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Original Research

Assessment of the Power Quality Problems and its Improvement Method at the Wama Sugar Factory Power Distribution System

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Abstract

When designing an electrical power system, power quality should be your first concern. A power quality problem occurs when there is an issue with the electrical power system due to nonstandard voltage, current, or frequency. This study presents the causes and consequences of power distribution system power quality problems. In order to collect the required data from the power distribution system of the Wama sugar factory, the Fluke 435 power quality analyzer was utilized. In addition, the data that was recorded was supplied by the factory. Another power quality improvement method that was implemented was the dynamic voltage restorer (DVR), which helped with voltage sag and other issues caused by various fault scenarios. When there is a voltage drop in the power distribution, DVR can help get the load voltage back up to the normal limit. The direct quadrature park's transformation (DQPT), phase locked loop (PLL), and proportional integral (PI) controller are used to accomplish DVR control. The suggested systems, with and without the DVR, were modelled using MATLAB / SIMULINK software.

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INTRODUCTION

According to Almohaimeed and Abdel-Akher (2020), when fluctuations in voltage or current disrupt the regular functioning of electrical or electronic devices, this is known as a power quality problem. The development of complicated technologies whose performance is heavily dependent on the quality of the power supply has made this an undeniably important worry in the current period (Choudhury & Sahoo, 2024; Al-Shetwi et al., 2020).Industrial loads are becoming increasingly intolerant of power quality issues due to the sensitivity of electronic equipment (Al-Shetwi et al., 2020). Any fluctuation in the voltage and frequency levels at which the power is supplied has an impact on its quality. This has an impact on the performance and longevity of end-user equipment (Al-Shetwi et al., 2020). In contrast, power system defects have an impact on the continuity of the power supply. To ensure the continuation of the power supply, the faults should be cleared (Ogheneovo, 2016).

The most common power quality problems that occur in the power distribution system are voltage sag, voltage swell, voltage flicker, harmonics, overvoltage, under-voltage, and transients (Sabin et al., 2022). These problems are sourced from utility or customer loads and tend to be caused by faults in the power distribution system. In order to enhance the behavior of the power system, all of these problems should be improved (Sabin et al., 2022). Power distribution systems should provide their customers with a continuous supply of energy at a smooth sinusoidal voltage at the designated magnitude level and frequency. But in reality, there are a lot of nonlinear loads in power systems, especially in power distribution systems (Hossain et al., 2018).

A bus voltage that corresponds to a sinusoidal waveform of the required magnitude might be considered acceptable power quality (Bajaj et al., 2020). These can seriously affect sensitive loads, leading to things like contactor burnouts, sensitive machine failure, motor drive failure, motor overheating, low power factor, fuse blowing, and so on (Kumar, 2022).

Wama sugar factory power distribution systems suffer power quality problems due to disturbances and the presence of nonlinear loads such as furnaces, motors, and adjustable speed drives, AC and DC drives, water pumps, cooling fans, and other nonlinear loads. Power interruptions (outages), three-phase short circuit faults, an unbalanced level between each phase, a poor power factor, etc. are all symptoms of power quality concerns in the Wama sugar factory.

When the voltage on at least one phase briefly falls below the prescribed tolerance, it is called a voltage sag condition (Kumar, 2022). The causes of voltage sags are associated with faults within the power distribution system. Due to the power outage and voltage sag, Wama Sugar Factory lost 1,755,000 and 1,200,000 ETB per year, respectively (source. Wama Sugar Factory, 2021).

Several technologies are currently available to give ride-through capability to important loads under voltage sag events. A DVR developed in the early 1990s, with its excellent dynamic capabilities, can compensate for voltage sag and restore line voltage to its nominal value (standard voltage) (Afonso et al., 2021).

Therefore, the overall goal of this study is to investigate the power quality issues that exist in the Wama sugar factory's power distribution system and come up with solutions if the problem or disturbance levels exceed the suggested IEEE standard 1159-2019.

Specifically, the study focused on the following objectives.

1. *To assess power quality problems in the Wama sugar factory power distribution system.*
2. *To assess the sources and effects of power quality problems in the Wama sugar factory power distribution system.*
3. *To design an improvement method for improving the power quality problem, especially for voltage sag.*

The main significance of this study includes.

1. *To maximize the life span of the different types of equipment, increase the efficiency and performance of the industrial motors in the factory.*
2. *To prevent different types of equipment from failure, damage, and burnout.*
3. *It will be used as a reference for researchers, technicians, and those who work in the electrical power distribution area.*

MATERIALS AND METHODS

Study area background

Wama sugar factory is one of the sugar factories in Ethiopia, Oromia regional state, East Wollega Zone, Sibu Sire woreda, Wama Jarso district, which is 283 kilometres from Addis Ababa and 15 kilometres from Sire town. The site map location of the factory is illustrated in Figure 1. Wama Sugar Factory is also known as Wama Raj Agro Industry.

Figure 1. *Location of Wama sugar factory site*

The 33 KV Billo feeder line supplies power to the Wama sugar factory's distribution system from the Bako substation. The Wama sugar factory's power distribution system is depicted in Figure 2, which is a simplified diagram. It reduces voltages from 33 KV to 0.4 KV using two service transformers, one with a capacity of 1250 KVA and the other of 800 KVA. The factory also has two diesel generators, which are used as emergency power supplies for some critical loads such as cooling towers, water pumps,lighting, workshops, and offices, with capacities of 250 KVA, and 500 KVA, respectively.

In addition, the factory is also supplied by one steam turbine generator (STG) with a capacity of 3.5 MW.his study is mainly focused on the factory loads that are supplied from the two distribution transformers.

RESULTS AND DISCUSSION

The power distribution panels mainly consist of variable speed drives, AC and DC drives, squirrel cages, and wound rotor type motors that drive the various drives such as cane unloading equipment, belt conveyors, band cane carriers, auxiliary cane carriers, inclined cane carriers, anvil cane carriers, horizontal cane handling, cane preparation, milling, raw juice cry, cooling tower pumps, cooling tower fans, centrifugal machines, crystallizers and agitators, elevators, and air compressors. As seen in Figure 2, Wama Sugar Factory's electrical power is distributed among three Central Main Distribution Boards (CMDBs) and five Main Distribution Boards (MDBs).

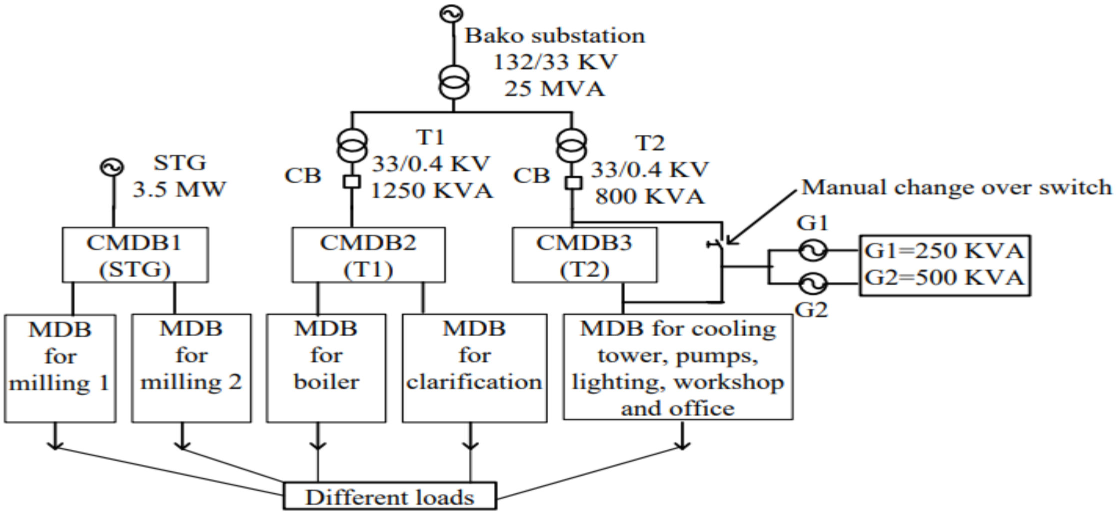

Figure 2. *Single line diagram of Wama sugar factory power distribution systems*

Power Quality Analysis

Voltage Sag

According to Afonso et al. (2021) (Figure 3), a voltage sag occurs when the root mean square (RMS) voltage or current drops by 0.1 to 0.9 units per unit in an electric power distribution system. Some factors that might cause electronic equipment to become damaged or temporarily lose power include system failures, energizing high loads, and starting motors that consume a lot of current (Mustafa et al., 2023).

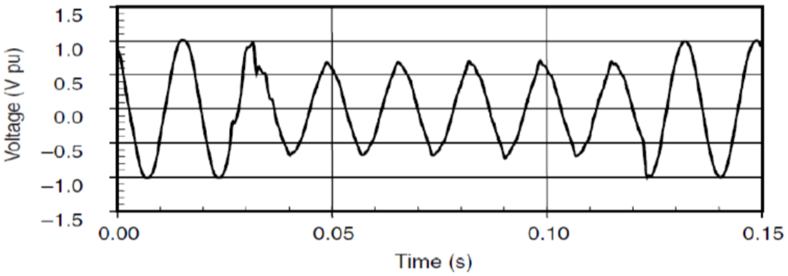

Figure 3. *Typical voltage sag wave form (Afonso et al., 2021)*

Tables 1 and 2 illustrate the voltage sag observed on phase-to-neutral and phase-to-phase lines at different periods of time throughout the measurement process. The primary source of this problem is a three-phase short circuit fault in the Wama sugar factory's power distribution system. A Fluke 435 power quality analyzer is used to measure the voltage sag from the central main distribution board of the factory.

Table 1

Long duration voltage variation (phase to neutral line)

Time & date	Type of problems	Voltage levels			Duration
		$L_1(V)$	$L_2(V)$	$L_3(V)$	
05.20.35 16/08/21	Voltage Sag	221.50	232.10	220.27	105ms
All day 17/08/21	Normal	Normal	Normal	Normal	All day
07.38.18 18/08/21	Sustained Interruption	0	0	0	25min
03.12.50 19/08/21	Voltage Sag	205.30	206.58	207.01	15ms
8.39.45 20/08/21	Voltage Sag	206.00	209.55	205.50	50ms
11.19.40 21/08/21	Sustained Interruption	0	0	0	10min

Table 2

Long duration voltage variation (phase-to-phase line)

Time & date	Type of problems	Voltage levels			Duration
		L_1(V)	$L_2(V)$	$L_3(V)$	
04.15.21 23/08/21	Voltage Sag	358.00	360.50	355.80	30ms
11.01.39 24/08/21	Voltage Sag	355.25	359.05	354.62	98ms
All day 25/08/21	Normal	Normal	Normal	Normal	All day
08.45.36 26/08/21	Sustained Interruption	0	0	0	40min
10.15.53 27/08/21	Voltage Sag	352.45	360.00	354.50	152ms
12.12.05 28/08/21	Sustained Interruption	0	0	0	20min

Imbalance in Voltage

Afonso et al. (2021) states that voltage imbalance can be stated as a percentage, which is the highest deviation from the average of the three-phase voltages or currents divided by the average of the three-phase voltages or currents. Unbalanced voltages occur when three-phase circuits are used with single-phase loads. Possible cause: a three-phase capacitor bank with blown fuses in one phase (Abas et al., 2020). To determine the percentage of voltage unbalance, Table 3 shows the measured values of the factory's highest voltage unbalance.

Table 3

Factory maximum voltage imbalance measurement result

Voltage		Measured voltage (V)
Phase to neutral	V_1	221.65
	V_2	232.10
	V_3	220.27
Phase to phase	V_{12}	385.40
	V_{13}	392.62
	V_{23}	372.00

The National Electrical Manufacturers Association of USA defines standard voltage imbalance as the largest deviation from the average of the three-phase voltages or currents divided by the average of the three-phase voltages or currents, expressed as a percentage (Sabin et al., 2022). This is derived from equation 1.First calculate average value for phase-to-phase voltages,

$$V_{av} = \frac{V_{12} + V_{13} + V_{23}}{3} \qquad (1)$$

$$V_{av} = \frac{385.40V + 392.62V + 372.00V}{3}$$

$$= \frac{1150.02V}{3} = 383.34V$$

Second calculate maximum deviation from the mean

$$V_{12} - V_{av} = 385.40V - 383.34V = 2.06V$$
$$V_{13} - V_{av} = 392.62V - 383.34V = 9.28V$$
$$V_{23} - V_{av} = 372.00V - 383.34V = -11.34V$$

From the above, deviation $V_{13} - V_{av} = 9.28V$ is the largest deviation.

% of Voltage unbalance

$$= \frac{\text{largest deviation}}{V_{av}} * 100$$

$$= \frac{-11.34V}{383.34V} * 100 = -2.96\%$$

Similarly, the percentage of voltage unbalance is calculated from phase to neutral voltage is 3.30%. The percentage of voltage unbalance as can be observed from the result is higher than the 2% of allowable limit set by IEEE standard 1159-2019 (Sabin et al., 2022).

Voltage Sag Improvement by DVR

Voltage sag is a frequent power quality problem in the Wama sugar factory power distribution system that requires the use of an appropriate improvement method. The most effective and popular custom power device to address voltage sag is the DVR (Abas et al., 2020).

A DVR consists of a solid-state power electronic switching device termed as injection transformer, an energy storage device, a DC-to-AC inverter, and a harmonics filter to restore voltage to essential loads (Abas et al., 2020). A DVR control system is used to maintain output voltage to the load when voltage sag happens in the distribution network (Rathi & Sushir, 2021).

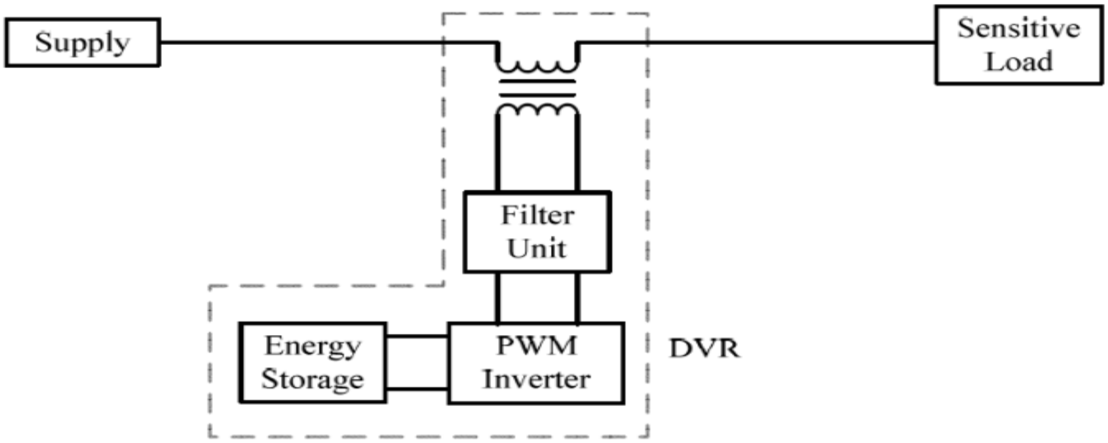

Figure 4. *Components of DVR (Rathi & Sushir, 2021)*

DVR Control Methods

To maintain the load voltage magnitude under any condition, the control mechanism implemented for the DVR to make load voltage magnitude balanced and constant (Figure 4). When there is a failure, a controller is needed to operate or regulate the DVR (Venkatesh & Kumar, 2023).

DQ Park's Transformation

In this paper, a DQ park transformation controller is used to transform the sinusoidal wave pattern of the three-phase load voltage into two phase DC signals. This was done in an effort to simplify or improve the understanding of the computations for the three-phase sinusoidal elements (Zaidi, 2019). As a result, procedures and analysis can be completed more quickly before the three-phase voltage (ABC) is transformed inversely to produce the sinusoidal alternating current (AC) outputs that represent the three-phase voltage in its true state as shown in Figure 5 (Abdullah Al-Karakchi et al., 2023). Equation 2 provides the DQ park transformation as a single matrix.

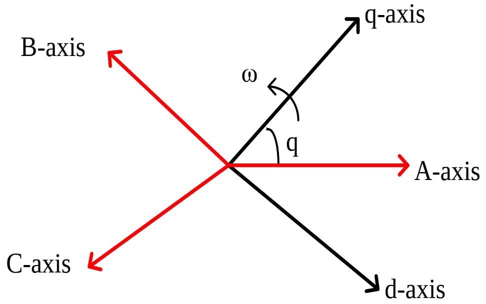

Figure 5. *DQ Park transformation axis phasor diagram*

$$K_{park} = \begin{bmatrix} \cos\omega t & \sin(\omega t) & 0 \\ -\sin\omega t & -\cos(\omega t) & 0 \\ 0 & 0 & 1 \end{bmatrix} \qquad (2)$$

Where ωt is equal to θ is the angle between the rotating and fixed coordinate system at each time.

$$\theta = \cos^{-1}(\sqrt{\frac{2}{3}}) \qquad (3)$$

Three-phase time domain signals are space vector transformed using the dq transform abc to dq rotational coordinate system (Abdullah Al-Karakchi et al., 2023).

The transform applied to time domain voltages in the natural frame of $V_a, V_b, \text{and } V_c$ is given by equation 4. -

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\omega t & \cos(\omega t - \frac{2\pi}{3} & \cos(\omega t + \frac{2\pi}{3} \\ \sin\omega t & \sin(\omega t - \frac{2\pi}{3} & \sin(\omega t + \frac{2\pi}{3} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} V_d \\ V_q \end{bmatrix} \quad (4)$$

The DQ inverse park transformation is given by.-

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} \cos\omega t & \sin\omega t & 1 \\ \cos(\omega t - \frac{2\pi}{3}) & \sin(\omega t - \frac{2\pi}{3} & 1 \\ \cos(\omega t + \frac{2\pi}{3}) & \sin(\omega t + \frac{2\pi}{3} & 1 \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (5)$$

Where, $V_a, V_b, \text{and } V_c$ are three phase AC quantities and $V_d \text{ and } V_q$ are direct current signals. The $V_d \text{ and } V_q$ are two phase quadrature voltage along the stationary frame (Abdullah Al-Karakchi et al., 2023). When rotating the dq0 frame directed at right angles behind the A axis, the following links are also made using equation 6.

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \sin\omega t & \sin(\omega t - \frac{2\pi}{3}) & \sin(\omega t + \frac{2\pi}{3}) \\ \cos\omega t & \cos(\omega t - \frac{2\pi}{3}) & \cos(\omega t + \frac{2\pi}{3} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} V_d \\ V_q \end{bmatrix} (6)$$

The inverse rotating the dq frame when aligned at right angles behind A axis is given by equation 7. -

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} \sin\omega t & \cos\omega t & 1 \\ \sin(\omega t - \frac{2\pi}{3} & \cos(\omega t - \frac{2\pi}{3}) & 1 \\ \sin(\omega t + \frac{2\pi}{3}) & \cos(\omega t + \frac{2\pi}{3}) & 1 \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} (7)$$

Proportional and Integral Controller

The linear feedback controller system, known as the PI control system, is used in this study (Figure 6). The goal of PI is to estimate error values from the measured values and to maintain a constant voltage magnitude at a sensitive load point under system disturbance (Habib et al., 2020).

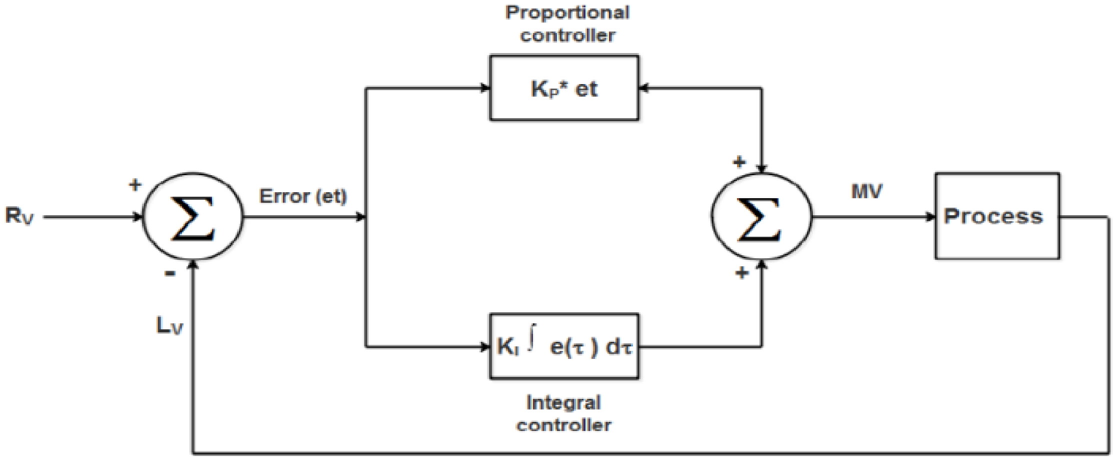

Figure 6. *PI controller closed loop block diagram*

Mathematically, PI controller is given by equation 8, 9, and 10 as follows. -

$$U = K_p e + K_i \int e d\tau \tag{8}$$

$$U = K_p e + \frac{1}{\tau_N} \int e d\tau \tag{9}$$

$$U = K_p (e + \frac{1}{\tau_N} \int e d\tau d) \tag{10}$$

Where. -

K_p is the proportional gain factor, K_i is the integration gain factor, τ_N is the reset time and the error (e) given is given by equation 11.

$$e(t) = R_v - I_v \tag{11}$$

Where. -

R_v is the reference voltage and I_v is the load voltage, $e(t)$ is the error.

The PI is modeled without difficulty in MATLAB/Simulink with Laplace operators can be described as follows.-

$$C = \frac{G(1 + \tau s)}{\tau s} \tag{12}$$

Where. -

$G = K_p$ is the proportional gain factor, and $\frac{G}{\tau s} = K_i$ is the integral gain factor.

Phase Locked Loop Controller

In order to create an output signal that is identical in frequency and phase to the input signal, a PLL controller is employed (Habib et al., 2020). Equations 13, 14, and 15 provide the modulated three-phase voltages, which are used for sinusoidal voltage control using angle or delta phase modulation with PLL (Habib et al., 2020).

$$V_a = \sin(\omega t + \delta) \tag{13}$$

$$V_b = \sin\left(\omega t + \delta - \frac{2\pi}{3}\right) \tag{14}$$

$$V_c = \sin\left(\omega t + \delta + \frac{2\pi}{3}\right) \tag{15}$$

The interrelationship between frequency and phase of phase locked loop controller is given by equation 16 and 17.

$$\omega(t) = \frac{d\varphi}{dt} \tag{16}$$

$$\varphi(t) = \varphi(0) + \int_0^t \omega(t')d \tag{17}$$

MATLAB / SIMULINK MODELS

A. Proposed System without DVR

Figure 7 depicts the simulated proposed system in the power distribution system without the DVR.

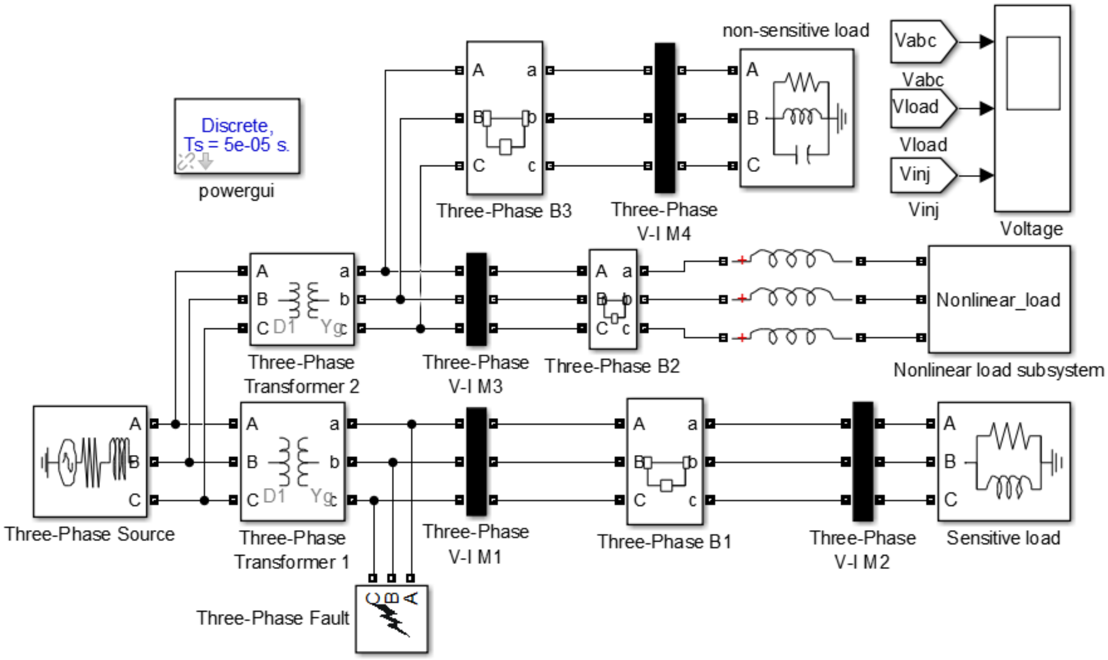

Figure 7. *Proposed system without DVR*

B. Proposed System with DVR

Here DVR is connected to the power distribution system in order to improve voltage sag by injecting the missed voltage to the load voltage (Figure 8-10).

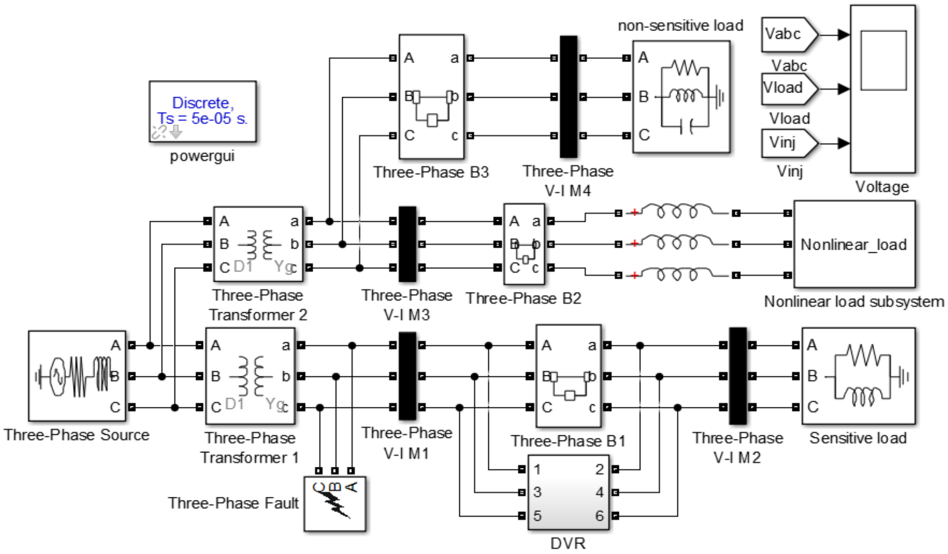

Figure 8. *Proposed system with DVR*

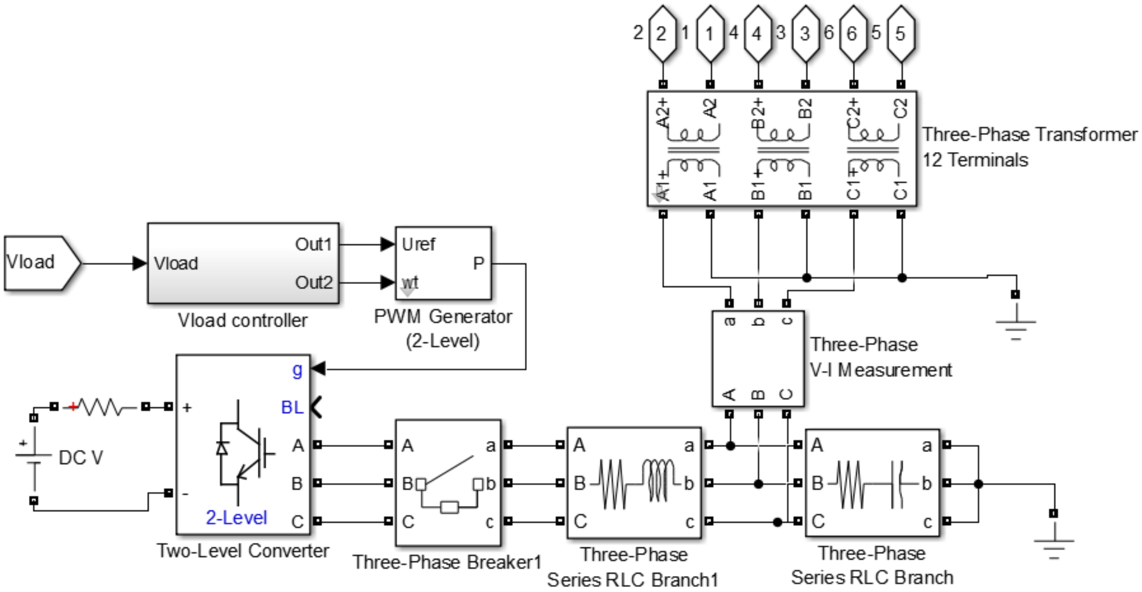

Figure 9. *DVR subsystem*

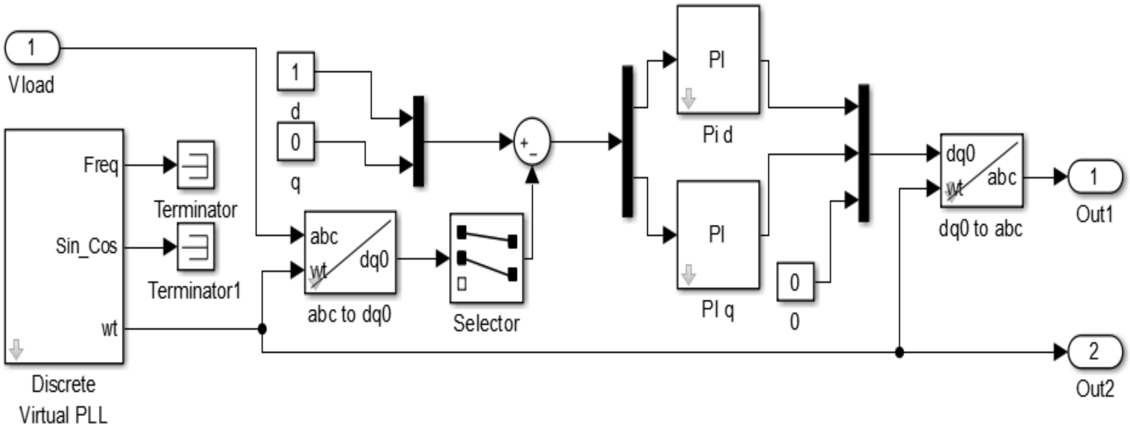

Figure 10. *DVR controller part*

Case 1. Three-phase to ground fault

A three-phase to ground fault in the distribution system is the main source of voltage sag. The source voltages of bus 1, bus 2, and bus 3 are all reduced from their nominal voltage for duration of 0.1 to 0.168 seconds when three phases are applied to a ground fault (Figure 11-13).

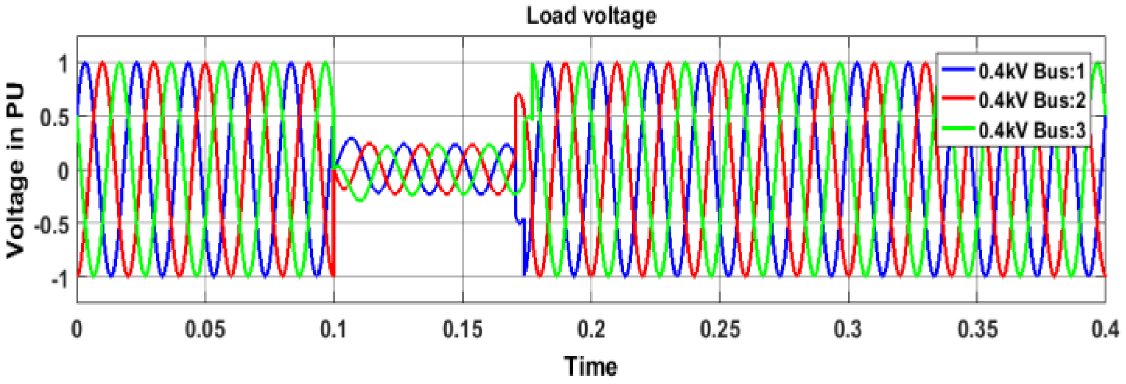

Figure 11. *Instantaneous voltage sag without DVR*

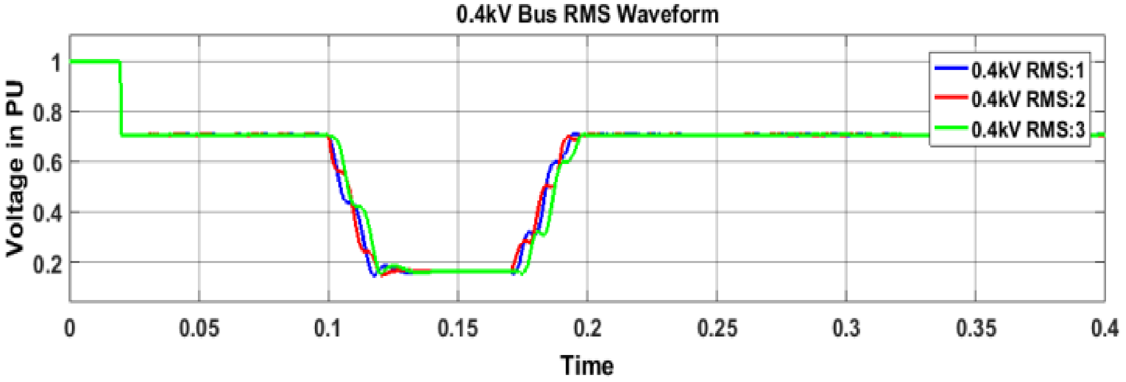

Figure 12. *RMS value of voltage sag without DVR*

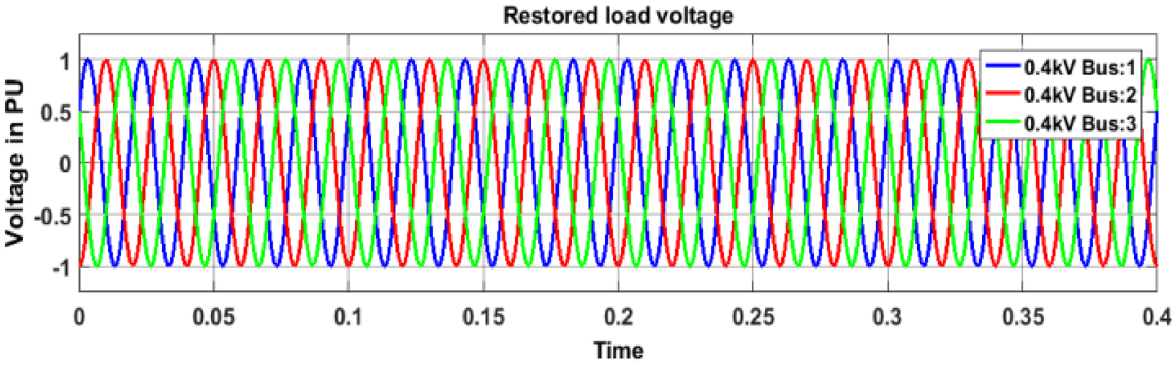

Figure 13. *Restored voltage sag by DVR*

Case 2. Double line to ground fault

In a power distribution system, a double-line to-ground fault can also generate voltage sag. Buses 1 and 3 experience a double line to ground fault, which results in a voltage decrease from its nominal value between the periods of 0.1 and 0.16 seconds, while bus 2 is unaffected (Figure 14-16).

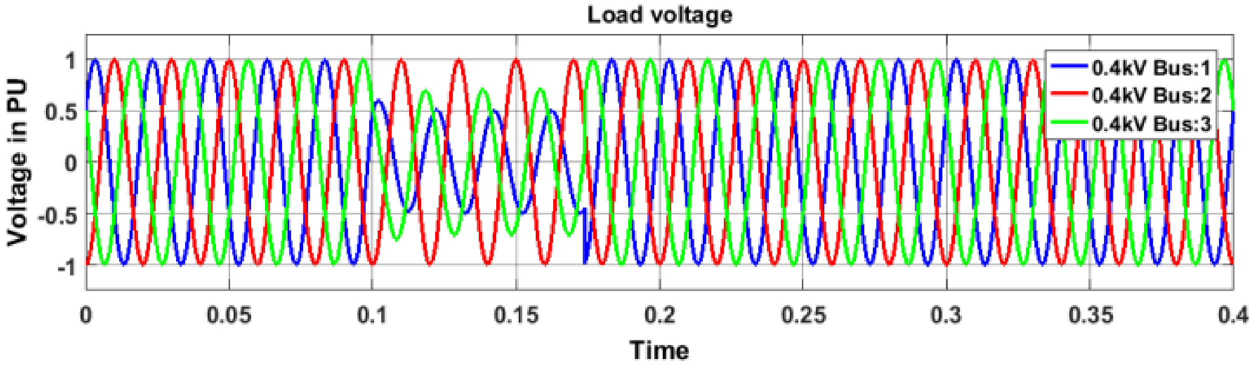

Figure 14. *Instantaneous voltage sag without DVR*

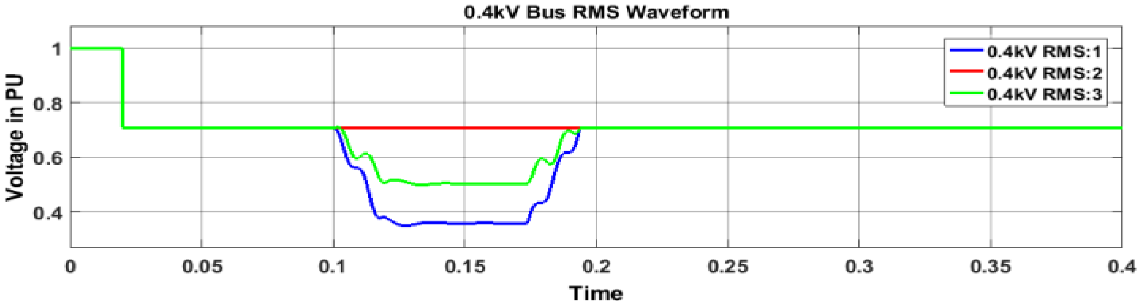

Figure 15. *RMS value of voltage sag without DVR*

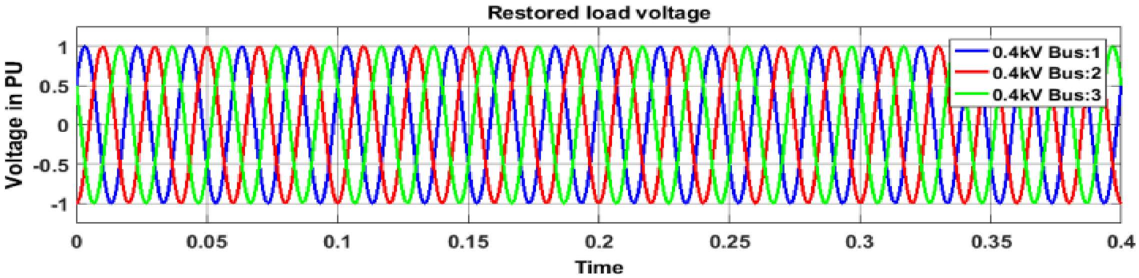

Figure 16. *Restored voltage sag by DVR*

The normal waveform of the load voltage after the insertion of DVR is shown in Figure 16 and the waveform shape of load voltages is perfectly restored to its nominal voltage (1.0pu) by using DVR (Table 4).

Case 3. Multi-stage Voltage Sag

When different voltage sag level is generated from all phases to the load voltage level, the simulation result is as in Figures 17, 18, 19, and 20. The multi-voltage sag at different voltage sag levels in the power distribution system occurs on phases/ buses 1, 2, and 3 resulting in a voltage decrease from its nominal value during the period 0.1s - 0.31s for a duration of 0.21s.

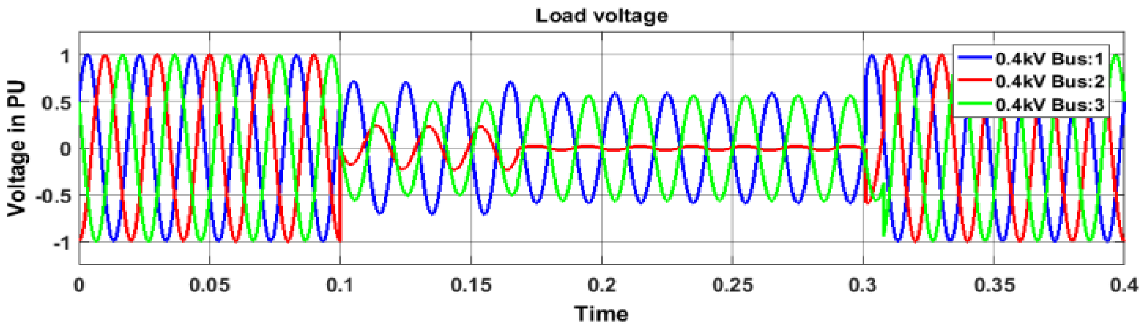

Figure 17. *Instantaneous voltage sag without DVR*

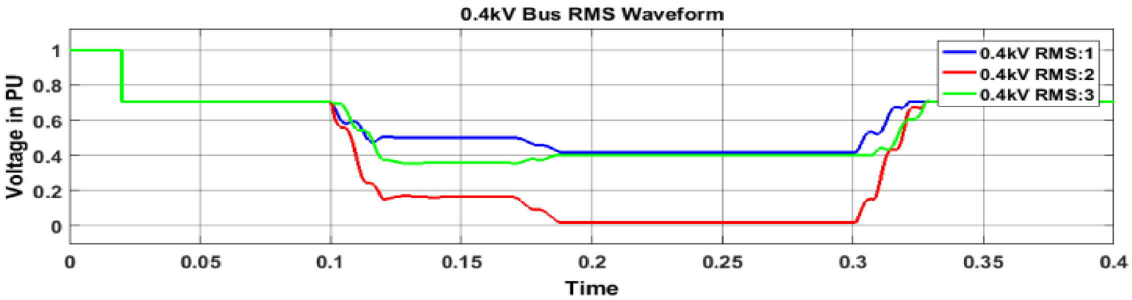

Figure 18. *RMS value of voltage sag without DVR*

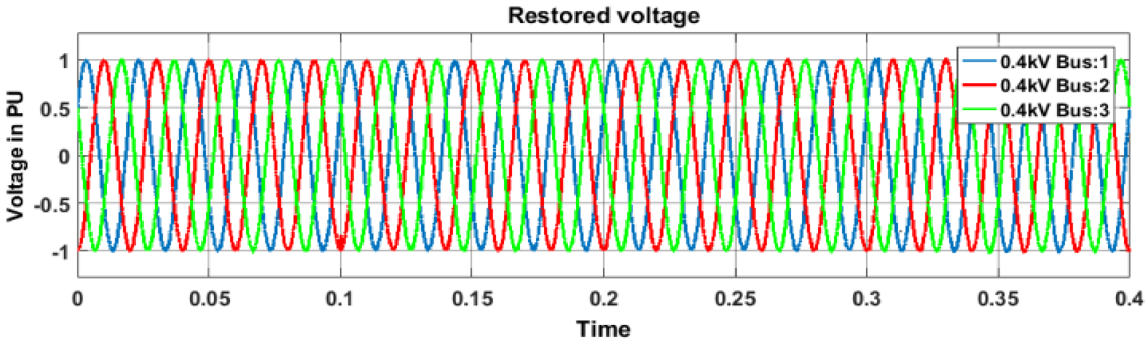

Figure 19. *Restored voltage sag by DVR*

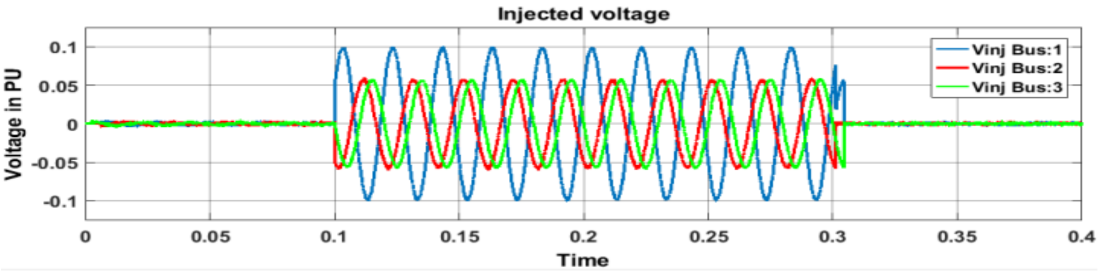

Figure 20. *Injected voltage by DVR*

Table 4

Summary of simulated different fault cases

Fault cases	Phases	Without DVR (load voltage in pu)	With DVR (load voltage in pu)
Three phase faults case 1	Bus 1	0.27	0.98 ≅ 1.0
	Bus 2	0.28	0.99 ≅ 1.0
	Bus 3	0.28	0.99 ≅ 1.0
Double line fault case 2	Bus 1	0.49	0.97 ≅ 1.0
	Bus 2	0.99	0.99 ≅ 1.0
	Bus 3	0.53	0.95 ≅ 1.0
Multi-stage sag case 3	Bus 1	0.58	0.97 ≅ 1.0
	Bus 2	0.47	0.99 ≅ 1.0
	Bus 3	0.25	0.96 ≅ 1.0

CONCLUSIONS

This paper presented the power quality problems such as voltage sag and its improvement method using DVR which is controlled by PI, DQ park’s transformation, and the PLL controller at the Wama sugar factory power distribution system. DVR improved different fault conditions like single line to ground fault, double line to ground fault, and three phase fault without any difficulties and injected the appropriate voltage to correct any fault situation that occurred in the supply voltage to keep the load voltage balanced and constant at the nominal value simulated using MATLAB / SIMULINK software. Therefore, DVR has the ability to inject the missing load voltage when voltage sag occurs in the power distribution system to the load voltage.

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DECLARATION

The authors declare that they have no conflicts of interest.

DATA AVAILABILITY STATEMENT

All data are available from the corresponding author upon request.

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