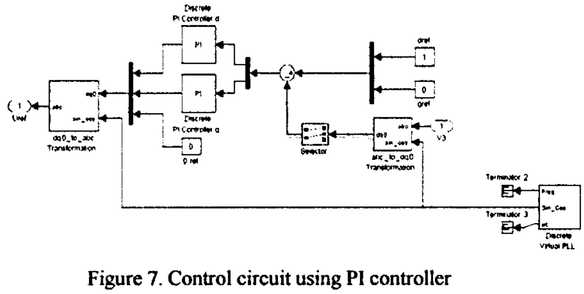


Figure 7. Control circuit using PI controller

*2) Fuzzy Logic Controller*

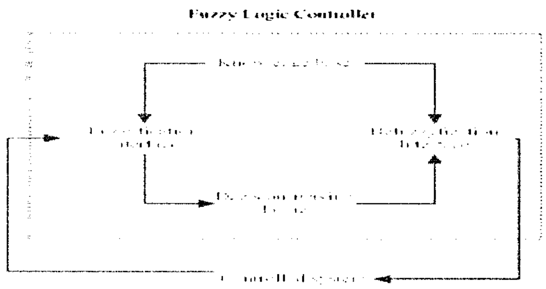


Figure 8. Basic configuration of FL controller

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 Figure 7 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.

For this paper, same as PI controller, two FL controller block are used for error signal-d and error signal-q as shown in Figure 9. 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 Figure 10.

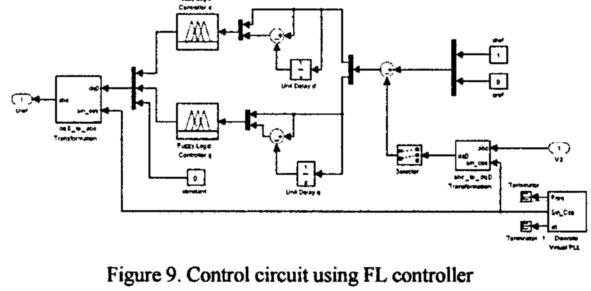


Figure 9. Control circuit using FL controller

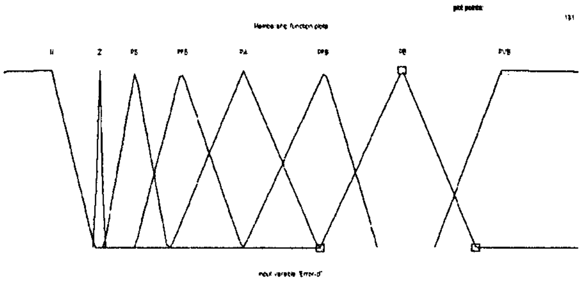


Figure 10.Linguistic variables from input

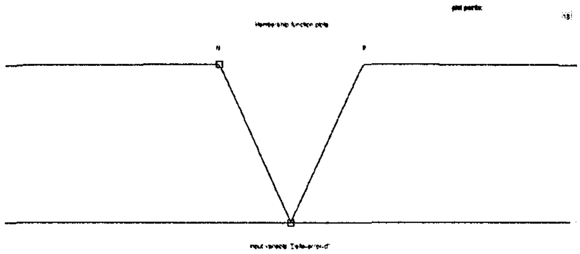


Figure 11. Linguistic variables from delta error

For delta error, there are two linguistic variables, Negative (N) and Positive (P). Both variables can be depicted as in Figure 11. 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). Figure 12 shows each parameter for output signal.

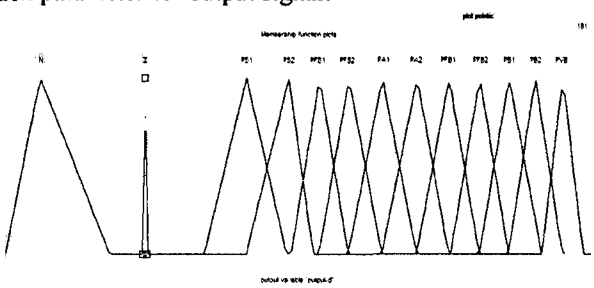


Figure 12. Linguistic variables from output signal

TABLE 1. 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. SIMULATION AND ANALYSIS

### *A. Simulation system without DVR inserted*

For this simulation, voltage sag disturbance on the industrial electricity system are produced by generating fault using 3-phase fault generator at load 2 until load 1 (sensitive equipment) are affected too by sag phenomenon. There'll be 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 sag that have been generate to load 1 for every fault (0.02 to 0.07 seconds duration) which are 30%, 50%, 80% and 90% voltage sags. It is shown that from Figure 13 to Figure 14, the moment where fault occurred at load 2 that resultant in sag happened at load 1 as dip as 50% voltage drop.

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

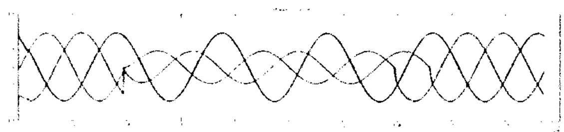


Figure 13. Voltage sag due to double-line-to-ground fault

*2) Three-phase-to-ground fault with 50% sagging*

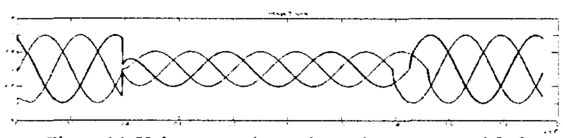
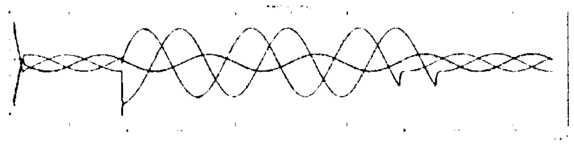


Figure 14. Voltages sag due to three-phase-to-ground fault.

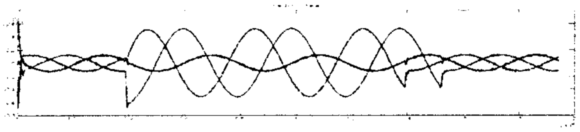
### *B. Simulation system with DVR inserted*

This time, voltage improver, DVR are inserted to industrial electricity system, load 1. Both controller, PI and FL controller will be simulated and performance of DVR will be analyzed to check how these two controller deal with all type of fault and which one will give a better efficiency. From Figure 17 to 20 shows the injection voltage and output voltage based on two type of fault, which are double line-to-ground fault (unbalanced) and balanced three phases fault. The complete assessment of all four levels of sags will be depicted in Table 2 and Table 3.

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

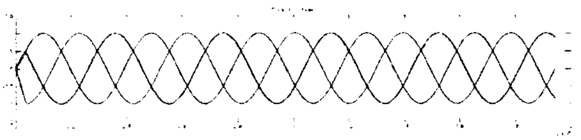


(a)

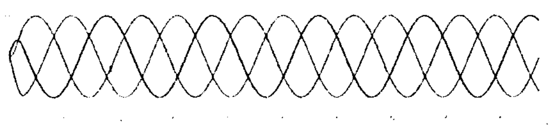


(b)

Figure 17. (a) Injection voltage from DVR controlled by PI ; (b) injection voltage controlled by FL



(a)

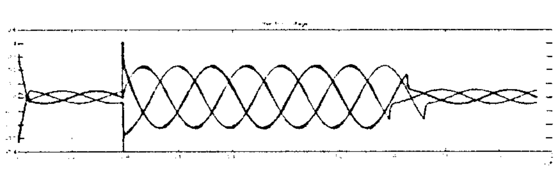


(b)

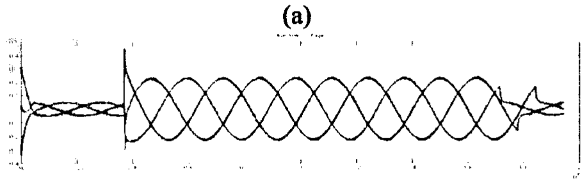
Figure 18. (a) Output voltage at load 1 after injection voltage from DVR controlled by PI; (b) Output voltage at load 1after injection voltage controlled by FL.

From Figure 17 and Figure 18 shows the injection voltage from DVR controlled by PI and FL and the output voltage at load 1. To be concluding, that at 50% sagging, both controller gave an optimum performance. Both have the ability to improve the source voltage back to 1 p.u before deliver it to the load. Now, the system is disturbed by balanced three-phase fault and 50% sagging. From Figure 19 and Figure 20, shows the voltage is injected by DVR controlled by PI and FL. Yet again, both gave an optimum performance and improve the voltage to 1 p.u.

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

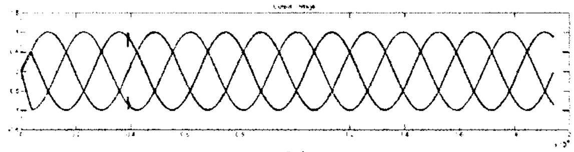


(a)

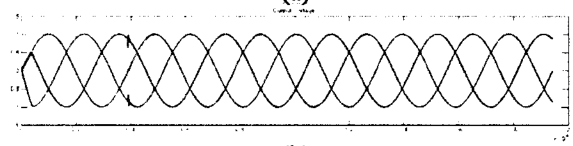


(b)

Figure 19. (a) Injection voltage from DVR controlled by PI; (b) injection voltage controlled by FL.



(a)



(b)

Figure 20. (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.

TABLE 2. 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 3. 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 |

Now, 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 can be seen in TABLE 2 and TABLE 3. From these two tables, we can see that there is no too much different between PI controller and FL controller. Both controller give an optimum performance, able to inject the required voltage to improve voltage stability back to 1 p.u .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, from Matlab simulation, FFT analysis shows the different between PI controller and FL controller. When DVR is controlled by PI, the total harmonic distortion (THD) generated, is about 1.68%. Meanwhile, when the controller is changed to Fuzzy Logic, the THD generated is merely 0.64%. Figure 21 and Figure 22 show the results. The

Matlab/Simulink also show that time taken by DVR to compensate sagging is about 70µs for both controller.

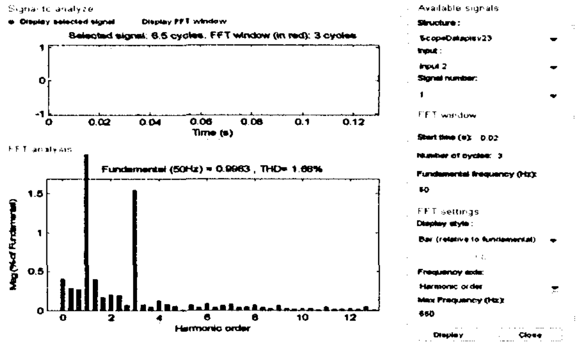



Figure 22. THD generated when PI controller is applied

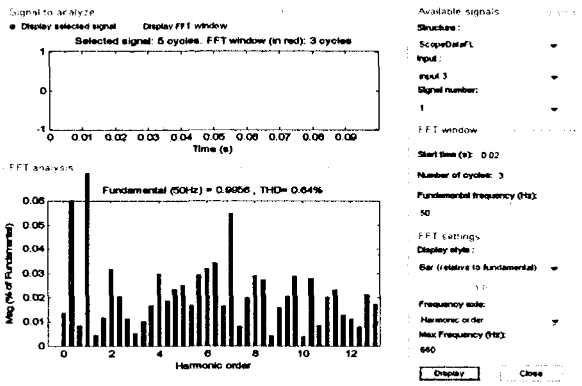



Figure 23. THD generated when FL controller is applied.

## IV. ANALYSIS ON DVR PERFORMANCE BASED ON OTHER FACTORS

The performance of DVR based on two controllers has just presented where other factors were set to constant. The result show that PI and FL controller give great performance, but FL controller slightly better than PI in term of THD generated. Now we are going to investigate on the other factors that can give significant effect on DVR performance. In this paper, there are two factors that have been analyzed which are the energy storage capacity and MVA rating and for these analysis DVR applied FL as controller since it gives the best performance and voltage sag is set to 20%.

### *A. Effect of Energy Storage Capacities*

The ability of DVR to compensate voltage sag depends on the capacity of energy storage. Table 4 shows the improvement of capability of DVR to mitigate voltage sag with respect to variation of energy storage capacities. We saw that 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. The tabulated data also has been plotted into a graph (as shown in Figure 23) to show the differences.

TABLE 4 IMPROVEMENT OF CAPABILITY OF DVR w.r.t ENERGY STORAGE CAPACITY

| 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 |

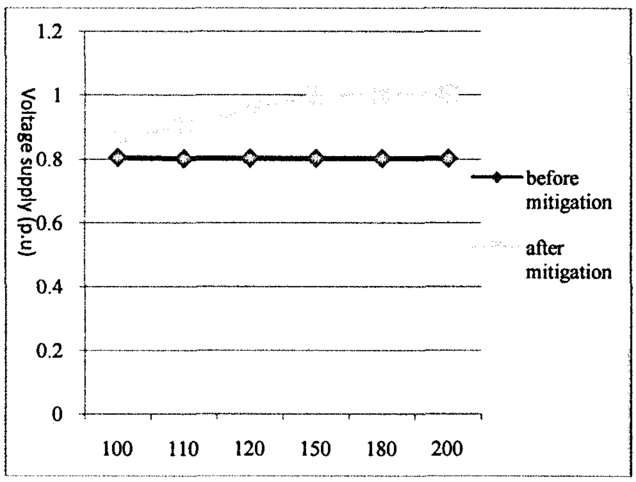



Figure 23. Comparison of voltage drop before and after mitigation with different dc voltage

### *B. Effect of Transformer Ratings*

Table 5 shows the differences of total harmonic distortion (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 use, the THD generated will be less. Table 5 also shows that 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 5 EFFECTS OF TOTAL HARMONIC DISTORTION w.r.t DIFFERENCE 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 |

## V. CONCLUSION

In this study, the modeling and simulation of Dynamic Voltage Restorer controlled by Proportional-Integral (PI) controller and Fuzzy Logic (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 controller has give an excellent performance and generate low THD (<5%). However, between these two controller, Fuzzy Logic has a better performance with THD generated 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 come to implementation, it is crucial to consider these factors, so that the performance of DVR is optimum yet the device still profitable.

## REFERENCES


[1] Omar, R. Rahim, N.A. "New Control Technique Applied in Dynamic Voltage Restorer for Voltage Sag Mitigation" Industrial Electronics and Applications, 2009. ICIEA 2009. 4th IEEE Conference on.

[2] Faisal, M.F. "Power Quality Management Program: TNB's Experience", Distribution Engineering, TNB 2005.

[3] Wahab, S.W. Yusof, A.M. "Voltage Sag Mitigation Using Dynamic Voltage Restorer (DVR) System, ELEKTRIKA, 8(2),2006, 32-37.

[4] IEEE Standard Board (1995), "IEEE Std. 1159-1995", IEEE Recommended Practice for Monitoring Electric Power Quality". IEEE Inc. New York.

[5] Kim H. "Minimal Energy Control for a Dynamic Voltage Restorer", In proceedings of the Power Conversion Conference, Osaka, Japan, 2002, pp. 428-433.

[6] V.K. Ramachandaramurthy, A. Arulampalam, C.Fitzer, C. Zhan, M. Barnes and N. Jenkins"Supervisory control of dynamic voltage restorers "IEE Proc.-Gener. Transm. Distrib. Vol. 151, No. 4, pp. 509-516, July 2004.

[7] P. Boonchiam and N. Mithulananthan, "Understanding of Dynamic Voltage Restorers through MATLAB Simulation," Thammasat Int. J. Sc. Tech., Vol. 11, No. 3, July-Sept 2006.

[8] Nise, N. S. "Control Systems Engineering" 5th Edition, John Wiley & Son, Inc. 2008

[9] Mattavelli, P. Rossetto, L. Spiazzi, G. Tenti, P. "General-Purpose Fuzzy Controller for DC-DC Converter" IEEE Transactions on Power Electronics, Vol. 12, No. 1, January 1997.

[10] Nemati, M. Yousefian, H. A. Afshari, R. "Recognize The Role of A DVR in Power Systems" International Journal of Recent Trends in Engineering, Vol 2, No. 7, November 2009.

[11] Benachaiba, C. Ferdi, B. "Voltage Quality Improvement Using DVR", Electrical Power Quality and Utilization, Journal Vol. XIV, No. 1, 2008.

APPENDIX

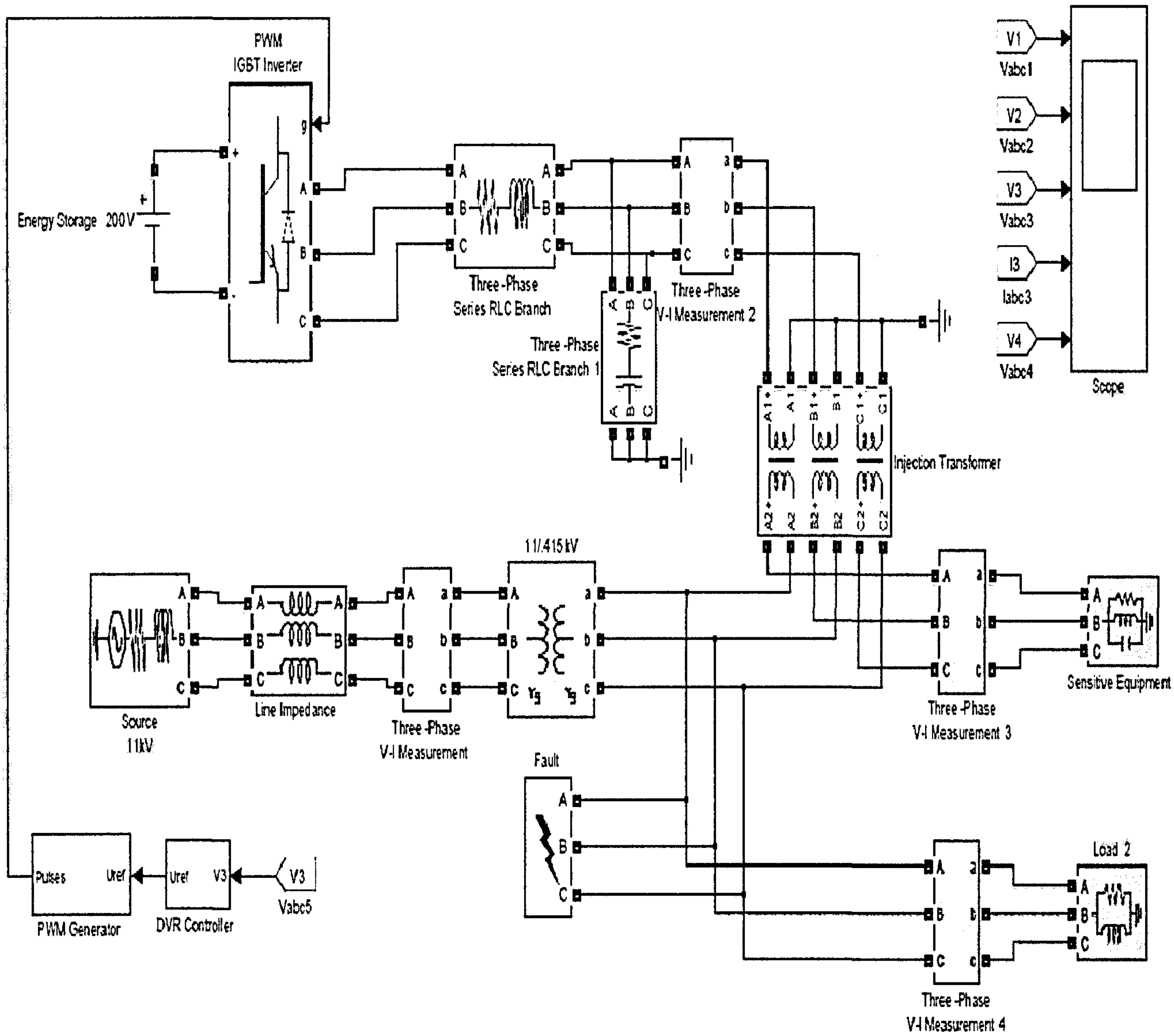



Figure 5. DVR modeling using Matlab/Simulink.