Application of DVR based Trinary Hybrid Multilevel Inverter to Improve Power Quality of Sensitive Loads

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ABSTRACT:
In this paper, a new dynamic voltage restorer (DVR) based on a Trinary Hybrid Multilevel Inverter (THMI) is proposed, which is capable of compensating for voltage sag, swell and flickers for sensitive loads. A Trinary Hybrid nine-level inverter is composed of a smaller number of IGBTs and circuitry compared to similar structures. The base structure of this inverter is based on the connection of the H bridges and consists of two inverters of a single-phase bridge with a different DC voltage, each of which has a voltage of HB three times the previous HB. The inverter is also able to produce a number of higher output voltage levels and less harmonic distortion than cascade topologies, floating capacitors and diodes. This feature enables the structure to be used to compensate for the power quality of power distribution networks. Nearest Level Control (NLC) in the inverter is used to create the desired waveform. The In-Phase control method is selected to control the proposed DVR and use the synchronous reference frame (SRF) method to detect the network voltage fluctuations. To verify and validate the proposed DVR performance, simulations are carried out in the MATLAB / SIMULINK software environment, and the results indicate the optimal performance and desirability of the proposed DVR to compensate for the voltage sag, swell and flicker power distribution grids.

KEYWORDS: Trinary Hybrid Multilevel Inverter, Dynamic Voltage Restorer, Voltage Sag, Voltage Swell, Voltage Flicker, NLC Switching.

1. INTRODUCTION

Today, one of the important issues in the electricity industry is the issue of power quality for sensitive loads. Sensitive loads such as computers, programmable logic controllers (PLCs), variable speed drives (VSDs), etc., often require high quality power supplies. Disturbances of the power quality of the various cases are, the shortage and lack of voltage, interruption, phase shift, harmonic, and transient conditions. One of the important issues regarding power quality is Voltage sag, Voltage swell and Voltage flicker. The voltage sag, according to IEEE 1159-1995 standard, reduces the effective value of the voltage from 10% to 90% of the nominal value during 0.5 to 1 minute. A recent power quality study shows that 92% of total turbulence in a power system results from a voltage shortage [1]. Lack of voltage can cause damage to production, loss of production, costs of restarting, and risk of disability. Setting up large induction motors, transformer switching, ground faults and short circuit short circuit leads to a lack of voltage. The voltage swell is defined as an increase in the effective value of the voltage between 1.1p.u to 1.8 p.u at a power frequency and 0.5 cycles to 1 minute. Extracting large Inductive loads from the grids and shielding large capacitor banks is one of the reasons for the voltage swell. According to IEC 61000-4-15, voltage flicker in the frequency spectrum of 1 to 35 Hz can produce a voltage flicker [3]. Among flicker sources of production, electric arc furnaces, melting machines, wind turbines, generators of electricity from the sea wave, the launch of induction motors and frequency converters are named. This phenomenon can cause eye irritation as a human factor, as well as impairment of sensitive electrical equipment such as medical and telecommunication devices as an industrial factor. Due to the use of sensitive equipment in modern industrial designs such as control processes, PLCs, speed drives and robots, other phenomena of voltage and voltage flicker in power distribution networks are not tolerated and methods there are various ways to reduce it. Conventional methods in this field include the use of capacitive banks, the construction of parallel new feeders and the installation of uninterruptible power supplies (UPS), but in recent years, due to the progress of the semiconductor industry, the use of compensation the instruments based on the voltage and current source converters are considered by the experts of the electrical industry. This equipment is called FACTS and it has the capability of fast, real-time, and controllable compensation [2]. The FACTS devices, which are used in power distribution systems to improve power quality, are called custom power devices. A kind of these electronic-powered compensators, used to improve power quality problems, is a Dynamic Voltage Restorer (DVR). This compensator is one of the custom power devices used to compensate and improve power quality problems at the power distribution grids. This compensator is mounted in series, close to the critical loads of the distribution system, and it protects sensitive loads against power quality impairments. The DVR is basically a controlled voltage source that is installed between the power supply and sensitive loads. The DVR can be considered as an external voltage source with controlled range, frequency, and phase, which is connected to the network by a series of injection transducers, in fact, during a voltage fluctuation, a series of DVRs in the power system With voltage injections, can produce the desired voltage for sensitive loads, which is the main function of the DVR. This equipment has the ability to generate or absorb the actual controlled reactive power and the AC output voltage that is connected to the distribution feeder series. In general, the DVR contains the following components [2]:

- Voltage Source Inverter (VSI)
- Energy Storage System (ESS)
- Harmonic filter
- Series Transformer Injection
- Control strategy

Figure 1 shows the schematic diagram of the DVR:

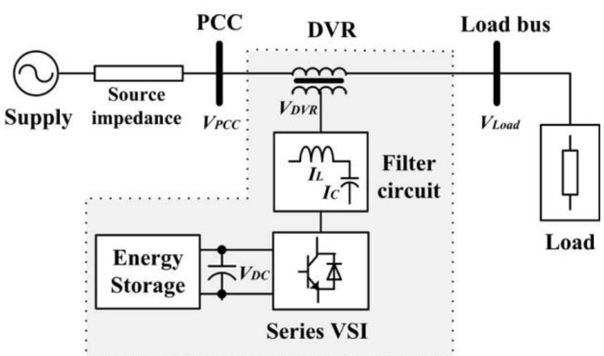

Fig. 1. DVR schematic diagram [3].

Voltage source inverters (VSI) are used with proper output voltage in DVRs. These inverters, which are usually two-level, have major disadvantages, including output voltage with high Total harmonic distortion, relatively high voltage variation and high switching losses [4]. Consequently, large LC filters need to be installed in the inverter output terminal, which greatly increases the cost and volume of the DVR. To overcome this problem, the use of multi-level voltage source inverters is recommended. Multi-level converters based on DVRs are capable of operating at higher voltages and power levels, and also have good harmonic characteristics. This category of inverters is due to the production of low output Total harmonic distortion (THD% low), limited voltage pressure on switching devices, high reliability, reaching high voltage (MV) levels, high voltage and high voltage operation, and The low voltage variation rates have been considered in recent years [5]. In this paper, the Trinity Hybrid Multilevel Inverter (DVR) DVR has been tested and simulated to compensate for the deficiency, deficiency and Flicker voltage in the power distribution network. The proposed multi-level voltage source Inverter (Trinary Hybrid Multilevel Inverter) is described below and the proposed Nearest Level Control (NLC) method is proposed for voltage control. Then the synchronous control and synchronous reference frame are described. Finally, the DVR function in terms of shortage, frequency and Flicker voltage is investigated. The simulation results in MATLAB software show the correct functioning of the system.

2. TRINARY HYBRID MULTILEVEL INVERTE STRUCTURE

The concept of a multi-level inverter was initially introduced by Nebae in 1975 [6]. A multi-level inverter is a power electronics system that produces multi-level voltages from multiple DC sources. Multilevel inverters include an array of semiconductor keys and power supplies, or DC sources of independent power. The switching of the keys makes the voltages of the independent capacitors or DC sources together and the high voltage values are obtained at the output of the inverter, while the rated voltage of the power key is far less than the sum of the voltages of the DC links. Not. The most important features of the multi-level inverters are: the production of low output distortion voltage, the output voltage at higher levels, the reduction of the stress of the semiconductor switches, the ability to operate at a lower switching frequency than the two-level inverters. Multilevel inverters are categorized into three categories [6]: Diode Clamped Inverter, flying capacitors inverter, CHB inverter with independent DC sources. Subsequently, with the replacement of the capacitor in place of the DC source, another type of multi-level inverter was introduced that reduced the number of independent DC sources. In researches, the production of voltage levels more than ever by the lesser equipment has always been a concern for researchers. In recent years, in order to reduce the number of constructive elements and isolated DC sources, multi-level inverters of hybrid structures (hybrid) are used. In this paper, a triple-hybrid multi-level inverter is proposed. The base structure is based on H (HB) bridges. Each HB is powered by a separate DC source. The phase voltage is combined with the sum of the voltages produced by different HB. Due to the different values of DC, HB links, this structure is called hybrid model. THMI nine-level triple with two HB connected serially in each phase is shown in Fig. 2 [8]. Due to the low level of the inverter THMI, the voltage of the switches has decreased compared to the two-level inverters. This inverter is suitable for medium and high voltage and power applications. Therefore, the proposed multi-level inverter can be used to drive Custom Power devices and interfaces between new energies with the network. In this paper, its application in the Dynamic Voltage Restorer (DVR) is reviewed. This structure is a three-component multi-level inverter designed to reduce the number of power electronics to produce multi-level triangular voltage with a low harmonic distortion.

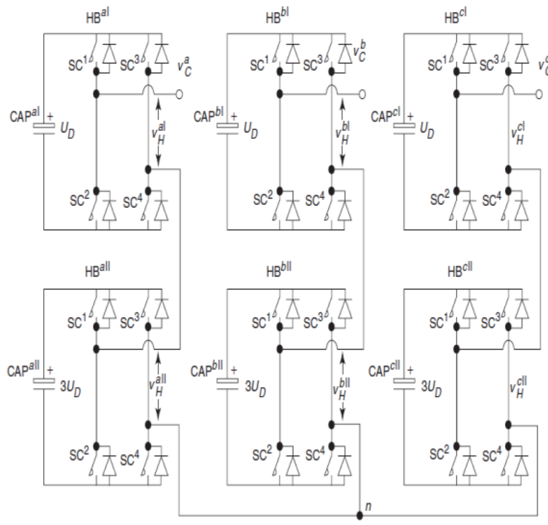

Fig. 2. Trinary Hybrid nine-level Inverter structure (with two HB in each phase) [8].

As shown in Fig. 2, V_{Hi} the output voltage of the i HB is shown. V_{dci} the DC link i, DC voltage is displayed on the HB. The key function F_i for linking V_{Hi} is V_{dci} as follows:

$$V_{Hi} = F_i V_{dci} \quad (1)$$

The value F_i can be either 1 or 1- or 0. For a value of 1, SC^1 and SC^4 switching must. For the value of -1, SC^2 and SC^3 switching must be turned on. For a value of 0, the SC^1 and SC^3 switching or SC^1 and SC^2 switching must. Table (1) shows the relationship between the switching function, the output voltage HB and the state of the switching.

Table 1. Switching Function Connection, HB Output Voltage, and switching Modes.

SC^1	SC^2	SC^3	SC^4	V_{Hi}	F_i
on	off	off	on	V_{dci}	1
off	on	on	off	$-V_{dci}$	-1
on	on	off	off	0	0
off	off	on	on	0	0

Output Voltage Inverter THMI Total Output Voltage HB.

$$V_{an} = \sum_{i=1}^{h} V_{Hi} \quad (2)$$

Equations (1) and (2) get the following:

$$V_{an} = \sum_{i=1}^{h} F_i V_{dci} \quad (3)$$

Which h displays the number of HB units. The THMI has nine-level $h = 2$ in each phase. In THMI, h-HB is $1:3:....:3^{h-1}$ the DC link voltage. Suppose that E is the single voltage, DC voltage can be expressed as:

$$V_{dci} = 3^{i-1} E \quad (4)$$

The equations (3) and (4) get the following:

$$V_{an} = \sum_{i=1}^{h} F_i 3^{i-1} E \quad (5)$$

Suppose the sequence l number is the expected voltage level of the inverter output. If l not negative, the inverter l output is positive voltage level. If l negative, the inverter $-l$ output is negative voltage level. The three-phase inverter is controlled separately and the principles of operation of each phase are similar. Further, phase inverter A is analyzed. $V_{H,ak}$ and $V_{C,ak}$, respectively, indicate HB_{ak} the output voltage and DC link voltage. Therefore, a three-phase THMI inverters with two HB can produce 9-level at each output phase, which output voltage changes between E and $2E$, $-E$, $-2E$. The value F_i in THMI is expressed by two HBs and l a given value [8]:

$$F_1 = \frac{S(l)}{l} B_b \left(S(l) - \sum_{k=3}^{h} \left(S(F_k).3^{k-1} \right) \right)$$
$$F_2 = \frac{S(l)}{l} B_b \left(S(l) - \sum_{k=2}^{h} \left(S(F_k).3^{k-1} \right) - 1 \right) \quad (6)$$

In which the S absolute value function is defined and B_b the bipolar dual function is defined as such:

$$B_b = \begin{cases} 1 & \tau \succ 0 \\ 0 & \tau = 0 \\ -1 & \tau \prec 0 \end{cases} \quad (7)$$

From Equation (6), we can calculate the relationship between the inverter output voltage and the values of switching functions in THMI with the number of HBs. The inverter voltage of phase A is $V_{G,a}$ as follows:

$$V_{G,a} = \sum_{k=1}^{2} \left(F_{ak} V_{C,ak} \right) \quad (8)$$

The value F_{ak} is calculated according to (6). Table 2 shows the relationship between the inverter output voltage and the values of switching functions for THMI with two HBs.

Table 2. Switching Function Connection, HB Output Voltage, and switching Modes (nine-level).

0	$-E$	$-2E$	$-3E$	$-4E$	V_{an}
0	-1	1	0	-1	F_1
0	0	-1	-1	-1	F_2
0	E	$2E$	$3E$	$4E$	V_{an}
0	1	-1	0	1	F_1
0	1	1	1	0	F_2

In THMI, the DC link voltage complies with the following:

$$V_{dci} = 1 + 2\sum_{k=1}^{i-1} V_{dck} \qquad i = 2,3,...,h \quad (9)$$

In order to realize the maximum voltage levels of the inverter output, the DC link voltage ratio is arranged, so the inverter can produce nine-levels in each output phase. But with two HBs in each phase, the multi-level CHB inverter can only produce 5 levels. As the number of output voltage levels of the multi-level inverter is higher, the sinusoidal waveform will be combined. Thus, with triangular combination therapy, the total harmonic distortion (THD) can be greatly reduced, which is an important advantage of this inverter (proposed).

3. SWITCHING STRATEGY NLC

The Nearest Level Control (NLC) in [9] is a convenient method with low computational and high-speed computing. In multilevel inverters there are many levels, and then calculating the equations for extraction of the switching angles in some methods is complicated and sometimes impossible. Therefore, in inverters with a large number of output levels, the NLC control method is used to create the desired waveform. The advantages of this method of control, the reduction of the number of switches, the reduction of dv/dt pressure on the power keys and the possibility of using lower-frequency semiconductors, thereby reducing the final price of the converter. Figure (3) describes this method of switching. As the processor samples from a point of the (V_{ref}) reference voltage, the processor will then round this amount to the (V_{aN}) nearest voltage level. Each level switches the status of the keys according to its switching table to the desired level at the output of the inverter (Fig. 3 (b)). Sampling is repeated for each sampling period.

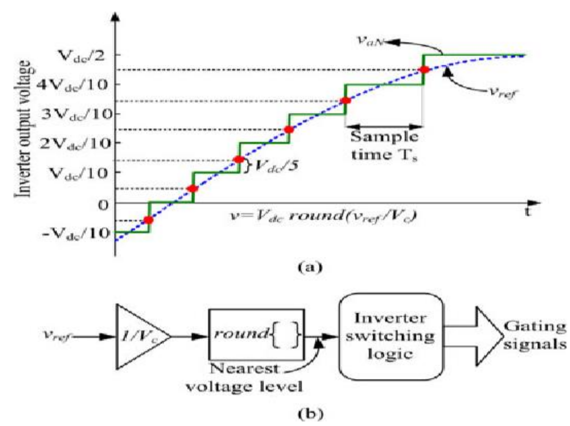

Fig. 3. NLC method a) waveform, b) control algorithm.

4. CONTROL STRATEGY USED IN THE DVR

The control strategy an important role in the DVR function. In fact, in this strategy, with the estimation of the size and angle of the voltage, voltage disturbances are detected and, consequently, reference and injection voltages are determined. In this strategy, the compensation method is also characterized by three methods of Per-Sag, in-phase and minimum energy. The speed and precision of the estimation and tracking pattern of the voltage used in the control strategy directly affect the response speed and compensation accuracy [7]. In this research, the synchronous reference frame (SRF) method is used to instantaneous simulation of the voltage grids symmetry components that can accurately and quickly extract the symmetrical components of the voltage. Also, the In-Phase Compensation method has been used in the proposed DVR. Figure 4 illustrates the block diagram of the control method used in this paper in the MATLAB / Simulink environment.

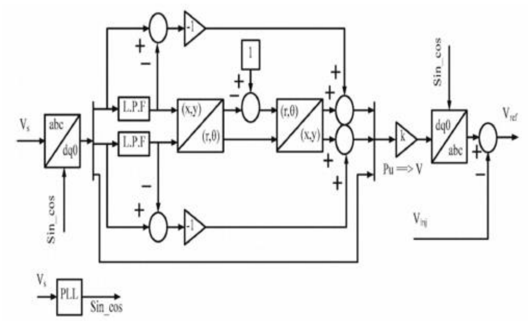

Fig. 4. Block In-phase Control Diagram in MATLAB.

In Fig. 5, the phasor diagram is shown in the phase-control strategy (In-Phase) [10]. According to the phasor diagram.

$$S_{DVR} = I_L \cdot V_{DVR} = I_L\left(V_L - V_S\right) \quad (10)$$

Active DVR power is equal to:

$$P_{DVR} = I_L V_{DVR} Cos\theta_s = I_L\left(V_L - V_S\right)Cos\theta_s \quad (11)$$

The amplitude and phase of the injection voltage by the DVR are:

$$V_{DVR} = V_L - V_S \quad (12)$$
$$\theta_{DVR} = \theta_S$$

In this method, only the amplitude of the voltage is compensated and the DVR performs the compensating operation by injecting the minimum voltage.

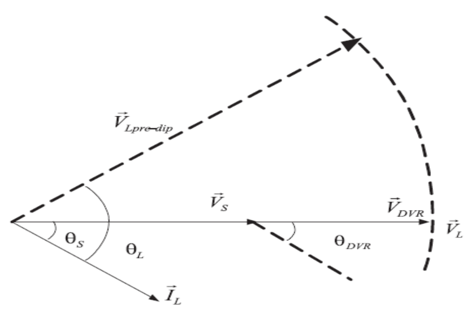

Fig. 5. phasor diagram of the In-Phase control method.

According to the vector diagram of Fig. 5, the size and angle of the injection voltage of the DVR can be calculated as follows.

$$\overline{V_{inj}} = \overline{V_L} - \overline{V_S} \quad (13)$$
$$V_{inj} = \left(V_{LX} + jV_{LY}\right) - \left(V_{SX} + jV_{SY}\right)$$
$$V_{inj} = \left(V_{LX} - V_{SX}\right) + j\left(V_{LY} - V_{SY}\right)$$

Where in

$$V_{LX} = V_L Cos\theta_L \qquad V_{SX} = V_S Cos\theta_S \quad (14)$$
$$V_{LY} = V_L Sin\theta_L \qquad V_{SY} = V_S Sin\theta_S$$

$$\left|V_{inj}\right| = \sqrt{\left(V_{LX} - V_{SX}\right)^2 + \left(V_{SY} - V_{LY}\right)^2} \quad (15)$$
$$\angle V_{inj} = \theta_{inj} = \tan^{-1}\left(\frac{V_{SY} - V_{LY}}{V_{SX} - V_{LX}}\right)$$

5. RESULTS AND SIMULATION

In this section, the proposed DVR is simulated to compensate for the deficiency, deficiency and voltage flicker in a sample power distribution grid by the MATLAB / SIMULINK software. Figure 6 shows the structure of the power distribution grid studied in the MATLAB / SIMULINK.

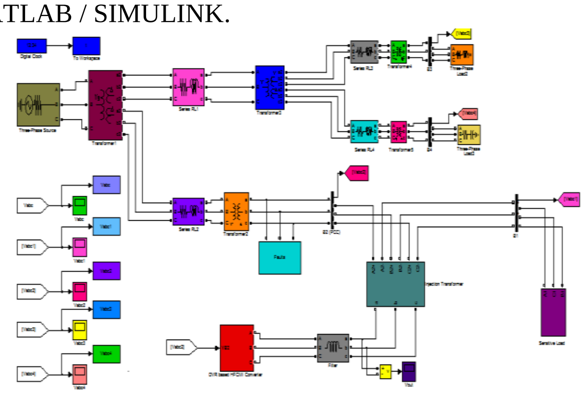

Fig. 6. Power distributed grid structure studied in MATLAB.

5.1. Simulation of the proposed DVR in the presence of voltage sag

In Fig. 7, the voltage sag of 0.4 p.u source voltage was occurred due to a three-phase short circuit fault with the impedance 0.3Ω of the proposed DVR to compensate for the in-phase strategy. The load voltage in Fig. 8 represents this issue. In Figure 9, the injection voltage is shown by the proposed DVR. In Fig. 10, the analysis of the harmonic voltage spectrum of the injected voltage is shown by the proposed DVR in the compensation of the voltage sag.

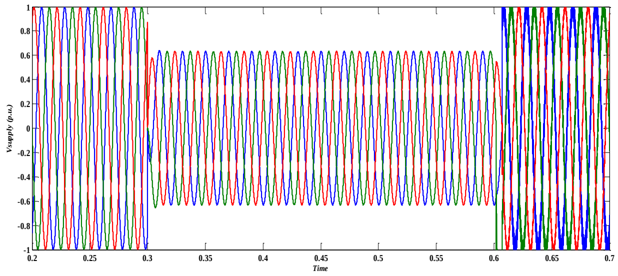

Fig. 7. Three-phase voltage sag 0.4 pu at the source (PCC).

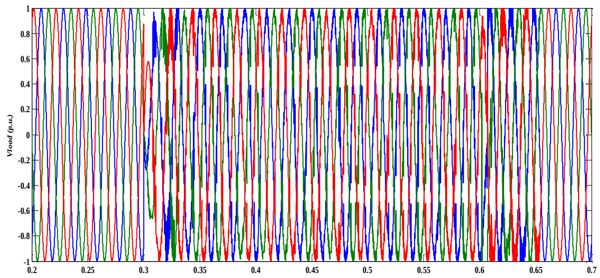

Fig. 8. Load voltage compensation by proposed DVR.

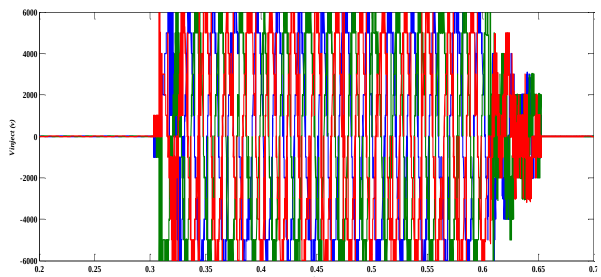

Fig. 9. The voltage injected by the DVR Proposed.

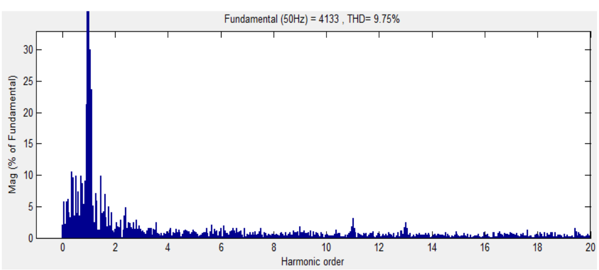

Fig. 10. DVR Proposed injected voltage harmonic spectrum analysis.

5.2. Simulation of the proposed DVR in the presence of voltage swell

Figure 11, Three-phase voltage swell of 1.3 p.u voltage source occurred due to the connection of a three-phase capacitor bank with a capacity of 100 Mvar, which proposed the DVR to compensate for the in-phase strategy. The load voltage in Fig. 12 represents this issue. In Figure 13, the injection voltage is shown by the proposed DVR. In Fig. 14, the analysis of the harmonic voltage spectrum of the injected voltage is shown by the proposed DVR in the compensation of the voltage swell.

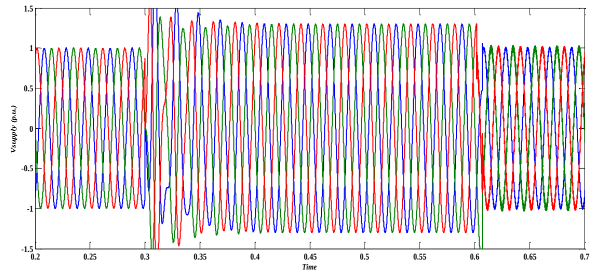

Fig. 11. Three-phase voltage swell 1.3 pu at the source (PCC).

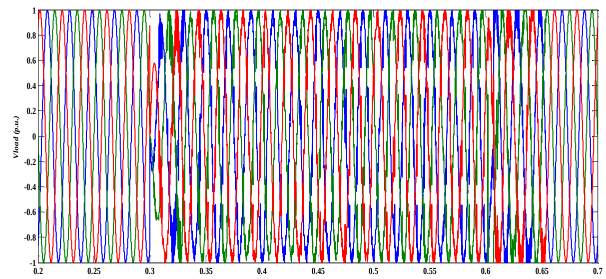

Fig. 12. Load voltage compensation by proposed DVR.

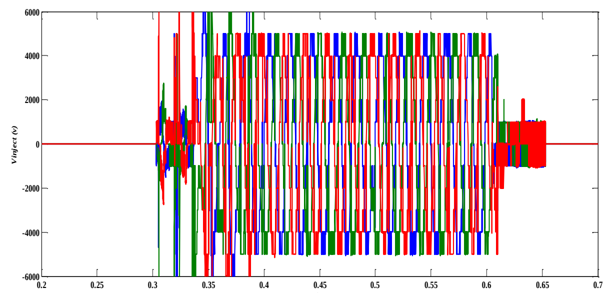

Fig. 13. The voltage injected by the DVR Proposed.

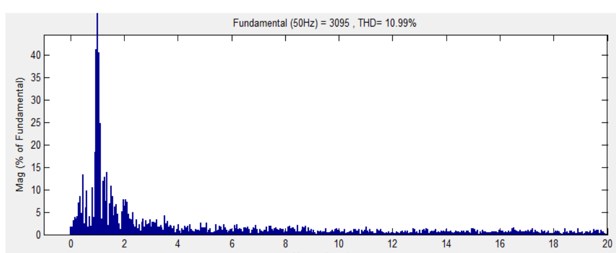

Fig. 14. DVR Proposed injected voltage harmonic spectrum analysis

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5.3. Simulation of the Proposed DVR in the Presence of Voltage Flicker

In Flicker, Figure 15 shows the three-phase voltage at the source voltage induced by the induction motor in the reference [8], which proposed the DVR to compensate for the in-phase strategy. The load voltage in Fig. 16 represents this issue. In Figure 17, the injection voltage is shown by the DVR. In Fig. 18, the harmonic spectral analysis of the injected voltage by the DVR is shown in the flicker Voltage Compensation.

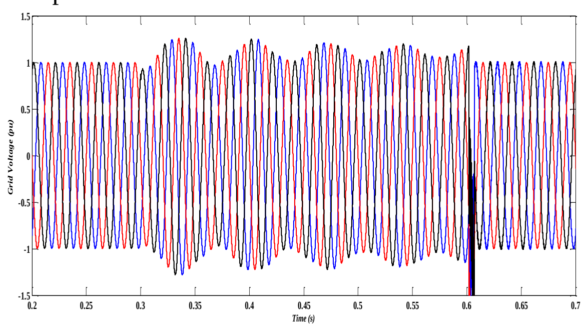

Fig. 15. Three-phase voltage flicker at the source (PCC).

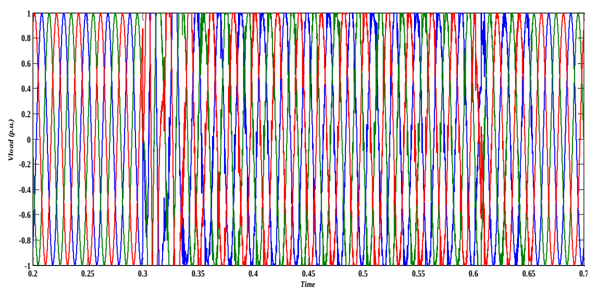

Fig. 16. Load voltage compensation by proposed DVR.

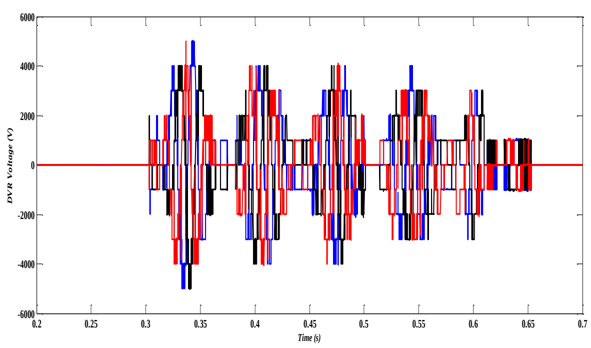

Fig. 17. The voltage injected by the DVR Proposed.

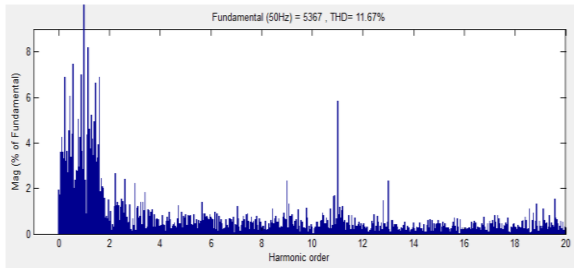

Fig. 18. DVR Proposed injected voltage harmonic spectrum analysis.

6. CONCLUSION

In this paper, a dynamic voltage restorer was proposed based on the THMI multi-level inverters based on the connection of the H bridges. In this structure, by increasing the number of H bridges, the number of voltage levels of each branch increases as a result of the number of line to line voltage levels (output). In the proposed structure, the difference between the DC voltage values and the triple (trinary) of it relative to the original HB, the low number of IGBT switches and the circuit-starter, the structure of the inverter and its control method. Given the results of the proposed DVR function in the test network in the presence of voltage sag, swell and Flicker. It can be said that the proposed DVR has a better performance in compensating for the voltage sag, swell and flicker of the load voltage, and this advantage is due to the use of a three-phase hybrid nine-level inverters. It was also observed that using a triple-harmonic THMI (THD%), the injected voltage by the DVR was reduced to a desirable level, which would reduce the harmonic filter size and thus reduce the final cost of the DVR.

REFERENCES

[1] J.D. J.D. Barros and J.F. Silva, "**Multilevel optimal predictive dynamic voltage restorer**," *IEEE Trans. Ind. Electron.*, Vol. 57, No. 8, pp. 2747-2760, Aug. 2014.

[2] E. Akbari, A. Sheikholeslami and j. Rouhi, "**operation DVR based Modular Multilevel Cascade Converter based on Double-star Chopper-cells (MMCC-DSCC) for Compensation Voltage sag and swell in Power Distribution Grids**, *Majlesi Journal of Mechatronic Systems (MJMS)*, Vol. 4, No. 1, pp. 39-47, March 2015.

[3] A. Elnady and M. Salama, "**Duall Role CDSC based Dual Vector Control for Effective Operation of DVR with Harmonic Mitigation**" *IEEE Transactions on Industrial Electronics*, Vol. 16, No. 8, pp. 2614-2625, Nov 2018.

[4] S. P. Gautam and L. Kumar, "**Hybrid topology of symmetrical multilevel inverter using less number of devices**" *IEEE Trans. Power Electron*, Vol. 8, No. 11, pp. 3135-3145, Jan 2016.

[5] K. Gupta and A. Ranjan, "**Multilevel inverter topologies with reduced device count a review**" *IEEE*

Trans. Power Electron, Vol. 31, No. 1, pp. 234-247, July2017.

[6] C. Silva and L. Cordova, "**Implementation and control of a hybrid multilevel converter with floting DC links for current waveform improvement**" *IEEE Trans. Ind. Electron*, Vol. 58, No. 6, pp. 1421-1432, May 2015.

[7] A. M. Rauf and V. Khadkikar, "**An Enhanced Voltage Sag Compensation Scheme for Dynamic Voltage Restorer**," *IEEE Transactions on Industrial Electronics*, Vol. 62, No. 5, pp. 2683-2692, May 2015.

[8] Y. Liu, and F. Luo "**Trinary hybrid 81-level multilevel inverter for motor drive with zero common-mode voltage**" *IEEE Trans. Power Electron*, Vol. 30, No. 1, pp. 450-462, Aug 2008.

[9] P. M. Meshram, V. B. Borghate and F. Nugater "**A simplified nearest level control (NLC) voltage balancing method for modular multilevel converter (MMC)**" *IEEE Trans. Power Electron*, Vol. 30, No. 1, pp. 450-462, Aug 2017.

[10] E. Ebrahimzadeh, S. Farhangi, H. Iman-Eini, F. Badrkhani Ajaei and R. Iravani, "**Improved Phasor Estimation Method for Dynamic Voltage Restorer Applications**," *IEEE Transactions on Power Delivery*, Vol. 30, No. 3, pp. 1467-1477, June 2016.