INTELLIGENT CONTROLLER-BASED DYNAMIC VOLTAGE RESTORER TO REDUCE THE VOLTAGE FLUCTUATIONS

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In today's power system research, improving power quality is a crucial issue. Due to the advent of numerous industrial equipment and sensitive loads, it has become increasingly vital. Distribution-side voltage sags and swells are the leading causes of power quality issues. Five-level multilevel inverters are too expensive for average-voltage applications and high-power applications due to higher voltage stress on switches, large dv/dt, and the need for extensive filtering. The proposed seven-level multilevel inverter-based dynamic voltage restorer (DVR) is a superior solution to these issues because it can be directly connected to the medium-voltage distribution system without an injection transformer. There are numerous ways to reduce voltage sags and swells, but the planned DVR is one of the most widely used techniques. As a series compensating device, the DVR is primarily used in applications involving low- and medium-voltage systems and employs a fuzzy logic controller (FLC)- based Proportional and Integral (PI) controller to compensate for voltage sags during a three-phase fault. Using simulation results from a fresh DVR setup available in MATLAB/Simulink, the effectiveness and performance of the proposed model are confirmed.

1. INTRODUCTION

Variations in voltage can affect sensitive loads, including computers, electrical devices, and automated systems. Several things can cause fluctuations in voltage. The voltage variations fall into two categories: short-term and long-term. With the right tools, it is possible to make up for the short-term events. The most frequent instances of these events are voltage sags, voltage swells, and brief disruptions. Voltage sag is the most frequent and economically detrimental event in many distribution power networks. This concept is implemented in inverter systems with two- and three-level structures [1]. Thus, it is crucial to investigate appropriate methods for compensating for voltage sags. There are numerous options for compensating for voltage disruptions. Because of their versatility and quick reaction, power electronic-based systems are the best options. The most practical, economical, fast-responding, low THD, and compensatory method for both voltage sags and swells is dynamic voltage restorers (DVRs) [2]. A three-level inverter and a fuzzy logic controller are used in this paper, primarily with a high THD content of 20.39% [3]. The three-level multilevel inverter and bus-clamped PWM technique are employed in this work. The harmonic analysis of the stator voltage (36.06%) and current (1.58%) has further demonstrated the utility of the suggested method [4].

The DVR is a voltage-source inverter (VSI) connected in series. Typically, an injection transformer is used to add the compensating voltage it produces to the grid voltage. In this manner, the sensitive load's voltage remains essentially constant, ensuring the load operates safely. There are numerous DVR circuit topologies to choose from. Together with the adaptive neuro-fuzzy inference system (ANFIS) controller, which has been shown to correct for both balanced and unbalanced PQ difficulties, an enhanced synchronous reference frame (SRF) Theory control algorithm [5] is suggested in the controller section. As the primary component of the DVR, the VSI may have several circuit topologies. In the DVR, the traditional two-level or otherwise multilevel VSIs must be used. The most basic type of inverter is typically used in the DVR construction when discussing control techniques or dynamic analysis. As an alternative, some publications have addressed the use of multilevel inverters within the DVR framework. In [6], a voltage-sag compensator based on a CHB multilevel inverter managed by a fundamental-frequency control approach is introduced. As a result, for some operating points, the output voltage quality is unacceptable due to its stepped nature. It has been investigated to apply a forced CHB multilevel inverter with pulse width modulation (PWM) to the DVR [7]. Both symmetric and asymmetric topologies have been considered in this work. Each H-bridge in the CHB multilevel inverters requires its own independent dc voltage supply. The DVR's use of the transformer-connected CHB multilayer inverter, which requires a single DC voltage source, is examined in Reference [8]. The design, simulation, and control of LCC DVR for a range of voltage instability circumstances are thoroughly described in this work. The primary innovation in this case is the straightforward control logic proposed for the DVR to correct for voltage fluctuations. The primary focus is on tests of the controller's performance under various voltage variation scenarios. The THD value is higher because a large inductor was employed [9].

We suggest combining the two approaches by employing a four-level multicell inverter and a smaller switching table than the traditional one. This solution significantly reduced the ripples (50.51%) [10]. This article demonstrates how DVRs work. The design and modelling of the bidirectional buck-boost dc-dc converter were performed to integrate unforced capacity (UCAP) as a DC input to the DVR. Analysis based on THD is not included in this work [11]. The DVR's capacity to provide active power and its maximum voltage-injection magnitude are the main factors influencing its alleviation ability. Typically, DVRs [12] use battery energy storage as an input to supply active power, but batteries remain expensive and bulky. Several multilevel inverters, including the flying-point-capacitor multilevel inverter and the neutral-point-clamped (NPC) multilevel inverter [13], have been employed in the DVR structure, along with CHB topologies. This research focuses on the nonlinear management of a 5L-filled U-Cell (PUC5) inverter used in a grid-on PV system. Based on the Lyapunov control method, this work introduced a sensor-less modulation method for grid-connected PUC5 inverters. The proposed control method maintained the capacitor voltage at appropriate levels under transient, steady-state, and challenging nonlinear load conditions, while achieving

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the system's asymptotic stability and effective grid current tracking [14]. In this study, a three-phase, three-level inverter is controlled via randomised carrier discontinuous pulse width modulation (RCDPWM). The output voltage of the suggested method has a significant harmonic content (42%) [15]. Moreover, the DVR structure has employed additional non-traditional multilevel inverter topologies [16]. The most common power electronic converters in the DVR architecture are VSIs. But lately, different circuit designs for DVRs that employ ac-ac converters rather than VSIs have been proposed [5,17–19]. Consequently, in these topologies, the energy storage components are removed, potentially leading to a smaller overall DVR. They might not perform well during prolonged voltage sags, though, because they lack energy storage components.

Additionally, a compensator based on a 3-phase, 9-switch converter was introduced in [20]. Furthermore, [21] discusses the use of the DVR to provide a fault ride-through of the spread power capital. By injecting the appropriate voltage component, the DVR can correct any issues with the voltage supply and maintain the load voltage within the ideal range. The THD was reduced to about 4% while the voltage profile correction remained constant. For example, the voltage profile for scenario 1 showed THD of 2.69%, 2.40%, and 2.69% with the DVR case, while scenario 2 showed THD of 3.74%, 4.04%, and 3.60% [22].

The control system's primary goal is to correct for the disturbance as soon as possible by employing a good PWM switching approach, optimal management variables for the organized circuit, and a fast detection mechanism. A variety of DVR topologies, as well as numerous compensation and control strategies, have been projected in the invented story and examined in this chapter [23]. This research compares the performance of a DVR using the suggested algorithm with a standard control method based on Synchronous Reference Frames (SRFs). Using MATLAB software, the performance is examined and verified using simulation results under various voltage sag and swell situations. It is challenging to adopt this traditional way [24]. This research proposes a novel 21-level asymmetrical fault-tolerant inverter structure. The suggested configuration comprises ten unidirectional switches and three asymmetric DC voltage sources. The key figures are THD (3.88%) [25].

The DVR construction has used a variety of multilayer inverter types to produce the necessary compensating voltage, in line with the literature review previously presented. The multilevel inverter's output voltage fluctuates with the voltage sag depth, which is the primary problem when using a multilevel inverter-based DVR. The productivity voltage magnitude must obviously be high for deep voltage sags and low for short voltage sags. This means that the amount of productivity voltage stage depends on the depth of the voltage sag if the DC-link voltage is held constant. There should be fewer voltage levels for minor voltage sags. That is, until there is a narrow band of profound voltage sags, a multilevel inverter produces the output voltage with the maximum number of levels. As a result, when there are lower-voltage sags, the multilayer inverter will be used appropriately. As a result, the multilevel inverters used during DVR construction are highly effective, particularly for shallow voltage sags. The primary goals of this study are to reduce overall harmonic distortion and to quickly mitigate voltage sag and swell.

- To use DVR to support reactive power in the three-phase transmission system quickly and effectively.
- To create a three-phase, seven-level DVR module based on an inverter-based voltage supply.
- To use an FLC-based PI controller to keep the load's voltage constant.

2. MATERIALS AND METHODOLOGY

To compensate for reactive power, this article proposes a three-phase, seven-level voltage-source inverter-based DVR shown in Fig. 1.
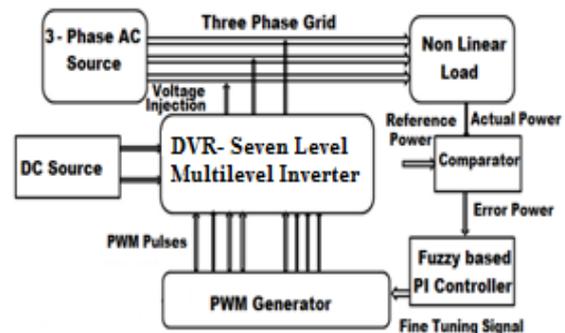

Fig. 1 – Proposed system block diagram.

To compensate for the distribution system's three-phase voltage profile and address voltage sags, an FLC-based PI controller is employed. Error power can be sent to an FLC controller based on a PI controller, after the grid power is compared to the reference power. Following the comparison, the error power is adjusted using truth table operations (see Tables 1 and 2). It is possible to identify the incorrect power using a fuzzy PI controller. The PWM generator generates the firing pulses based on the fuzzy PI controller's output. The DVR contains a ready-to-use DC-to-AC converter that compensates for the grid system's voltage sag. A cascade H-bridge (CHB) inverter is constructed by cascading many H-bridges that receive their power from separate DC sources. Multiple H-bridges connected in series provide different AC voltage levels. An existing 5-level CHB MLI is constructed via a sequence of connections between two H-Bridges, as seen in Fig. 2. Five levels of AC output are produced by this inverter: +2 Vo, +1 Vo, 0 Vo, -1 Vo, and -2 Vo. Similarly, to construct a seven-level proposed system, as shown in Fig. 3, three H-bridge modules must be connected in series. The AC output of this inverter has seven levels: +3 Vo, +2 Vo, +1 Vo, 0Vo, −1 Vo, −2 Vo, and −3 Vo. A cascaded inverter with H bridges for each phase can have a maximum of 2H+1 levels, which is always an odd number. Fig. 4 illustrates how the H-bridge productivity voltages are identical as well as exiled through a phase angle of 360/(N-1), as soon as using the phase-shifted modulation method. The switching function of the seven-level multilevel inverter is displayed in Tab. 1

2.1 MULTI-LEVEL INVERTER

Equations (1) and (2) are used to establish the lower and upper limits of the voltage levels; Equations (3) and (4) are used to determine the number of solid-state switches and capacitors, among other components.

$$\text{Vmin} = -\text{Vs}\frac{(n-1)}{2}, \qquad (1)$$
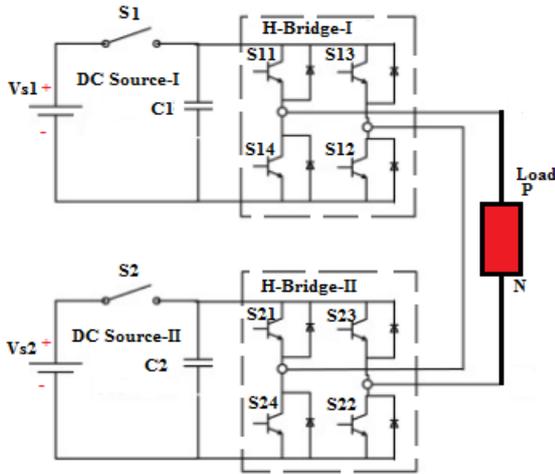
$$Vmax = Vs \frac{(n-1)}{2}. \qquad (2)$$
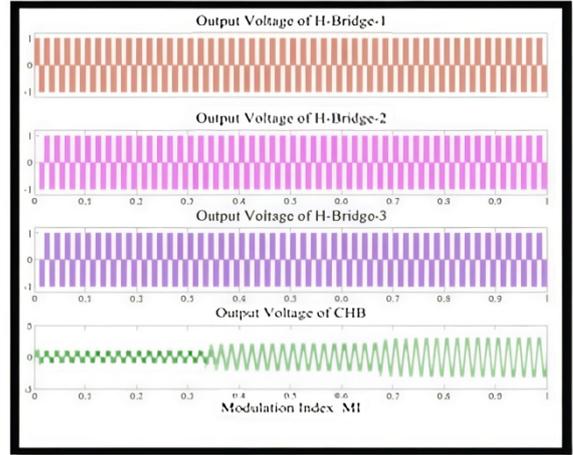

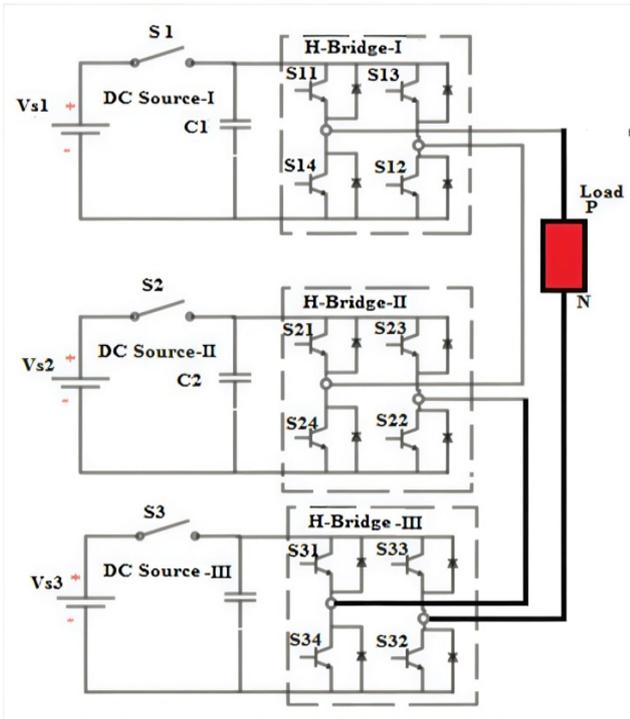Fig. 2 – Basic five-level multilevel inverter.

Fig. 3 – Proposed seven-level multilevel inverter.

$$NQ = (2n - 1), \qquad (3)$$

$$NC = \frac{(n-1)}{2}. \qquad (4)$$

Table 1

Switching table of the proposed seven-level multilevel inverter
(0 = OFF & 1 = ON)

S. No.	S11	S12	S13	S14	Vo
1	0	0	1	0	3Vo
2	0	1	0	0	2Vo
3	1	0	0	0	1Vo
4	0	0	0	0	0
5	1	0	0	1	-3Vo
6	0	1	0	1	-2Vo
7	0	0	1	1	-1Vo

Fig. 4 – Voltage waveforms of 1, 2, and 3 H-Bridges, along with the entire
voltage through enhancement during modulation index via
fuzzy PI controller-based Phase Shifted PWM

2.2 FUZZY BASED PI CONTROLLER

A seven-level multilevel inverter has less overall harmonic distortion in its output waveform than a five-level inverter. A fault signal, moreover, its derivatives are used as input signals by fuzzy-PI controllers, which are a generalization of the traditional PI controller. Figure 5 shows a fuzzy-PI controller with two inputs (E and EC) and two outputs (ΔKp and ΔKi), which is a typical and legitimate architecture, particularly for self-tuning applications, even though some fuzzy logic controllers (FLCs) employ two inputs and one output. Figures 6 and 7 display the membership error functions (E) and the error change (EC), as well as the gain variations ΔKp and ΔKi. Due to their essentially distinct tasks in a fuzzy control system, the membership functions for fuzzy controller inputs, such as error (E) and change in error (EC), differ from those for the outputs, such as changes in the proportional and integral gains (ΔKp, ΔKi). In the Automatic Voltage Regulator (AVR) control loop, the exciter's voltage response is represented by the exciter gain constant, Ke. Kec stands for the load compensator's gain, an optional function that occasionally appears in the AVR's control loop. It is used to optimize the voltage regulation process. Seven linguistic values NB (negative big), NM (negative medium), NS (negative small), Z (zero), PS (positive small), PM (positive medium), and PB (positive big) are used for the fuzzy reasoning rules in this study. The fuzzy interpretation methods in Tables 2 and 3 are applied to ΔKp and ΔKi, based on a large number of simulation trials.
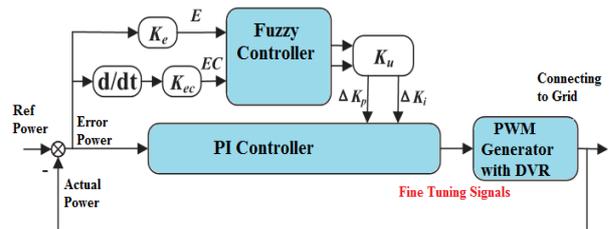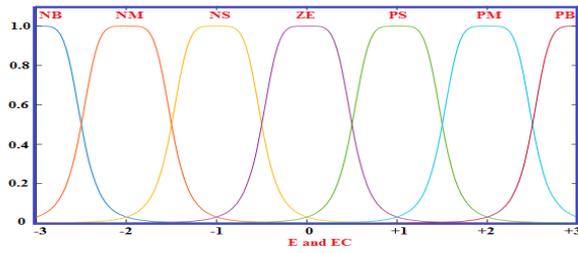

Fig. 5 – Fuzzy PI controller.

Fig. 6 – Membership function E and EC.

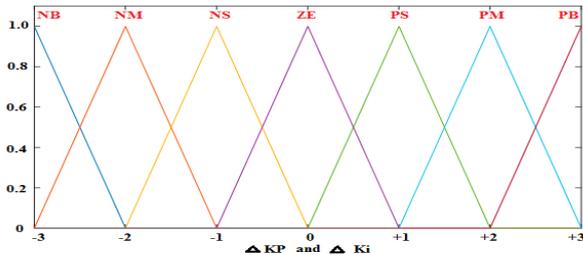Fig. 7 – Membership function ΔKp and ΔKi.

Table 2

Fuzzy interpretation policy for ΔKp.

	EC						
E	NB	NM	NS	Z	PS	PM	PB
NB	PB	PB	PM	PM	PS	Z	Z
NM	PB	PB	PM	PS	PS	Z	NS
NS	PM	PM	PM	PS	Z	NS	NS
Z	PM	PM	PS	Z	NS	NM	NM
PS	PS	PS	Z	NS	NS	NM	NM
PM	PS	Z	NS	NM	NM	NM	NB
PB	Z	Z	NM	NM	NM	NB	NB

Table 3

Fuzzy interpretation policy for ΔKi

	EC						
E	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NM	NM	NS	Z	Z
NM	NB	NB	NM	NS	NS	Z	NS
NS	NB	NM	NS	NS	Z	PS	PS
Z	NM	NM	NS	Z	PS	PM	PM
PS	NM	NS	Z	PS	PS	PM	PB
PM	Z	Z	PS	PS	PM	PB	PB
PB	Z	Z	PS	PM	PM	PB	PB

3. RESULTS AND DISCUSSION

A DVR continuously tracks the source voltage. To maintain a steady load voltage, it injects a compensating voltage in series with the line when it senses a sag (voltage drop) or a swell (voltage rise).

In normal conditions, it guarantees that the load side receives a clear, stable voltage waveform by injecting a precise voltage in time with the grid voltage. The DVR is in standby mode when the system voltage is within its typical range. It uses very little energy and injects no voltage.

If the sag condition occurs, the DVR's fuzzy control mechanism continuously monitors the incoming supply voltage. When it detects a voltage sag or low voltage condition, it quickly calculates the required compensating voltage. Reactive power lagging problem can be present in the source voltage side during the interval 0.2 to 0.4 s, as seen in Fig. 8. The source current increased from 35 A to 48 A (0.2 s to 0.4 s) because of the voltage drop, as seen in Fig. 9. Now, a fuzzy-controlled seven-level multilevel inverter (DVR) is sensitively involved. The grid output voltage is increased from 350 V to 440 V based on the fuzzy output, as seen in Fig. 10. Finally, the grid current is maintained at 35 A, as seen in Fig. 11.

If the swelling condition occurs, the DVR's fuzzy control mechanism continuously monitors the incoming supply voltage. It rapidly determines the necessary compensation voltage when it senses a voltage swell, or an overvoltage condition. During a swelling voltage is increased 440V to 480V period (0.2 to 0.4 s) to maintain the steady load voltage as exposed in Fig. 12. The source current decreased from 35 A to 25 A (0.2 s to 0.4 s) because of the voltage swelling as seen in Fig. 13. The seven-level multilevel inverter (DVR) and energy storage unit are set up to collect excess energy from the grid. The reactive power leading can be changed after the DVR is connected (from 480 V to 440 V), and the grid current ranges from 25 A to 35 A, as shown in Figs. 14 and 15.

A seven-level multilevel inverter (DVR) is fed a 600 V DC from a battery source, as shown in Fig. 16. The 600 V DC is then converted to AC. This inverter (DVR) can be controlled using a fuzzy PI controller. Figures 17 and 18 now display the output voltages of the PI controller and the fuzzy-based PI controller DVR. Here, the proposed system displays a total harmonic distortion of 1.07%, as shown in Fig. 19. Fuzzy-based PI controllers and a seven-level multilevel inverter are used in this approach. The use of a fuzzy-based PI controller enables rapid fine-tuning of the error signal. The impact of the suggested seven-level multilevel inverter and intelligent control method is to maintain power quality and lower THD level compared to the usual method [3,4,10,15,22,25]. Thus, the work concludes by raising the CHB inverter level while simultaneously increasing the output voltage and reducing the THD. The proposed system's power quality can be swiftly maintained, and voltage profiles can be readily compensated for under various voltage fluctuation conditions.
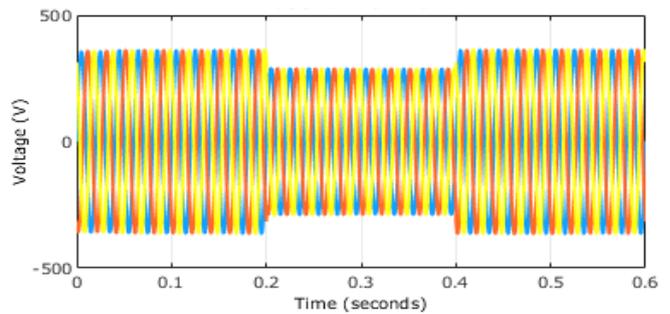

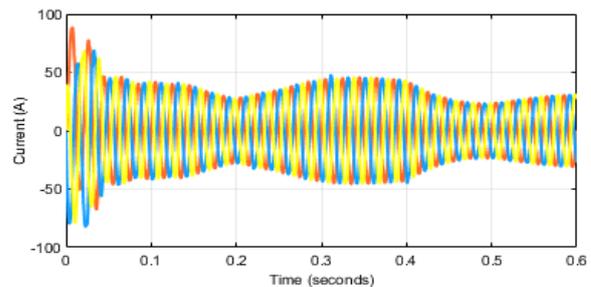Fig. 8 – Sag condition source voltage.
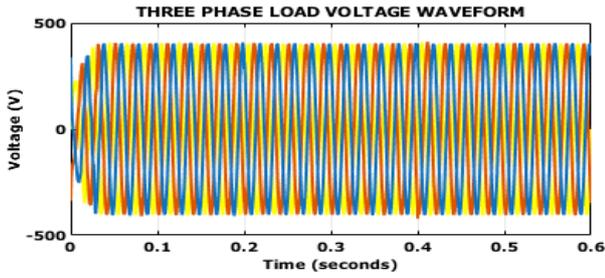

Fig. 9 – The sag condition source current.
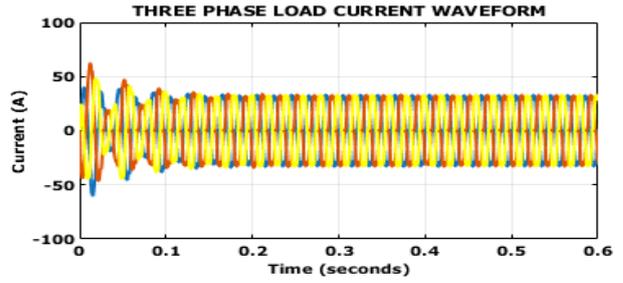
Fig.10 – Output load voltage after DVR compensated (Sag).

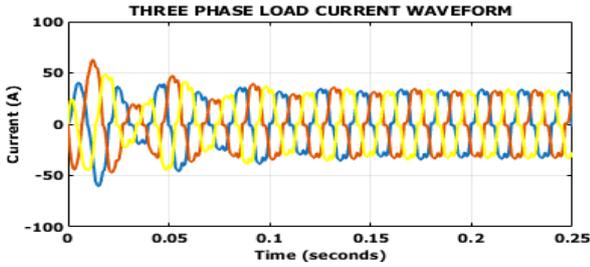
Fig.11 – Output load current after DVR compensation (Sag).

Fig. 12 – If the swelling condition occurs for the source voltage.

Fig. 13 – If the swelling condition for the source current.

Fig. 14 – Output load voltage after DVR compensation (swell).

Fig.15 – Output load current after DVR compensated (swell).
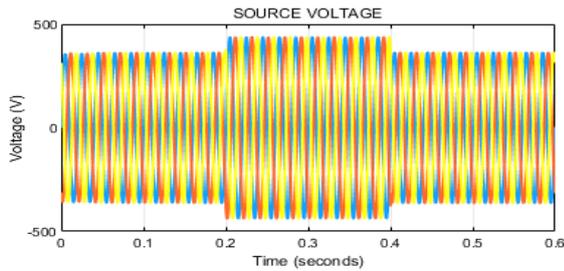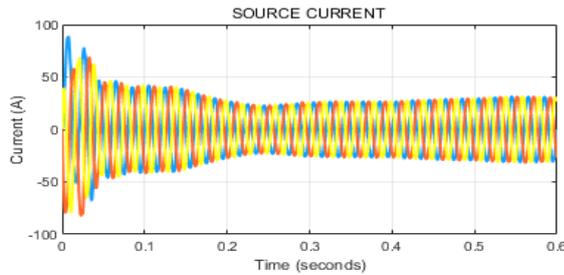

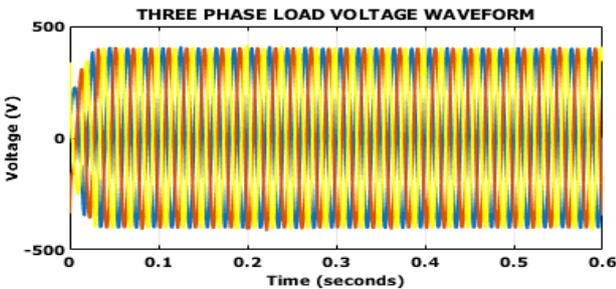Fig. 16- DC input voltage of DVR from battery source.

Fig. 17- PI controller output voltage in DVR.
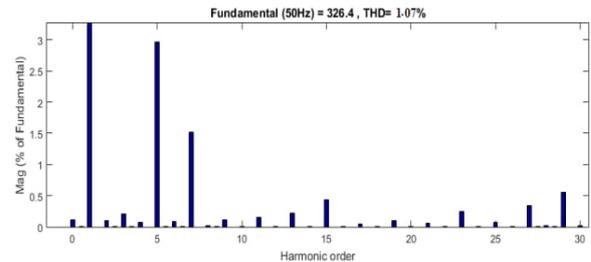

Fig. 18- Output voltage of DVR.

Fig. 19- Represents the harmonic content.

4. CONCLUSION

To effectively compensate for voltage fluctuations, a novel seven-level multilevel three-phase inverter (DVR) is proposed. This research presents a novel DVR structure supported on the energy storage unit and an inverter division. In contrast to a traditional DVR, the proposed DVR eliminates the injection transformer and filter unit. This proposed method uses a seven-level multilevel inverter and fuzzy-based PI controllers.

The use of a fuzzy-based PI controller enables quick fine-tuning of the error signal. Compared to the existing method, our proposed inverter and intelligent control method preserve power quality and reduce THD by 1.07% [3,4,10,15,22,25]. The suggested seven-level multilevel

inverter systems compensate for effective voltage fluctuations. The hardware model is being prepared for feature implementation and to support an increasing number of inverter levels; moreover, various intelligent algorithms will be employed to verify the results.

CREDIT AUTHORSHIP CONTRIBUTION

Author_1: Contributed equally to the current study at every level, from problem formulation to results and resolution.
Author_2: Contributed equally to the current study at every level, from problem formulation to results and resolution.

APPENDIX

Table 4
Simulation parameters

Specifications	Rating
Grid	440 V, 50 Hz
RLC branch	$R = 100\ \Omega$, $L = 1e^{-3}$ H, $C = 18e^{-6}$ F
3-phase source	440 V, 50Hz
3-RLC load	400 V, 50 Hz, P = $5.5e^3$, QL=500, QC=500
DVR input voltage	600 V DC
Inverter	$R = 1e^{-3}\ \Omega$, $Rs = 1e^5\ \Omega$, Cs = infinity

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