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Enhancing Power Quality in Distribution Networks with Multilevel STATCOM and Improved One-Cycle Controller using Five-Level Clamp Diode Multilevel Inverter

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ABSTRACT

This paper aims to enhance the power quality in distribution networks by utilizing a multilevel STATCOM (Static Synchronous Compensator) compensated system based on an improved one-cycle controller using a five-level clamp diode multilevel inverter. The proposed system utilizes the clamp diode multilevel inverter to generate voltage with a high number of voltage levels, which results in reduced total harmonic distortion (THD) and lower switching frequency. The improved one-cycle controller ensures the accuracy and reliability of the system's control, allowing it to operate seamlessly and efficiently. The multilevel STATCOM, on the other hand, provides reactive power compensation, voltage regulation, and harmonic filtering to mitigate power quality issues such as voltage sags, swells, flickers and harmonics. The simulation results demonstrate the effectiveness of the proposed system in improving the power quality of the distribution network. The proposed system offers an efficient and reliable solution for enhancing power quality in distribution networks.

Keywords : Multilevel STATCOM, one cycle control, PWM control, voltage disturbances, multi-bus system, voltage sag, voltage swell.

I. INTRODUCTION

Due to the increase in sensitive loads, paying attention to power quality problems is necessary. Failure to pay attention to these problems will cause great financial losses. Voltage stability is important in improving the safety and reliability of power systems and is one of the main factors in the power quality of networks [1], [2]. Reactive power compensation is an effective solution for stabilizing the voltage of the network. Among reactive power compensators, STATCOM equipped with a voltage source inverter has always been considered by researchers due to its considerable flexibility and controllability. This compensator has gained considerable popularity over the past decade due to power systems' support and dynamic voltage supply [3]. Compared to a conventional two-level inverter, a multilevel inverter configuration has advantages such as a higher voltage level on the AC side and improved waveform under harmonic distortion [4], [5]. In the category of multilevel inverters, there are three dominant configurations: 1) clamp diode inverter [6]; 2) floating capacitor inverter [7], and 3) Integrated bridge H cascade inverter [8]. Compared to other topologies, it is possible to connect back to back in the clamp diode topology due to the common DC source, which leads to the input and output current waveforms approaching the sinusoidal state with a lower switching frequency and a smaller filter.

The STATCOM system injects current into the network from a common connection point, resulting in harmonic filtering, voltage control, power factor correction, neutral current compensation, and load balancing. In the STATCOM applications include reactive power compensation voltage conservation strategy in low voltage networks. A three-level clamp diode structure in each phase and a three-phase phase voltage waveform in the past, various methods have been proposed to control STATCOM.

The PI is a common two-loop control strategy for controlling STATCOM active and reactive currents. This control strategy establishes a connection between active and reactive currents [9]. The presence of an unbalanced voltage at the point of common coupling (PCC) leads to the emergence of a negative sequence current component, which worsens the control performance. Therefore, it is very difficult to maintain the PCC point voltage in the event of a small disturbance in the dc voltage link. It is also difficult to set PI controller parameters and requires complex mathematical modeling of the system under study.

The PI controller parameters are set for the best performance within the normal operating range of the system. In the event of changes in network load and parameters and nonlinear network conditions, the PI controller may not work properly. Various methods have been proposed to eliminate this problem in the design of the PI controller. Since all of these designs for PI controllers are based on the STATCOM linear model and the nonlinear static compensation model, the nonlinear control method is used directly without the need for linearization [10]. On the other hand, many previous methods may not be resistant to different operating conditions. Optimal linear control based on the quadratic linear regulator is proposed in [11]. A fuzzy PI control method has been proposed to adjust the PI control gains [12]. In multilevel converters, there is a significant increase in the number of components and the problem of voltage imbalance at different capacitor voltage levels. However, PLL service must generate the required reactive current or synchronize the PWM voltage waveform. Designs based on one cycle control became important because of their simplicity in the controller structure [13].

In the reference [14], the PWM method is compared with the one cycle control method, and its advantages are shown. Compared to PWM, this method has less error in the permanent state response and better response in the dynamic state, as well as it is very easy to understand, and it can be used as a switching method in many cases. In this paper, by presenting an optimal control method in the compensating switching structure of STATCOM, switching pulses can be generated for different purposes. These goals can be achieved with a network voltage control approach against possible disturbances. In some cases, some circuit parameters may change momentarily, which can interfere with the proper functioning of the control system. By improving the proposed control structure, the control system can be sensitive to such phenomena. The second section is a study of STATCOM structure and STATCOM

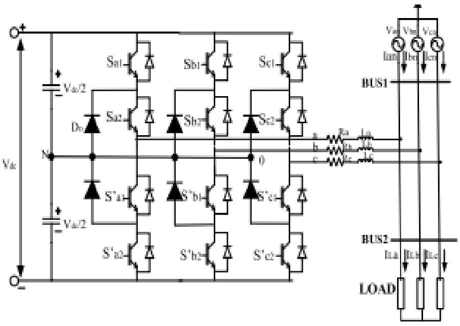

Fig.1. Three-level clamp diode structure, based on STATCOM connected to network and load of the system

Performance. STATCOM control methods and a comparison of the proposed method with other methods are presented in the third section. The fourth section deals with the design of the proposed one-cycle controller. The system simulation and the conclusion of the work are summarized in the fifth section.

- To propose a novel robust and flexible structure for enhancing the performance of the one-cycle controller.

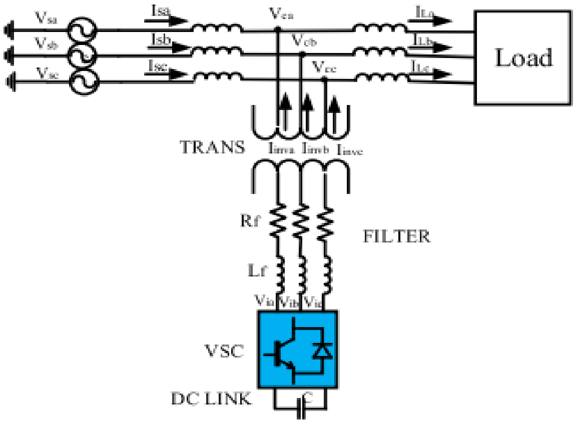

Fig.2. The equivalent circuit of a STATCOM connected to a grid and load system

Fig. 2, which includes a transformer with a parallel connection, a voltage source inverter, a low-pass filter, and a capacitor in the DC link parallel to the network, the relationship between the load current and the network with the STATCOM current can be obtained. Section-II possesses a system description in various cases, Section-III depicts the proposed topology, Section-IV includes the results and Discussion, and Section-V concludes this work.

II. SYSTEM DESCRIPTION

A. THREE-LEVEL STATCOM BASED ON NEUTRAL POINT CLAMP INVERTER

Multilevel clamp diode inverter can produce different levels of voltage waveform by clamp diodes and dc capacitors. This inverter can generally be configured as a three, four, five, or seven-level topology, which the three-level inverter is called a neutral point clamp inverter (NPC), as shown in Fig.1. In the three-level arrangement, each leg consists of 4 switches, which according to Fig. 1, the switches are two complementary to each other (Sa1, S'a1) and (Sa2, S'a2). Switches Sa1 and S'a1 work in a complementary way, meaning that when one switch is on, the other must be off. The capacitor's midpoint is the inverter's neutral point, and the output voltage is measured relative to this point. DD control diodes are an advantage over dual-level inverters. The main function of these diodes is to maintain the DC voltage to generate the step output voltage and limit the voltage stress of the power devices The STATCOM of Fig. 1 can control the power factor or voltage at the load terminal by exchanging reactive power with the system by a three-level clamp diode inverter. To control the active and reactive power components of STATCOM, the magnitude and angle of the voltage at the STATCOM terminals must be controlled. In this paper, the magnitude and angle of the STATCOM voltage are adjusted based on the one cycle control technique presented in the next section. By this neutral point clamp inverter (NPC) we can control active and reactive power components of the STATCOM.

B. ONE CYCLE SWITCHING CONTROL METHOD

The proposed switching method is based on the one cycle control mentioned in the previous section. Since in threephase STATCOM, according to Fig. 1, each phase has two parts, negative and positive, the switches Sa1 and S'a1, Sa2 and S'a2 belong to phase a, the switches Sb1 and S'b1, Sb2 and S'b2 belong to phase b and the switches Sc1 and S'c1, Sc2 and S'c2 correspond to phase c. In this type of naming, by connecting the odd switches, i.e., Sa1, Sa2, Sc1, Sc2, and S'b1, S'b2, the positive voltage is injected into the secondary, and by connecting the even switches, i.e., S'a1, S'a2, Sb1, Sb2, and S'c1, S'c2, the negative voltage is injected. The symbol (') indicates the reverse switches. In the proposed method, the negative part injects a negative voltage, and the positive part injects a positive voltage into STATCOM. But this is part of the controller function, and more needs to be done to improve this approach.

1. **FIRST IMPROVEMENT**

To increase the speed in one cycle control (OCC), the output of the integrator can be multiplied by the coefficient of integration. By doing this, the integral is a function of the high-speed input voltage

2. SECOND IMPROVEMENT

To generate a reference signal, three signals are made up of three phases of sine voltage, which is expected to be equal to that value. These three signals have the same amplitude and 120-degree angle difference. These three signals are regularly compared to network voltages at each stage to obtain a control reference signal. To eliminate various disturbances, this signal needs to be corrected. But instead of modifying the reference signal, a better way is used in this article. Instead of improving the reference signal, several paths reset the flip-flop. The design of these routes is very simple, and only a few comparators are used. According to Equation (1), the first way to reset the flip-flop is to compare the three load voltages V_L, the supply mains voltage V_S and the desired reference voltage V_{ref}.

$$\frac{\mathbf{dt_{inva}}}{\mathbf{dt}} = \frac{1}{L_S}\left[\mathbf{V_{ia}} - \mathbf{V_{ca}} - \mathbf{R_s i_{inva}}\right]$$

$$\frac{\mathbf{di_{invb}}}{\mathbf{dt}} = \frac{1}{L_S}\left[\mathbf{V_{ib}} - \mathbf{V_{cb}} - \mathbf{R_s i_{invb}}\right]$$

$$\frac{d}{dt}\mathbf{v_{dc}^2(t)} = \frac{2}{C}\left[\mathbf{V_{ia}i_{inva}} + \mathbf{V_{ib}i_{invb}} + \mathbf{V_{ic}i_{invc}}\right] \text{--} \ (1)$$

The second way to reset the flip-flop is to compare the reference signal and the integrator's output to increase the controller's reliability. When the error between the reference voltage and the network voltage is a very small number (ε = 10−5), the flip-flop should be reset, which is mentioned in Equation (2)

$$\mathbf{I_{L,a}(t)} = \mathbf{I_{s,a}(t)} + \mathbf{I_{inv,a}(t)}$$

$$\mathbf{I_{L,b}(t)} = \mathbf{I_{s,b}(t)} + \mathbf{I_{inv,b}(t)}$$

$$\mathbf{I_{L,c}(t)} = \mathbf{I_{s,c}(t)} + \mathbf{I_{inv,c}(t)} \qquad \text{--}(2)$$

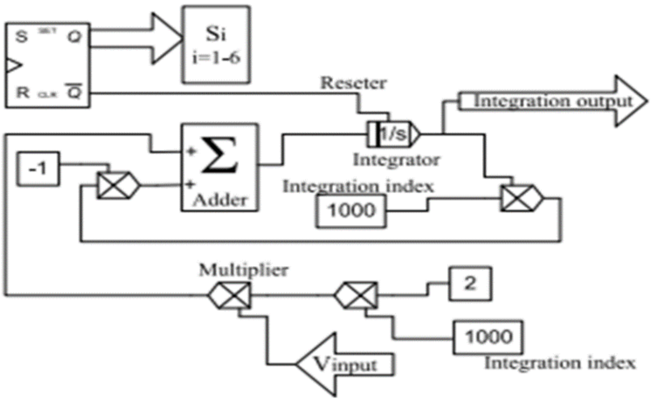

Fig.3. Speed increase in the composition of occ

Equation (3) states the third path of resetting the flip-flop, which compares the opposite switch and the desired voltages, load, and network

$$\frac{1}{T_s}\int_0^{t_{on}} \mathbf{v\,G^{dt}} = \mathbf{V_{ref}} \quad \rightarrow \ (3)$$

Finally, Equation (4) describes the fourth path of flip-flop reset when the integral value reaches the reference value

$$\mathbf{K(t)} = \begin{cases} 1, & 0 < t < \mathrm{Ton} \\ 0, & \mathrm{Ton} < t < \mathrm{Ts} \end{cases} \quad \rightarrow (4)$$

Because in this type of control, In the RS flip-flop, the Reset commands should take precedence over the Set command. Two gates do this command priority.

III. PROPOSED TOPOLOGY

A 5-level clamp diode multilevel inverter is a type of inverter that is used to convert DC power to AC power at a higher voltage level. The inverter is made up of a series of power electronic switches that are arranged in a clamp diode configuration. This allows for the generation of AC voltage levels that are higher than those that can be generated by a conventional two-level inverter.

A multilevel inverter is a power electronic device that converts DC (direct current) voltage into AC (alternating current) voltage with several levels of voltage output. The multilevel inverter has become popular in recent years due to its high efficiency, low harmonic distortion, and improved output waveform quality.

The advantage of using a clamp diode 5-level multilevel inverter is that it can produce a high-quality output voltage waveform with very low harmonic distortion. The multilevel output voltage waveform is composed of several steps resulting in a sinusoidal waveform that more closely approximates a pure sine wave. This reduces the amount of harmonic distortion and improves the overall quality of the output voltage waveform.

The advantages of the 5-level clamp diode multilevel inverter include reduced harmonic distortion, reduced voltage stress on the power devices, and improved output waveform quality. However, the complexity of the circuit and the cost of the components are some of the disadvantages of this type of inverter.

One application of a clamp diode 5-level multilevel inverter is in renewable energy systems such as solar and wind power systems. These systems typically operate at low voltage levels and require a DC-AC inverter to convert the DC power to AC power at a higher voltage level. The high-quality output voltage waveform produced by a clamp diode 5-level multilevel inverter can improve the efficiency of the renewable energy system and reduce the amount of harmonic distortion that is generated.

In conclusion, his inverter can operate at higher switching frequencies than conventional two-level inverters and is well-suited for renewable energy systems. Overall, the 5-level clamp diode multilevel inverter is a promising technology for high-power applications that require high-quality output waveforms and low harmonic distortion.

B. FIVE-LEVEL DIODE CLAMPED MULTILEVEL INVERTER

The Fig 4 shows a 5 level diode clamped multilevel inverter. The number of levels of a diode clamped inverter, if N is the total no of capacitors used is N + 1. Increasing the levels in an inverter leads to reduced harmonics in the output voltage. So Fig 4 is a 5 level inverter. It is to be noted that an m-level diode-clamped inverter has a level output phase voltage and a (2m-1)-level output line voltage [1]. i.e., above inverter has 5 level phase voltage waveform and 11 level line voltage waveform. Also although each switch has to block a voltage of V, different diodes will have to block different voltages. For example D2 will have to block 2 Vdc. So different diodes should have different ratings. For diodes having same ratings, any m level inverter will have to employ (m – 1)*(m – 2) diodes .Thus, the number of blocking diodes is quadratic ally related to the number of levels in a diode clamped converter.

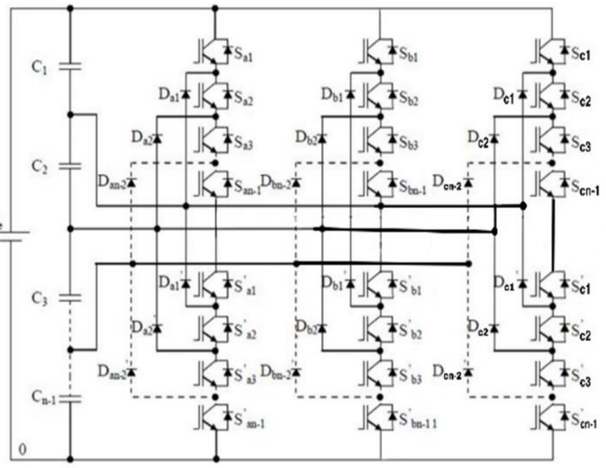

Fig.4. Five- Level Diode Clamped Multilevel Inverter

All of the phases share a common dc bus, which minimizes the capacitance requirements of the converter

For this reason, a back-to-back topology is not only possible but also practical for uses such as a high-voltage back-to-back inter-connection or an adjustable speed drive.

The capacitors can be pre-charged as a group.
Efficiency is high for fundamental frequency switching.

IV. SIMULATION RESULTS:

CASE-1: SYMMETRIC VOLTAGE SAG AND SWELL OF THE NETWORK VOLTAGE

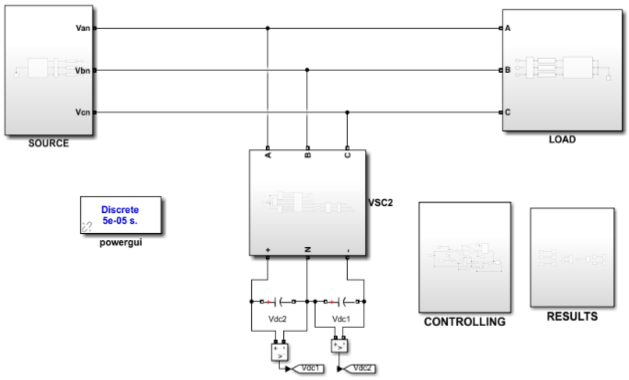

Fig.5. 5-level D-STATCOM at symmetric voltage sag and voltage swell of the network voltage

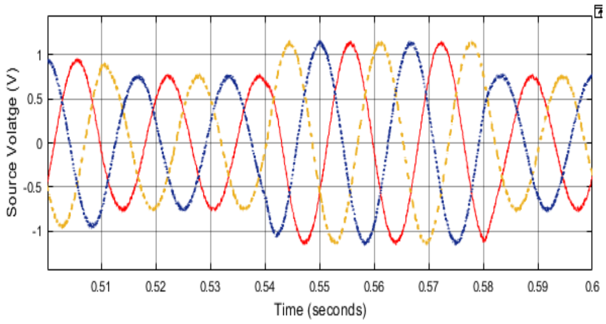

Fig.5.1. Source Voltage (V)

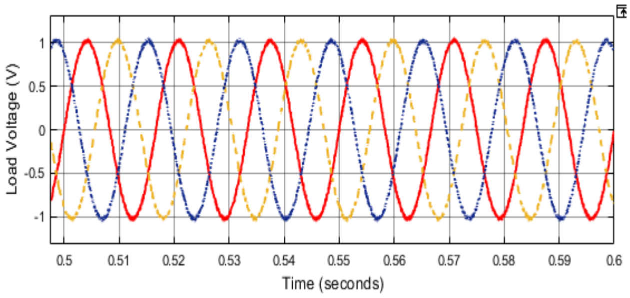

Fig.5.2. Load Voltage (V)

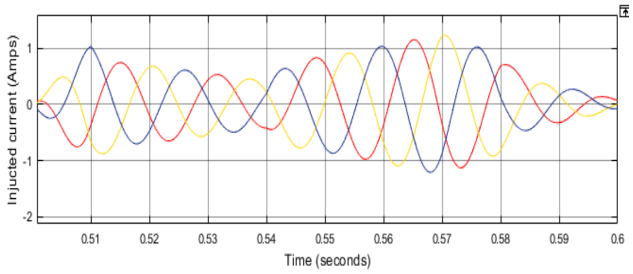

Fig.5.3. Injected Current (Amps)

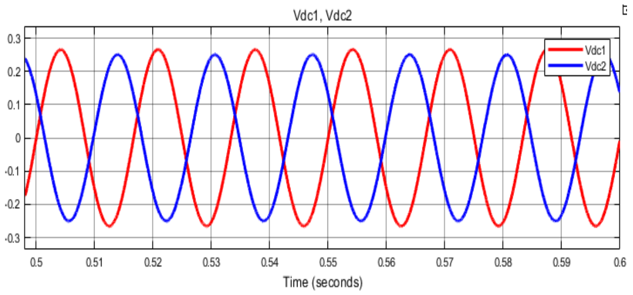

Fig.5.4. Vdc1&Vdc2

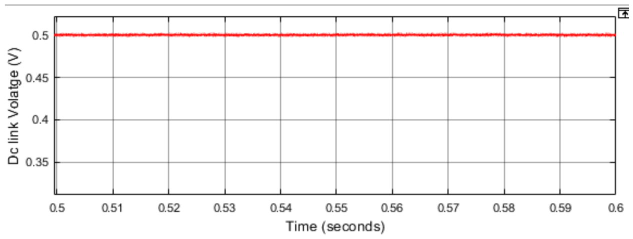

Fig.5.5. Dc Link Voltage (V)

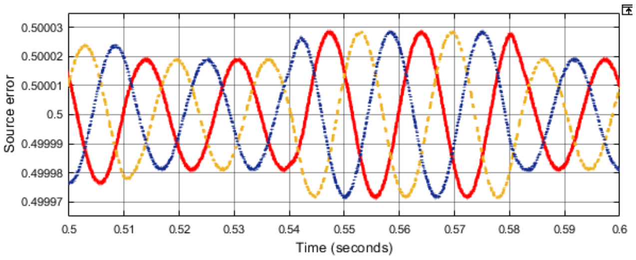

Fig.5.6. Source Error

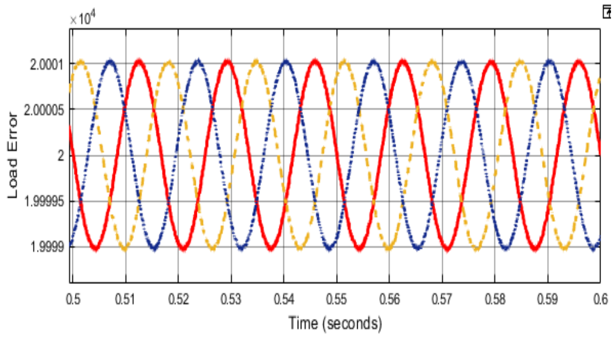

Fig.5.7. Load Error

Fig. 5 shows the simulation results for symmetric Voltage sag and voltage swell. To show the better performance of the proposed method, the voltage difference between the desired voltage, network voltage, and load voltage has been investigated. In this case, the network voltage has the symmetric voltage sag and voltage swell with 30% of the voltage drop from 0.51 to 0.54 and 30% of the voltage swell from 0.54 to 0.57.

CASE-2: ASYMMETRIC VOLTAGE SAG AND SWELL OF THE NETWORK VOLTAGE

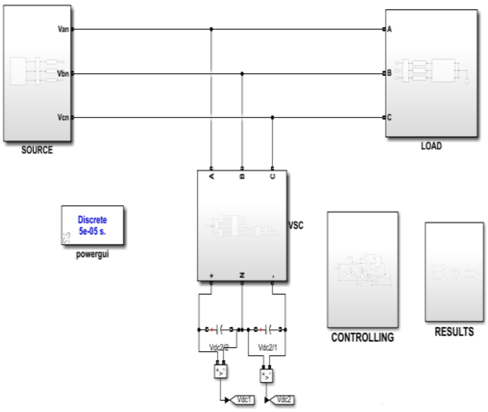

Fig.6. 5-level D-STATCOM Asymmetric voltage sag and voltage swell

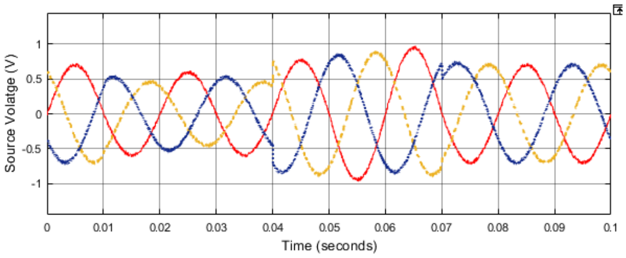

Fig.6.1. Source Voltage

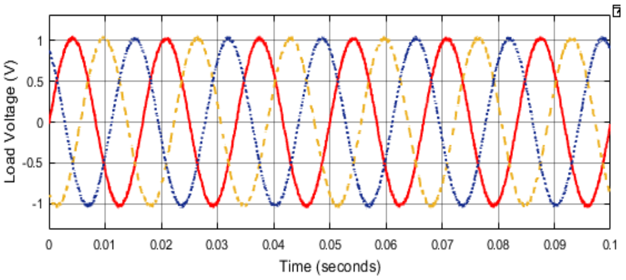

Fig.6.2. Load Voltage

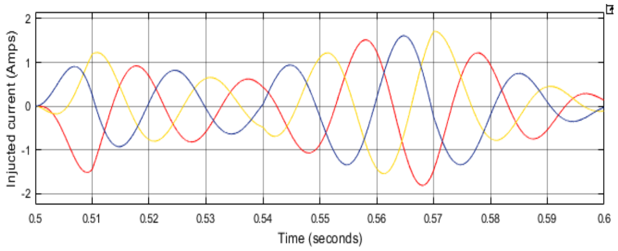

Fig.6.3. Injured Current (Amps)

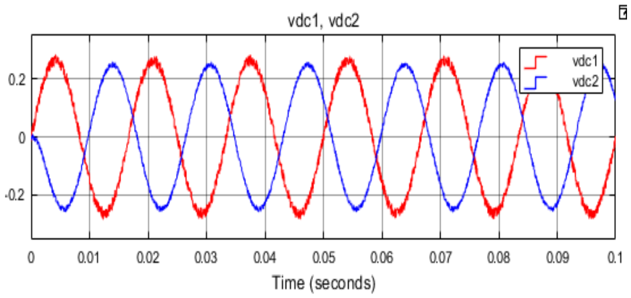

Fig 6.4 vdc1& vdc2

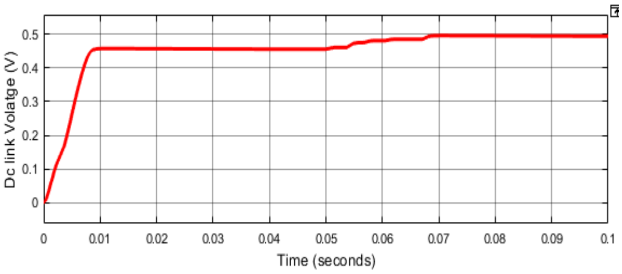

Fig.6.5. Dc Link Voltage (V)

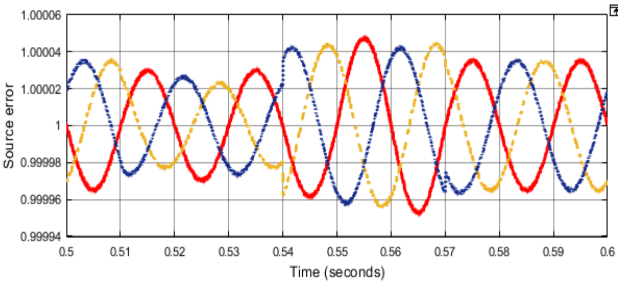

Fig.6.6. Source Error

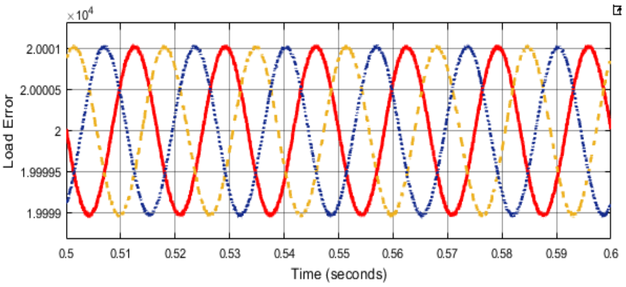

Fig.6.7. Load Error

Fig. 6 shows the asymmetric voltage sag and voltage swell simulation results. Similar to the first case, to show the proposed method's better performance, the voltage difference between the desired, network, and load voltage has been investigated.

CASE-3: NETWORK VOLTAGE FLUCTUATIONS

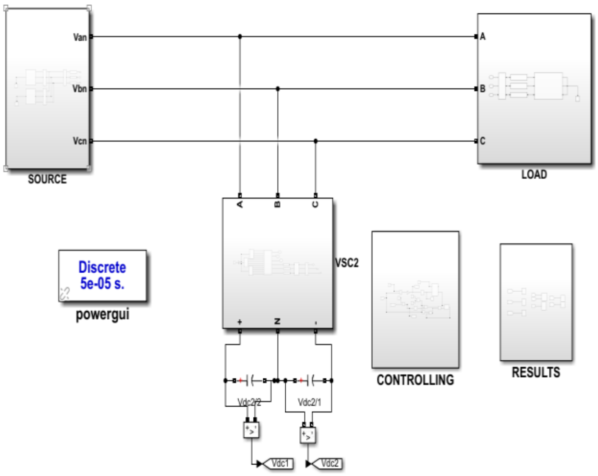

Fig.7. 5-level D-STATCOM during Network voltage fluctuations

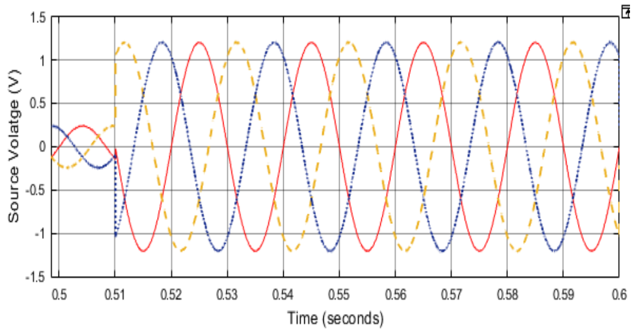

Fig.7.1. Source Voltage

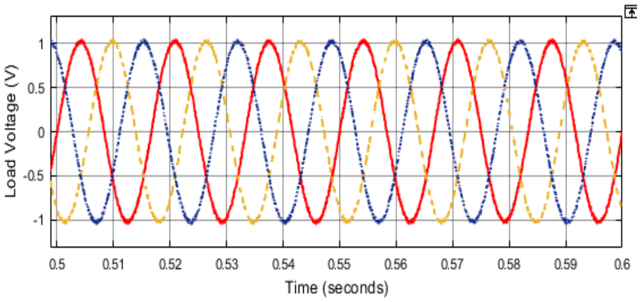

Fig.7.2. Load Voltage

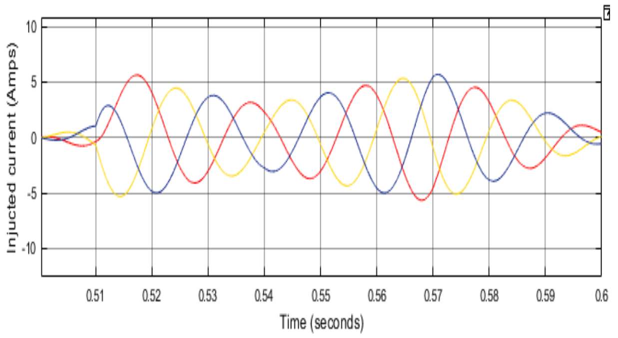

Fig.7.3. Injected Current Amps

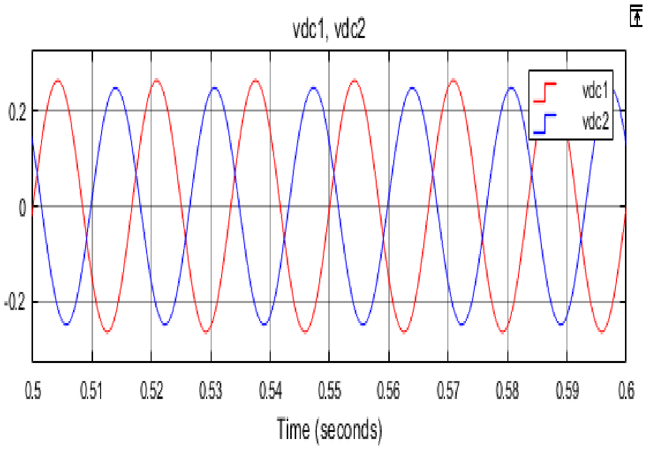

Fig.7.4 Vdc1&Vdc2

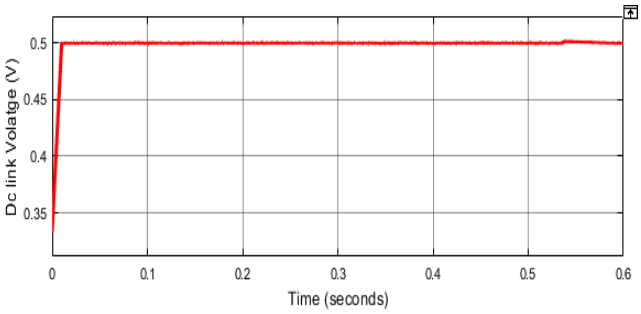

Fig 7.5 Dc Link Voltage

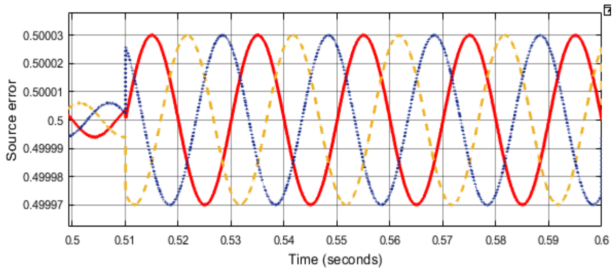

Fig .7.6. Source Error

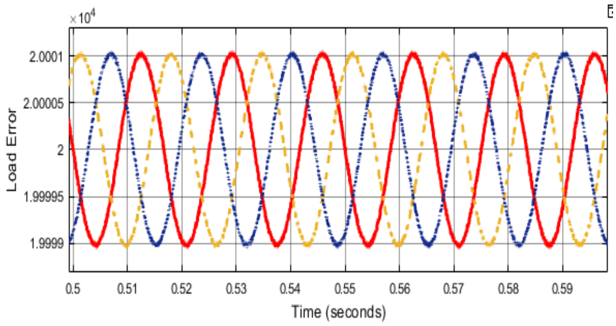

Fig.7.7. Load Error

Fig. 7 shows the simulation results of network voltage fluctuations. The injection current by STATCOM shows that in this case, STATCOM, by injecting the reverse current of the added voltage to the network, was able almost to eliminate the effect of this perturbation on the load voltage and have a sinusoidal voltage on the load side. In this section, to create a fluctuation in the network voltage, a voltage with an amplitude of 0.4 and a frequency of 4 Hz has been added to the network voltage to confuse the network voltage. This operation has lasted from 0.51 to 0.6 seconds.

CASE-4: HARMONIC IN NETWORK VOLTAGE

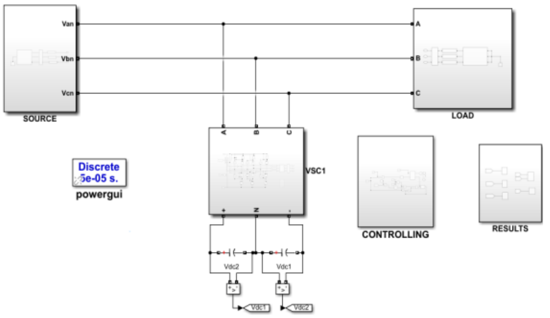

Fig.8. 5-level D-STATCOM during Harmonic in Network Voltage

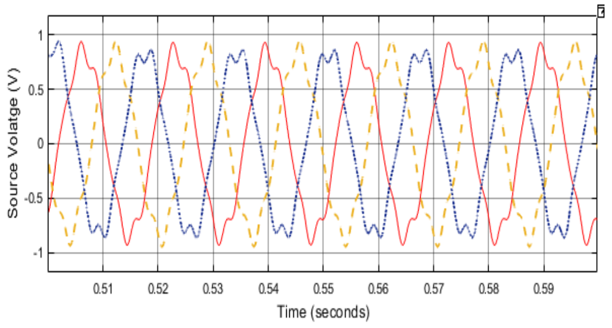

Fig.8.1. Source Error

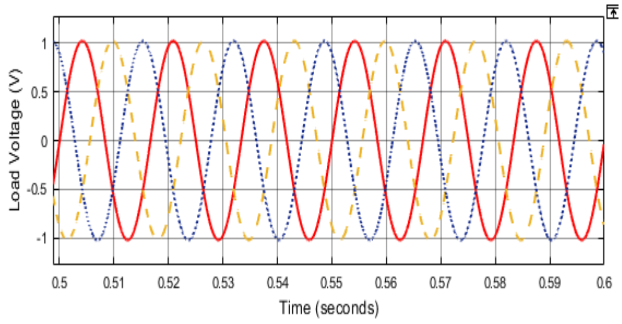

Fig. 8.2. Load Voltage

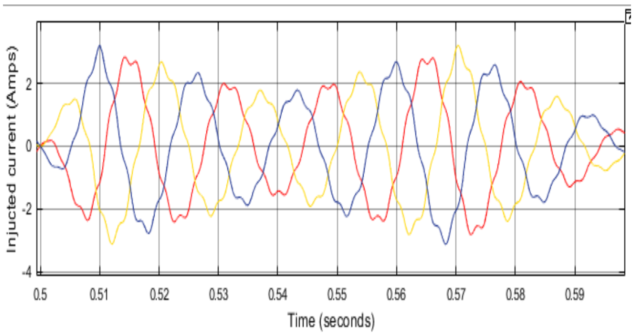

Fig.8.3. Injected Current (Amps)

Method	Level	THD (V_{source})	THD (V_{load})
Existing	3 - level	5.71%	4..28%
Proposed	5 – level	2.86%	2.48%

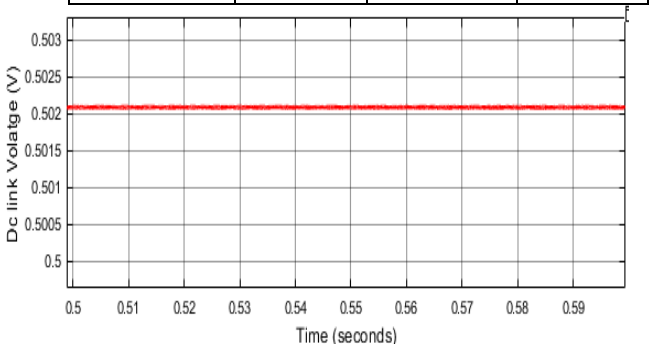

Fig.8.4. Dc Link Voltage

Fig. 8 shows the results of harmonic simulation at network voltage. the harmonic spectrum of load voltage without STATCOM and load voltage with STATCOM, respectively. As it turns out, the THD value of the load voltage is lower, and the harmonic value is reduced. In this section, we inject a harmonic with an amplitude of 0.2 and a frequency of 350 Hz into the network voltage, similar to the seventh harmonic injection. This operation lasted from 0 seconds to 0.6 seconds.

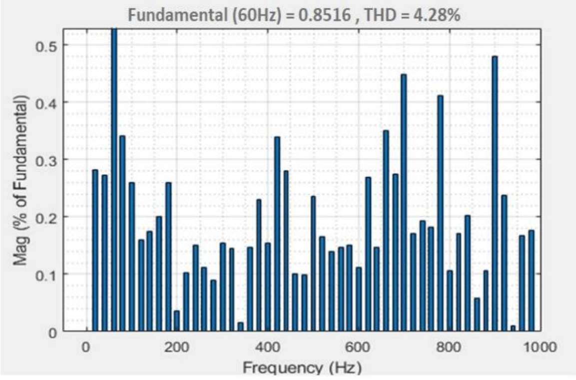

Fig.8.5. Harmonic spectrum of load voltage in (3-level) Multilevel STATCOM

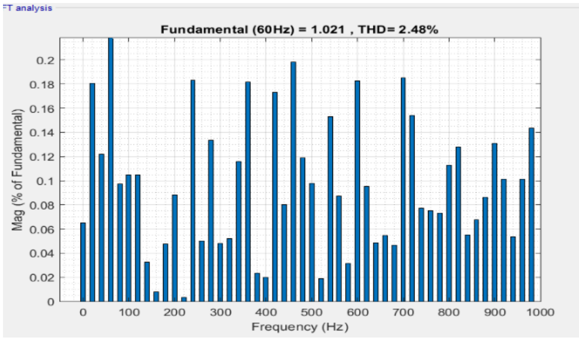

Fig.8.6. Harmonic spectrum of load voltage in (5-level) Multilevel inverter

Table.1: Comparison between 3-Level And 5-Level Topology

V. CONCLUSION

This paper has successfully presented a solution for enhancing power quality in distribution networks using a multilevel STATCOM compensated system based on an improved one-cycle controller using a five-level clamp diode multilevel inverter. The proposed system provides significant advantages such as reduced THD, lower switching frequency, and reliable control, making it an efficient and reliable solution for power quality enhancement. The simulation results demonstrated the system's effectiveness in mitigating power quality issues such as voltage sags, swells, and flickers. Moreover, the proposed system can be implemented in real-world scenarios with minimal modifications, making it a practical and cost-effective solution for distribution network operators to improve the quality of their power supply. In summary, this paper provides a valuable contribution to the field of power systems and demonstrates the potential for multilevel STATCOM compensated systems to enhance power quality in distribution networks.

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