

ANALYSIS AND SIMULATION OF A NEW SHUNT ACTIVE POWER FILTER USING CASCADED MULTILEVEL INVERTER

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To provide high power quality at the Point of Common Coupling (PCC) of power distribution systems, elimination of the harmonic is indispensably necessary. Most of the important international standards (like IEEE-519-1992, IEC-6100) have defined the power quality and given some harmonic limits. Different methods are proposed in literature for solving the harmonic problems. One of these methods, the Active Power Filters (APFs) technique has been studied and developed in the recent years to solve the harmonic problems. The main objective of this paper is to model a new shunt active power filter using a three-phase 11-level cascaded multi level inverter for both harmonic filtering and reactive power (var) compensation under the steady-state condition which is mainly suitable for high and medium power applications. In this paper, the shunt active power filters are designed using a three-phase, 11-level cascade-inverter and a three-phase conventional pulse width modulation (PWM) based inverter in MATLAB (using power system simulink tools), finally they are compared and their simulation results verified for a distorted three-phase, 500 kVA, 440 V, 50 Hz power system utility.

Key words: PWM based NPC-inverter, cascaded multilevel inverter, shunt active power filter, THD, FFT

1 INTRODUCTION

Traditionally, a multipulse like 6-pulse or 12-pulse inverter consisting of several voltage-source inverters connected together through zigzag arrangement of transformers is used for both harmonic and reactive power (VAR) compensations. These transformers: 1) are the most expensive equipment in the system; 2) produce about 50 % of the total losses of the system; 3) occupy a large area of real estate, about 40 % of the total system; 4) cause difficulties in control due to dc magnetizing and surge over voltage problems resulting from saturation of the transformers; and 5) are unreliable.

Correspondingly, Pulse Width Modulated (PWM) inverters (with 10 kHz of high switching frequency) have been used for both harmonic compensation and static VAR compensation [5]. However, the high initial and running costs have been hindering their practical use in power distribution systems. In addition, it is difficult for PWM-inverter-based active filters to comply with electromagnetic interference (EMI) requirements.

A cascade multilevel inverter [8] has been proposed for both harmonics and static var compensation applications [7], [9–11]. The new cascade inverter eliminates the bulky transformers required by Static VAR Compensators (SVC's) that employ the multipulse inverter and can respond much faster. This inverter generates almost sinusoidal staircase voltage with only one time switching per line cycle. Its superior suitability has been demonstrated for VAR compensation. When the cascade inverter is applied to line conditioning and active power

filtering of a distribution system, it is expected that the initial and running costs and the EMI will be dramatically reduced below that of the traditional PWM inverter. The new cascaded multilevel inverter, however, poses challenging problems for both harmonic filtering and reactive power (VAR) compensation, such as voltage control and balance of each dc capacitor.

In this paper, the shunt active power filters are simulated in MATLAB using both a three-phase conventional PWM-based voltage source inverter and the proposed three-phase 11-level cascaded voltage source inverter, which is applied to a distorted three-phase 500 kVA, 440 volt, 50 HZ power system utility for both harmonic mitigation and reactive power compensation under the steady state operating condition. Finally their simulated results are verified and compared.

2 SYSTEM CONFIGURATION OF A SHUNT APF USING CONVENTIONAL PWM BASED INVERTER

The basic function of the shunt active power filter is to eliminate harmonics and meet the reactive power requirements of the load locally so that the ac supply feeds only the sinusoidal balanced unity power factor currents.

The desired APF currents are estimated by sensing the load current, dc bus voltage, and source voltage [5, 6]. In this section a shunt active power filter is designed for a 500 kVA power distribution systems using a conventional

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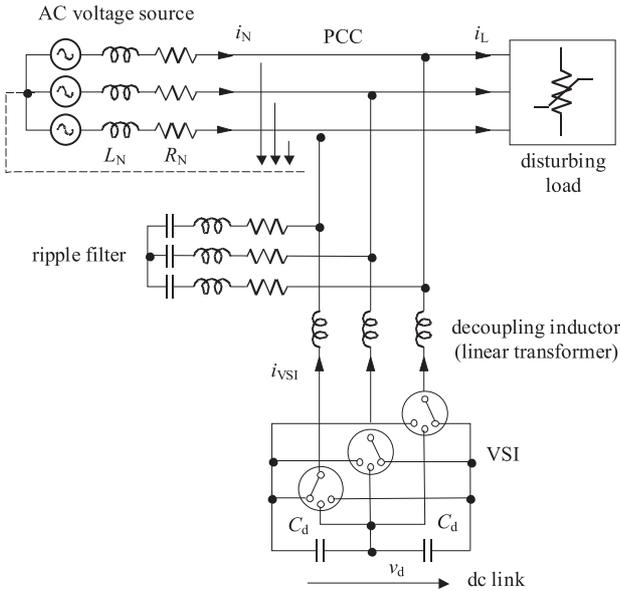


Fig. 1. The basic building block of a three-phase conventional shunt active power filter

PWM based inverter, which is used for both harmonics and reactive power compensation. The basic building block of the conventional shunt active power filter is shown in Fig. 1.

A. Analysis and Modelling:

The active power filter is composed of standard three-phase PWM based neutral point clamped (NPC) voltage source inverter bridges with two dc-bus capacitors to provide an effective current control [6]. A hysteresis based carrier less PWM current control is employed to give fast response of the active filter. Figure 2 shows the neutral point clamped two three-phase (PWM) voltage source inverter is simulated by MATLAB/SIMULINK, is connected in parallel to a harmonic polluted, 500 kVA power distribution system (at PCC).

Here, two dc-bus capacitors are connected to the input side by replacing the dc voltage source. Harmonics have little contribution to the capacitors charge because of their higher frequency, but the reactive current may dominate voltage ripples of the dc capacitors at the fundamental frequency. The modelled system (shown in Fig. 2) comprises an ac source, non-linear load, the shunt active power filter and the control scheme. The components of the system are analyzed separately and integrated to develop the complete model for the simulation.

B. AC Source and Nonlinear Loads:

An 11 kV, 50 Hz, 500 kVA ac source equivalent is stepped-down to 440 V, 50 Hz supply by a distribution transformer and this supply is fed to the point of common coupling (PCC), at which all the consumer loads (both linear and nonlinear loads) are connected as shown in Fig. 2, where a three-phase controlled thyristor bridge

with RL-loads, two uncontrolled diode bridge rectifiers are supplied to an industrial drive system and RL-loads, and a three-phase linear loads are taken as a nonlinear loads here.

C. Control Scheme:

The control scheme of each PWM inverter must calculate the current reference waveform for each phase of the inverter, maintain the dc voltage constant, and generate the inverter gating signals [1]. The block diagram of the current control scheme for each NPC inverter is shown in Fig. 3, which was implemented by MATLAB/SIMULINK tools. The switching frequency may be fixed by controlling the time between commutations and by not applying a new switching pattern if the time between two successive commutations is lower than a selected value ($t = 1/2f_c$) [5].

The discrete Phase-Locked Loop (PLL) block is a feedback control system that automatically adjusts the phase of a locally generated signal to match the phase of an input signal [14]. This block is most appropriate when the input is a narrowband signal. This PLL has these three components:

1. A multiplier used as a phase detector.
2. A filter specifies its transfer function using the low pass filter numerator and low pass filter denominator mask parameters.
3. A voltage-controlled oscillator (VCO) specifies the characteristics of the VCO using the VCO quiescent frequency, VCO initial phase, and VCO output amplitude parameters.

The three output ports of PLL produce

- i) The output of the filter,
- ii) The output of the phase detector, and
- iii) The output of the VCO.

The numerator of the low pass filter transfer function is represented as a vector that lists the coefficients in the order of descending powers of s . The denominator of the low pass filter transfer function is represented as a vector that lists the coefficients in the order of descending powers of s . This value scales the input to the VCO and, consequently, the shift from the VCO quiescent frequency value. The units of VCO input sensitivity are hertz per volt. The quiescent frequency of the VCO should match with the carrier frequency of the input signal when the applied voltage is zero.

D Performance of Shunt APF:

The following performances are observed by the system configurations:

1. The shunt APF current increases almost instantaneously to feed the increased load current demand by taking the energy instantaneously from dc-bus capacitors and its voltage recovers within a cycle.

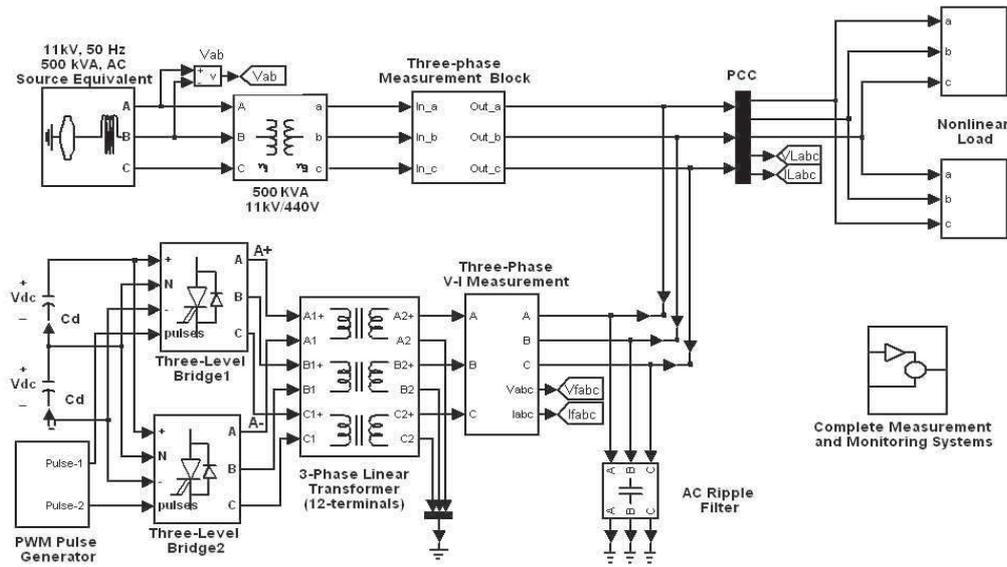


Fig. 2. Simulink block set for a shunt APF using three-phase NPC-PWM Inverter.

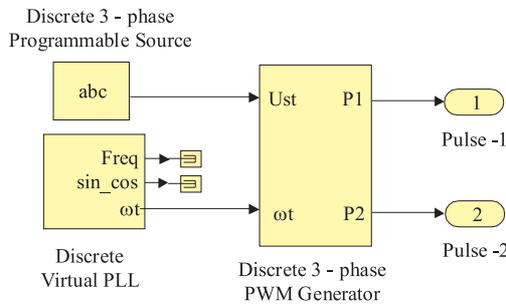


Fig. 3. Control block set of PWM generator for NPC inverter.

2. Source currents always remain sinusoidal and lower than the load currents under all operating condition and they settle to steady state value within a cycle.
3. The shunt APF meets the requirements of harmonic and reactive components of load current and maintains

the source currents sinusoidal under the steady state condition.

All the performance characteristics of the shunt APF, connected in parallel to a 500 kVA power distribution system are given in Figs. 4–7 illustrating under the steady state behaviour for different constant loads. The parameters of the system studied are given in the Appendix-I. Figure 4 shows the simulated source voltages (V_{abc}), 3-phase line currents (I_{abc}), corresponding active power (P) consumed by the loads from PCC, and reactive power waveforms. Figure 5 shows the simulated results on filter side, are three-phase filter output voltages (V_{fabc}) and currents (I_{fabc}), and its harmonic power (losses) output waveform.

Figures 6 and 7 illustrate the FFT of both (harmonic spectra) source voltage (V_{an}) and line current (I_a) at heavy (≈ 450 kW) load conditions. It may be observed from the harmonic spectra of Fig. 7 that the dominant

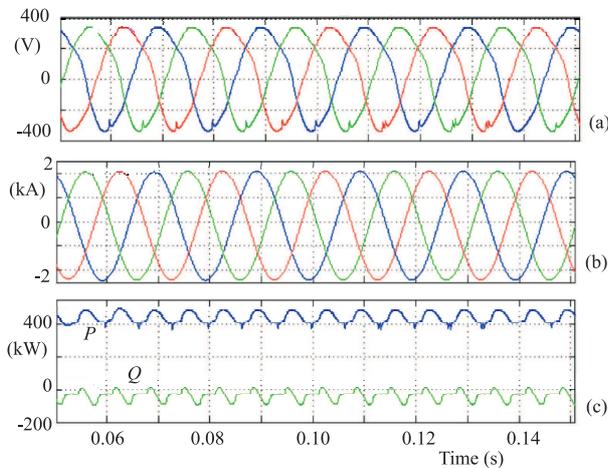


Fig. 4. Simulated waveforms on input source side: (a)- ac supply voltage, (b) - ac source current, (c) active and reactive power

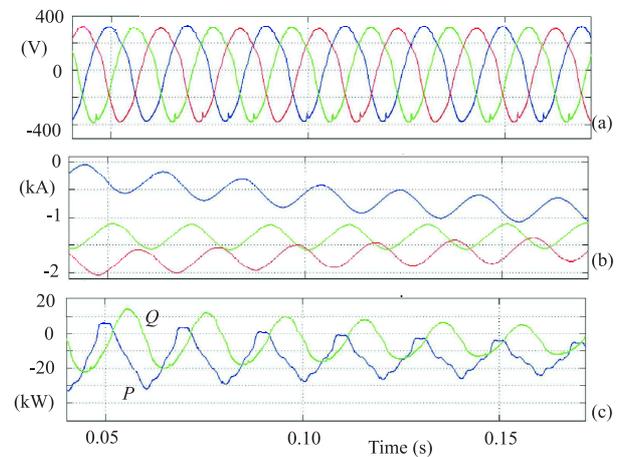


Fig. 5. Simulated waveforms on shunt APF output side: (a)- ac filter voltage, (b) - ac filter current, (c) active and reactive power

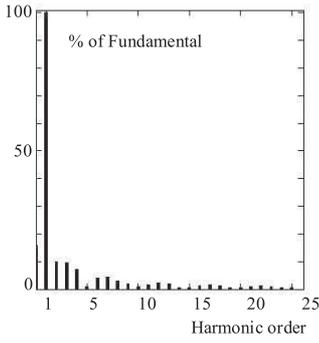


Fig. 6. Spectrum of input source voltage: $V_{an} = 290.5$ V peak at 50 Hz, THD=17.82%

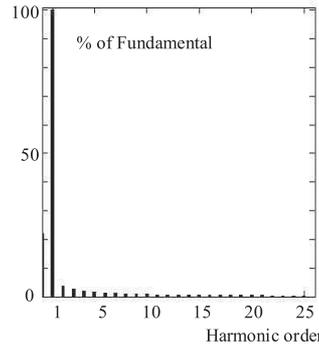


Fig. 7. Spectrum of input source line current: $I_a = 2.41$ kA peak at 50 Hz, THD=5.87%

harmonics in line currents are of order below 25th and the shunt APF is found not an effective to eliminate them.

However, the source currents are practically sinusoidal and in phase with the source voltage (*ie*, power-factor close to unity), the value of THD is 5.87 % during heavy load (≈ 450 kW) condition. So that, this type of shunt APF is not quit effective to reduce the THD well below the specified 5 % limit of standard IEEE-519 [15] and its harmonic power losses also increased in a manner. To reduce the harmonic power losses and obtain a high quality of both source voltage and current waveform with minimum amount of ripple content, a new multilevel inverter based shunt APF is proposed in the next section.

3 SYSTEM CONFIGURATION OF A NEW SHUNT APF USING THE PROPOSED CASCADED MULTILEVEL INVERTER

In this section, the proposed new shunt APF using a three-phase 11-level cascaded voltage source inverter is presented for getting high quality of source voltages and currents waveforms to the same distorted power system utility as taken in the previous section. Figure 8 shows the single line diagram of a power distribution system with the proposed new shunt APF, which is connected in parallel to the PCC. This section focuses on modelling of a new shunt active power filter and reveals a new switching angle control method for dc voltage balancing of 11-level cascade inverters.

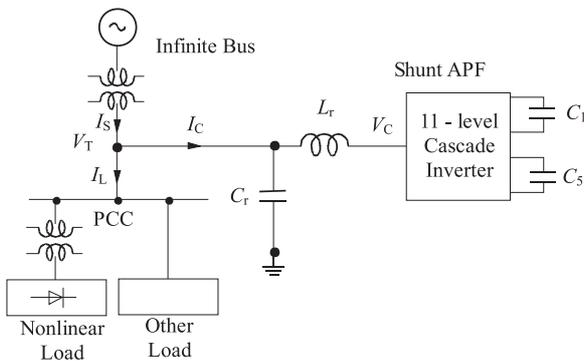


Fig. 8. Single line diagram of power distribution system with proposed new shunt APF.

A. Analysis and Modeling of a New Shunt APF:

The 11-level cascaded-inverter is connected to the power distribution system through a small filter, L_r and C_r . The control block diagram for the shunt APF is shown in Fig. 9. To compensate for reactive and harmonic current, the load current I_L is sensed, and its reactive and harmonic components are extracted. The current reference I_C^* can be the load reactive current component, harmonic component, or both, depending upon the compensation objectives. The cascade inverter has to provide a voltage V_C^* so that the filter current I_C tracks the current reference I_C^* . V_t is the line terminal voltage, and K is a gain. In a distribution system, the purpose of a shunt active power filter is to provide a constant and stable terminal voltage to loads. In this case, a constant sine wave is assigned to the voltage reference V_C^* .

An 11-level cascade-level inverter consists of 5 H-bridges, in which each bridge has its own separate dc-bus capacitor source. This new inverter can make possible direct connection to the 500 kVA, 440 V, 50 Hz distribution system in parallel without any additional transformer. By using MATLAB simulink tools the modeling of a new shunt active power filter implemented by 11-level cascaded-inverter, as shown in Fig. 10. A series reactance is required for coupling to the ac system. This required reactance can be naturally provided by leakage inductance of the service transformer that already exists in the power system [13]. Each phase of the cascade inverter consists of five H-bridge inverter units in series. With this structure, any voltage level is easy to obtain by increasing the number of inverter units.

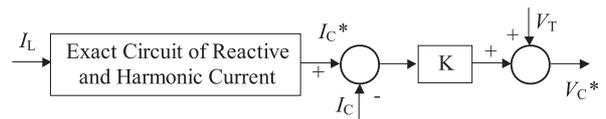


Fig. 9. Control block diagram of shunt APF

B Control of Cascade Inverter

1 Voltage Control:

The output phase voltage V_{Ca-n} is the sum of five H-bridge inverter units' outputs. The phase voltage magnitude is controlled by each inverter's duty cycle. For var compensation, the phase current i_{Ca} is always leading or lagging the phase voltage by 90° . The average charge to each dc capacitor is equal to zero over every half-line cycle for all pulses $P1-P5$. In other words, the voltage of each dc capacitor is always balanced [10], [12].

However, this is not true when the cascade inverter is applied to harmonic filtering. Figure 11 shows the waveforms, where, for instance, a fifth harmonic current needs

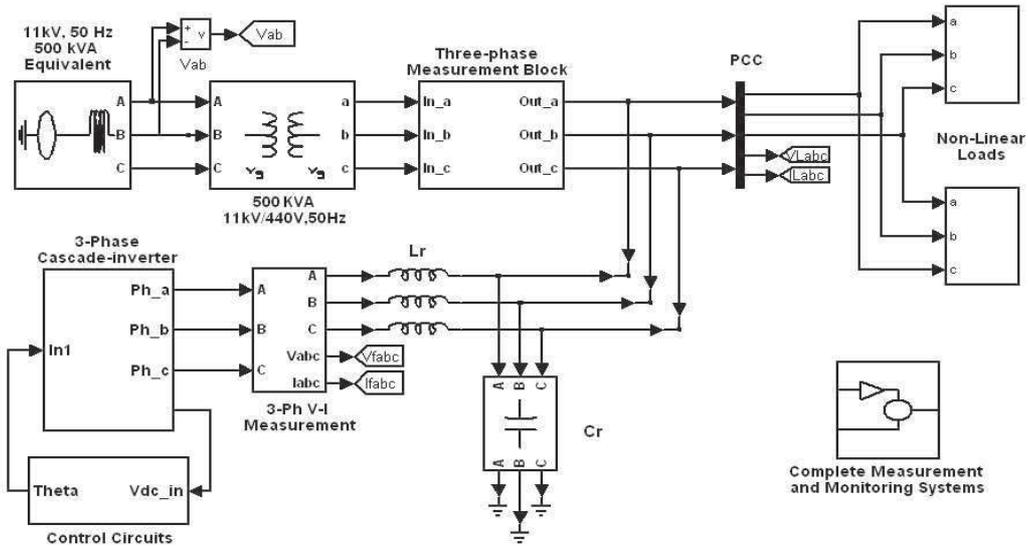


Fig. 10. Simulink model of a new shunt APF using 11-level cascaded-inverter

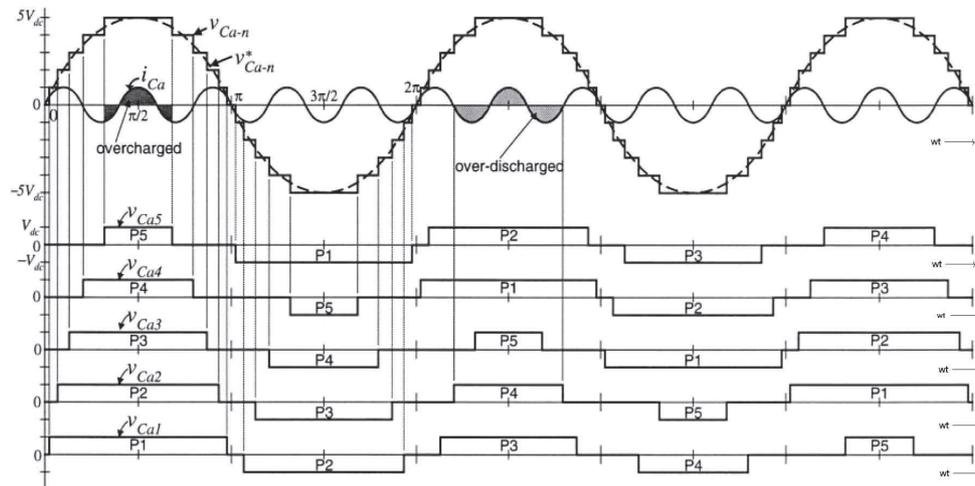


Fig. 11. Waveforms of the 11-level cascade inverter for harmonic filtering

to be absorbed by the inverter. In this case, as shown in Fig. 11., an H-bridge inverter unit will be overcharged if it repeats pulse P_5 and over discharged if it repeats pulse P_4 . In order to overcome this problem, swapping pulses every half cycle, as shown in Fig. 11, is proposed. As a result, all dc capacitors will be equally charged and balanced.

2 Voltage Balancing Control:

As shown in Fig. 11, rotating pulses P_1 - P_5 every half cycle among the five inverter units makes all dc capacitors equally charged and balanced over five half cycles. Therefore, in order to regulate all dc capacitors' average voltages, only one dc capacitor's voltage needs to be monitored and fed back. This feature makes control very simple and reliable. Figure 12 shows the complete control block diagram of the shunt APF.

To control all dc capacitors' voltages, a feedback loop is used. Note that only one dc capacitor's voltage is detected. In Fig. 12, a vector phase-locked loop (PLL) is used to get the phase angle of the line terminal voltage [9], [10], [13]. A proportional and integral (PI) controller is employed to regulate the dc capacitor's voltage.

A PI controller is the most popular feedback controller used in power systems. It is a robust controller and provides excellent performance despite their varied dynamic characteristics of power systems. The control action allows the process to accurately maintain set value by adjusting control outputs. Set value is required value and measurement are process variable. The variable being adjusted is called the manipulated variable which usually is equal to the output of the controller [9], [14].

Coefficients K_P and K_I are calculated under steady state method of limits [Refer Appendix-II]. The duty-cycle lookup table is shown in Fig. 13, the duty cycle data, θ_1 - θ_5 , is stored over one fundamental cycle. θ is the phase angle of the source voltage. Then the switching gate

signals are generated from the amplitude reference V_C^* and phase reference θ_C^* through the look-up table as shown in Fig. 13. Table 1 shows the switching phase sequences for single-phase leg of an 11-level cascaded-inverter, to control 20 switches at a fundamental cycle. A duty-cycle swapping circuit rotates pulses every half cycle.

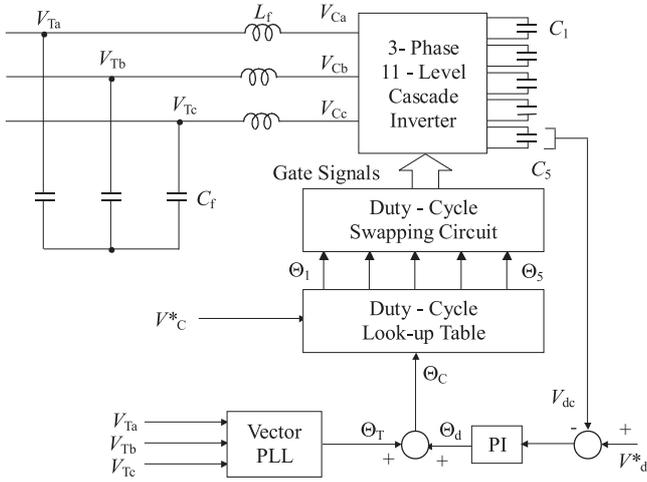


Fig. 12. Control diagram of a 3-phase 11-level cascaded-inverter

3 Required DC Capacitance:

From the cascade inverter structure, more capacitance is needed compared with a traditional two-level inverter. For the 11-level cascade inverter to compensate reactive power only, it has been shown that 1.36 times of conventional var compensator’s capacitance is required [2], [9]. For reactive power (var) and harmonic compensation, all dc capacitors should have an equal capacitance because of pulse rotation among the H-bridge units instead of fixed pulse patterns. In addition, the required capacitance should be determined in the worst case, which har-

monics have little contribution to the capacitors’ charge because of their higher frequency, but *the reactive current may dominate voltage ripples of the dc capacitors at the fundamental frequency*. Therefore, the required dc capacitance of each capacitor can be expressed as

$$C_{dc} = \frac{\Delta Q}{\Delta V_{dc}} = \frac{\int_{\theta_1}^{T/4} \sqrt{2} I_{Cq} \cos \omega t dt}{\Delta V_{dc}} \quad (1)$$

For modelling the power distribution system rating 500 kVA at 440 V ac line voltage the required capacitance C_{dc} is calculated from the equivalent of two-level dc-link voltage = $\sqrt{3} \times 5V_{dc} = 622$ V, the empirical value of discharging time is 15 to 30 ms. The dc capacitance is typically designed from the following formula [10]

$$\frac{1}{2} C_{dc} V_{link}^2 = 15-30 \text{ ms} \cdot P \quad (2)$$

where $sV_{dc-link}$ is the dc-link voltage and P the power rating. Therefore, for $P = 500$ kVA and 440 V ac line voltage, the energy storage capacity is $\frac{1}{2} C_{dc} V_{dc-link}^2 = 7500-15000$ Joules and the required dc capacitance C_{dc} is 3100–6200 μF . For the cascade inverter, dc capacitors are separately disposed to each H-bridge unit. From the above description, that the required dc capacitance of the cascade inverter is very practical, and the required energy storage capacity is actually smaller than that of the traditional neutral point clamped dc-link capacitance. An additional feature about the cascade inverter is that it boosts voltage, *ie*, each dc capacitor’s voltage is very low (72 V), whereas the ac output voltage is 440 V. This low-voltage/high-capacitance requirement makes multi-level inverters perfect for ultra capacitor (UC) applications.

C. Performance of the Proposed New Shunt APF:

The proposed shunt APF is modelled using an 11-level (21 line-to-line level) three-phase cascade inverter

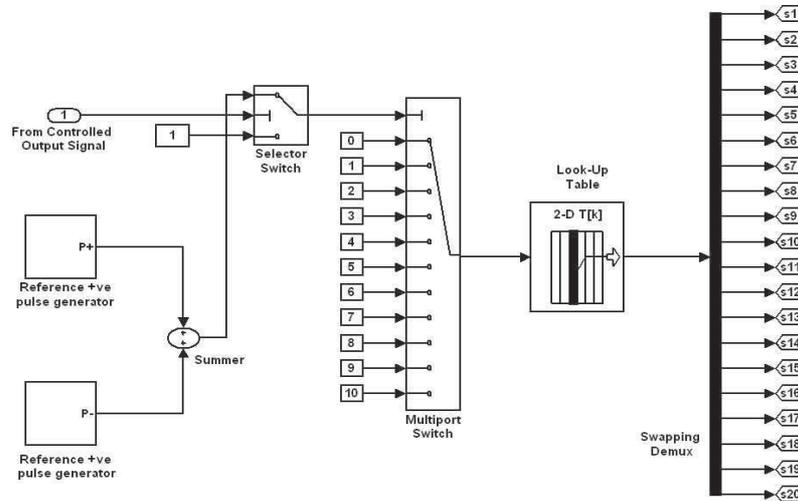


Fig. 13. Simulink block set for gate pulse generator of single-phase 11-level cascaded-inverter

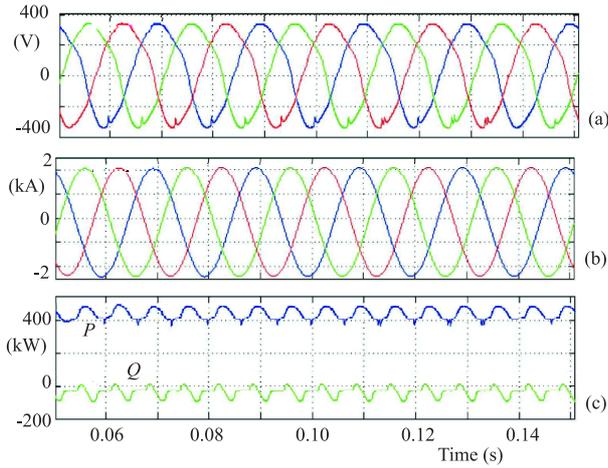


Fig. 14. Simulated waveforms on input source side: (a)- ac supply voltage, (b) - ac source current, (c) active and reactive power

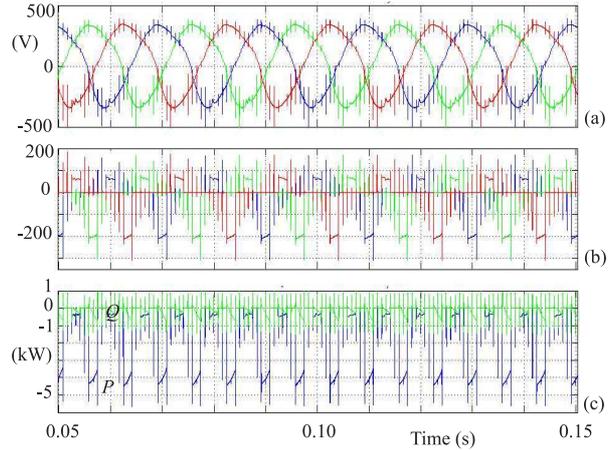


Fig. 15. Simulated output waveforms on filter side: (a)- ac filter voltage, (b) - ac filter current, (c) active and reactive power

in MATLAB and its performance characteristics are illustrated in Figs. 14–17. The new shunt APF adopts the conventional current injection method to compensate load harmonics and reactive power.

Table 1. Switching sequences of a single phase leg of three-phase 11-level cascaded-inverter.

switches used per leg		to generate positive waveform	to generate negative waveform	to obtain ground potential
S. N.	output level (M)	1 2 3 4 5	6 7 8 9 10	11 +ve side -ve side
1	S_1	1 1 1 1 1	0 0 0 0 0	1 0
2	S_2	0 0 0 0 0	1 1 1 1 1	1 0
3	S_3	0 0 0 0 0	1 1 1 1 1	0 1
4	S_4	1 1 1 1 1	0 0 0 0 0	0 1
5	S_5	1 1 1 1 1	0 0 0 0 0	1 0
6	S_6	1 0 0 0 0	0 1 1 1 1	1 0
7	S_7	0 0 0 0 0	1 1 1 1 1	0 1
8	S_8	0 1 1 1 1	1 0 0 0 0	0 1
9	S_9	1 1 1 1 1	0 0 0 0 0	1 0
10	S_{10}	1 1 0 0 0	0 0 1 1 1	1 0
11	S_{11}	0 0 0 0 0	1 1 1 1 1	0 1
12	S_{12}	0 0 1 1 1	1 1 0 0 0	0 1
13	S_{13}	1 1 1 1 1	0 0 0 0 0	1 0
14	S_{14}	1 1 1 0 0	0 0 0 1 1	1 0
15	S_{15}	0 0 0 0 0	1 1 1 1 1	0 1
16	S_{16}	0 0 0 1 1	1 1 1 0 0	0 1
17	S_{17}	1 1 1 1 1	0 0 0 0 0	1 0
18	S_{18}	1 1 1 1 0	0 0 0 0 1	1 0
19	S_{19}	0 0 0 0 0	1 1 1 1 1	0 1
20	S_{20}	0 0 0 0 1	1 1 1 1 0	0 1

Figures 14 and 15 show the simulated waveforms of source side and filter side voltages, currents and corresponding active and reactive powers. After the proposed shunt APF is connected in parallel with a 500 kVA power system utility, both the terminal voltage (at PCC) and

source current became sinusoidal. In addition, the source current became in phase with the terminal voltage. The shunt APF is injected compensation current containing both harmonic and reactive current. Note that the source current is a pure sine wave, whereas the terminal voltage is still slightly distorted. This is because the source current has to include some harmonics to cancel the source voltage background distortion (this is normally accomplished by a series passive or active filter combined with this shunt APF).

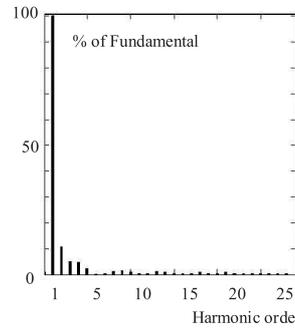


Fig. 16. Spectrum of input source phase-voltage: $V_{an} = 328$ V peak at 50 Hz, THD=13.36%

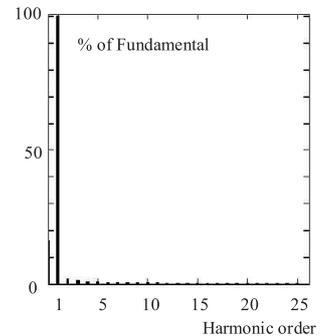


Fig. 17. Spectrum of input source line current: $I_a = 2.246$ kA peak at 50 Hz, THD=3.15%

Figures 16 and 17 illustrate the FFT of both source voltage (V_{an}) and line current (I_a) at heavy (≈ 450 kW) load conditions. It may be observed from the harmonic spectra of Fig. 17 that the dominant harmonics in line currents are of order below 25th and the proposed shunt APF is found an effective to eliminate them over the conventional shunt APF approach. The THD values of both voltage (V_{an}) and current (I_a) are 13.36% and 3.15% during heavy load (≈ 450 kW) condition respectively. So that, this type of shunt APF is quit effective to reduce the THD of current well *ie*, below the specified 5% limit of standard IEEE-519 [4], [15] and its harmonic power losses are dramatically reduced over the conventional PWM based shunt APF approach, stated in the previous section.

Table 2. Content of harmonics in source voltage (V_{AN}) (from the simulated results).

S No	Order of Harmonics	with shunt APF using PWM based inverter (in %)	with Shunt APF using cascaded-inverter (in %)
1	Fundamental	100	100
2	2 nd	10.92	10.00
3	3 rd	9.71	7.12
4	4 th	7.01	3.91
5	5 th	1.05	1.6
6	6 th	4.06	0.17
7	7 th	4.19	1.14
8	8 th	2.92	0.79
9	9 th	1.77	0.77
10	11 th	1.54	0.44
11	13 th	2.29	0.11
12	15 th	0.47	0.23
13	17 th	1.45	0.57
14	19 th	0.45	0.45
15	21 st	0.93	0.31
16	23 rd	0.76	0.41
17	25 th	0.41	0.12
	THD	17.82%	13.36%

4 COMPARISON BETWEEN PWM TECHNIQUE AND MULTILEVEL INVERTER APPROACH FOR SHUNT APF

The following results give the comparison between PWM and Multilevel Inverter methodologies of shunt APF. These results have been obtained using a FFT tool in MATLAB called 'Power-GUI editor' [14]. Tables 2 and 3 give the comparison of the voltage and current quality in terms of individual and total harmonic distortion (THD) obtained [3] with a shunt APF implemented by both the conventional PWM based inverter working at 10 kHz switching frequency, and the proposed 11-level cascaded inverter working at ≤ 1 kHz switching frequency.

Both tables 2 and 3 show the harmonics contents of source voltage (V_{an}) and current (I_a). There is an evident difference between the bad quality of the currents when PWM techniques are used and the excellent quality of the currents when multilevel-inverters are used for a shunt APF application. In fact, the more levels has the converter, the better the current, but with only five inverters the source current is almost a perfect sinusoidal waveform, because the active filter has 11-levels of voltage. In economical point of view, the proposed scheme could result in lower cost than the conventional PWM techniques. Because, the switches are used in multilevel inverters will be cheaper for their lower power ratings.

5 CONCLUSIONS

The shunt active power filters are implemented by using a conventional PWM based inverter and a three-phase

11-level cascaded voltage source inverter in MATLAB (using power system Simulink tools) and finally their simulated results are verified and compared (shown in table 4) for the harmonic polluted 500 kVA, 11 kV, 50 Hz power system utility.

Table 3. Content of harmonics in supply current (I_A) (from the simulated results).

S No	Order of Harmonics	with shunt APF using PWM based inverter (in %)	with Shunt APF using cascaded-inverter (in %)
1	Fundamental	100	100
2	2 nd	3.57	2.2
3	3 rd	2.55	1.38
4	4 th	1.91	1.07
5	5 th	1.52	0.83
6	6 th	1.25	0.7
7	7 th	1.08	0.62
8	8 th	0.94	0.54
9	9 th	0.85	0.48
10	11 th	0.69	0.39
11	13 th	0.59	0.33
12	15 th	0.51	0.29
13	17 th	0.45	0.25
14	19 th	0.40	0.23
15	21 st	0.36	0.20
16	23 rd	0.33	0.19
17	25 th	0.3	0.17
	THD	5.87%	3.15%

Table 4. Comparison of simulated results between PWM-based inverter and multilevel inverter approach for the shunt APF.

S No	power distribution parameters with two types of shunt APFs	for PWM-based shunt APF	for the new shunt APF
1	Active Power (P) in KW	443.1	441.2
2	Reactive Power (Q) in KVAR	47.08	57.2
3	Apparent Power (S) in KVA	445.62	445.00
4	Harmonic Power Losses in KW	15.58	2.050
5	Working Power-Factor $\cos(\varphi)$	0.9943	0.9916
6	THD of Supply Voltage (V_{an}) in % of fundamental component	17.82 %	13.36 %
7	THD of Supply Current (I_a) in % of fundamental component	5.87 %	3.15 %

The comparison results have shown that the proposed new shunt APF has been provided high-quality of both source voltages and currents to the power system utility than the conventional PWM based inverter approach. It has been shown in this paper, that the proposed shunt APF is only given a better solution and most suitable for both harmonics mitigation and reactive power (var)

compensation in power distribution systems, especially for medium/higher-voltage and high-power applications.

Thus, the proposed multilevel inverter provides higher performance, less EMI, and higher efficiency than the traditional PWM inverter. Because the switching frequency is the line frequency, switching losses and related EMI are negligible. A simple control scheme has been presented for both reactive power (VAR) and harmonic compensation, which ensures dc voltage balance.

Appendix

1 System Parameter Studies:

Source voltage line-line $V_s(rms) = 440$ V, $f = 50$ Hz, $C_{dc} = 4.7$ F calculated from the equation $C_{dc} = .0345 S_n / V_n^2$, where $V_n = V_C / 1.83$, $S_n = S_C^* / 0.087$, from [15] and the switching frequency $f_C = 10$ kHz with the switches (GTOs) parameters $R_s = 1$ M Ω , $C_S = \infty$ F, and $R_I = 0.1$ m Ω . Where,

- C_{dc} – dc-bus capacitance,
- V_n – nominal voltage rating of the capacitor C_{dc} ,
- V_C – RMS value of the line voltage ($V_C = V_s$),
- S_C^* – power rating of the capacitor at 50 Hz,
- S_n – apparent power rating of the distribution line,
- R_s, C_s – snubber resistance and capacitance of the switches,
- R_I – internal resistance of the switches.

2 PI Controllers Gain Constants

DC-Bus voltage PI controller gain constants are: $K_P = 0.1$ and $K_I = 1.0$

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