Neutral-point Voltage Control of Three-level NPC Inverter for Three-phase APF based on Zero-sequence voltage injection

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Abstract— **Active Power Filter (APF) has already adopted the three-level inverter topology in medium voltage and high-power application for solving power quality problems. Neutral-point voltage clamped (NPC) Inverter has become matured and widely used topology due to its robustness. However, neutral-point voltage at the DC-side need to be maintained as close to zero as possible. This paper focusses on the neutral point voltage control of the three-level NPC inverter based on multicarrier PWM by manipulating dwell time of small vectors by injecting zero-sequence voltage in modulating signal. The effectiveness of the presented method on three-level NPC inverter is validated via simulation in MATLAB/ Simulink. The results confirms the potentiality of the method in maintaining the neutral point voltage to minimum value with overall desired good APF compensation characteristics.**

I. INTRODUCTION

Industrial loads are mostly non-linear loads such as power electronic converters, frequency changers and motor drives are the prime sources for the harmonic pollution in power system. These non-linear devices not only deteriorate the power quality and power factor but also result in equipment failure connected to the grid [1], [2]. The Active Power Filters (APF) are the most viable solution to improve the power quality by mitigating these harmonics from power system [3], [4]. Although, there is a variety of two-level APF available for low voltage (below 690 volts) applications yet, for medium and high voltage filtering, APF with multilevel converter topologies is an optimal solution [5]. Unlike two-level voltage source converters, multilevel converters consist of cascaded sub-modules which improve waveform quality thereby reducing the losses and electromagnetic interference. Thus, multilevel converters such as (NPC) specifically has gained more attention in the research community in recent years [6], [7].

Although NPC is very popular for its performance, however, it has voltage unbalancing issue at its neutral point. This issue is more considerable when operating conditions such as load variations and modulation index are changed. This further enhances the voltage difference among capacitors; which eventually shifts the neutral point of NPC. The resulting imbalances do not only cause damages to switching devices, but it also introduce lower order harmonics in output voltage. As a result, the overall THD of the output current is increased [9]. There are several reasons for the change in dc link voltages which are:

- Inaccuracies during manufacturing process.
- Imbalance operation in three phases due to variations in operating conditions.
- Unreliable switching device characteristics.
- The differences caused by small voltage vector dwell time may influence the potential neutral point deviation.

As a rule of thumb, the voltage across each dc link capacitor in three level NPC must be half of the overall dc link voltage that can only be achieved via switching control algorithms. In literature, several neutral point voltages balancing schemes for space vector and carrier-based modulation techniques have been presented [9]–[11].

This paper focuses on sinusoidal PWM based zero-sequence voltage injection algorithm for neutral point voltage balancing in three-level NPC inverter for shunt APF.The algorithm is then verified and implemented in NPC inverter based APF in MATLAB/Simulink which shows the effectiveness of the algorithm.

II. THREE-LEVEL SAPF CONTROL STRUCTURE

A generalized control architecture for the three phase SAPF is shown in Fig. 1. The control system comprises of four sub-systems that includes reference current estimation, DC side voltage control, inner current controller and a feed-forward neutral point voltage controller. APF based three-level NPC inverter is the same as two-level inverter except a feed forward control is used to control neutral point voltage. In order to achieve compensation characteristics, the DC-link voltage should be at least as high as the nominal line to netural voltage, given as

$$vs \leq Vdc \leq 2vs$$

Compared to two-level inverter, the DC-side capacitor voltage rating in three-level NPC inverter is half of the total dc side voltage, and the minimum capacitance can be found by [11]

$$C \geq \frac{\left| \int_0^t idt \right|}{4\Delta V_{max}}$$

"i" represents injecting current, and ΔV_{max}" is the maximum allowable ripple voltage on DC-side capacitors.

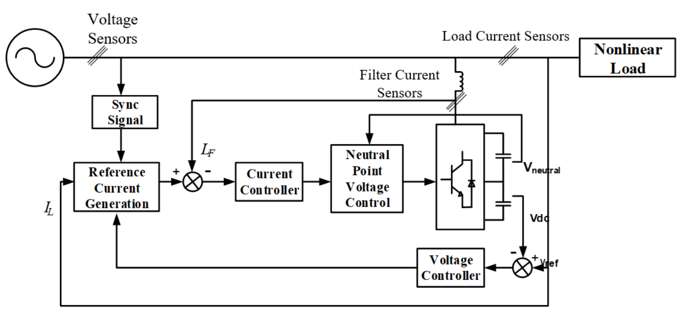

Fig. 1: Generalized Block of Three-level Shunt APF

III. Topology Review and Multi-carrier PWM

The NPC inverter comprises of the bidirectional switching devices (e.g. IGBTs, MOSFETs etc) and clamping diodes. The dc-side of NPC inverter consists of two capacitors which divide the dc-link voltage into three different voltage levels as shown in Fig. 2. The pair of switches operate in complementary fashion such that when switches S_1 and S_3 are ON, S_2 and S_4 are OFF and vice versa. The converter output is connected to $V_{dc}/2$ when S_1 and S_2 are ON; whereas, the output is -$V_{dc}/2$ when S_3 and S_4 are ON.

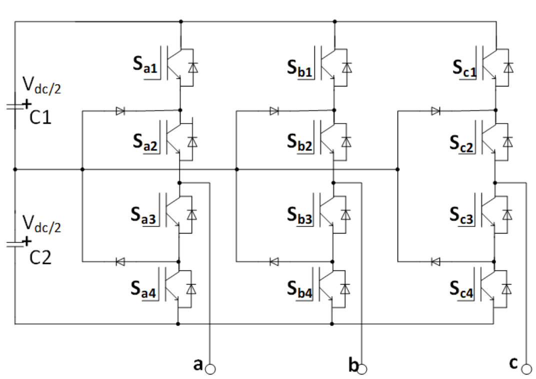

Fig. 2: Three-level NPC Inverter Topology

The different switching states for the NPC has been provided in Fig. 3. There are 27 (i.e. 3^3) different switching states in total for the three level NPC that are further bifurcated into small, medium, and large vectors. It is worth noting that not all vectors influence the neutral point potential. Since zero and large vectors do not connect any phase to neutral point, they do not influence neutral-point voltage. However, small and medium vectors do affect the voltage by connecting one or two phases to neutral-point and neutra-point voltage may rise or drop depending upon the current direction of the neutral point potential. Three phase positive sequence modulation voltage can be expressed,

$$\begin{cases} e_a = m\cos(\omega t) \\ e_b = m\cos(\omega t - \frac{2\pi}{3}) \\ e_c = m\cos(\omega t + \frac{2\pi}{3}) \end{cases} \tag{1}$$

where m is the modulation index. Sinusoidal PWM is

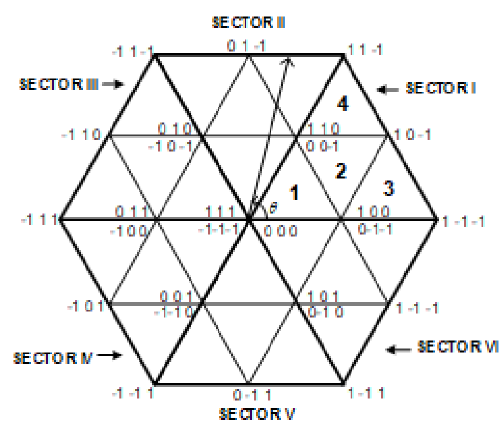

Fig. 3: Switching States of Three-level NPC Inverter Topology

one of the most popular modulation techniques in which a sinusoidal modulating (control) signal is compared with the triangular carrier signal as shown in Fig. 4. It works in a fashion when a modulating signal is higher than the carrier signal, the switch is ON otherwise OFF. For a positive half cycle of the modulating signal switches S1 and S3 are turned ON once in each control period and reverse is true for switches S2 and S4 in negative cycle. Besides, During positive cycle S2 and S4 remain invariant and keep themselves at 1 and 0 respectively, while the state of S1 and S3 remain unchanged for negative cycle.

IV. Neutral-Point Voltage Balance Control through Zero-sequence Voltage Injection

Switching states for the three-level NPC are expressed as:

$$V_{ss} = [S_a, S_b, S_c]^T$$

$$S_x \in [-1, 0, 1], x \in [a, b, c]$$

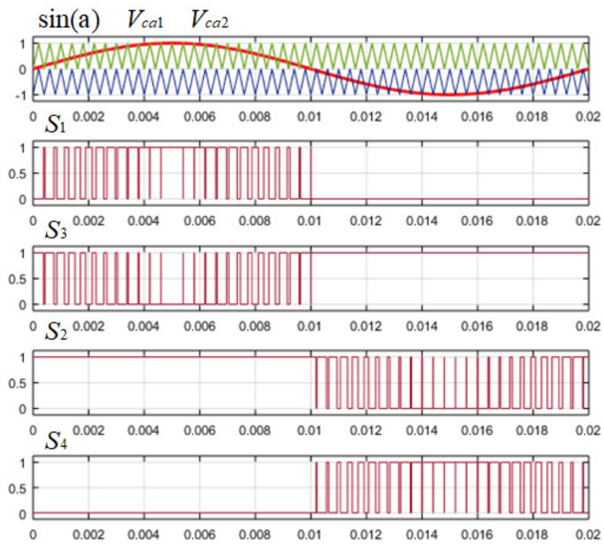

Fig. 4: Multi-carrier PWM Strategy for three-level NPC inverter

The load current of one phase which is clamped to neutral point flows out of the neutral point through the respective clamped diodes. This neutral current can be written as

$$i_{neu} = (1 - |S_a|)i_a + (1 - |S_b|)i_b + (1 - |S_c|)i_c$$

$$i_{neu} = - |S_a| \, i_a - |S_b|)i_b - |S_c| \, i_c \tag{2}$$

The zero sequence voltages are injected into reference voltages given by

$$\begin{cases} U_a = e_a + U_0 \\ U_b = e_b + U_0 \\ U_c = e_c + U_0 \end{cases} \tag{3}$$

The sign function can be defined as

$$sgn(v) = \begin{cases} 1 & v \geq 0 \\ -1 & v < 0 \end{cases} \tag{4}$$

Hence, average neutral current can be obtained by inserting (3) and (4) into (2)

$$\begin{aligned} i_{neu} = & -[\text{sgn}(e_a).e_a.i_a + \text{sgn}(e_b).e_b.i_b + \text{sgn}(e_c).e_c.i_c] \\ & -U_0[\text{sgn}(e_a).i_a + \text{sgn}(e_b).i_b + \text{sgn}(e_c).i_c] \end{aligned} \tag{5}$$

In steady state, the average neutral current should be controlled to zero in order to implement the NP balancing control. The zero-sequence voltage can be controlled as

$$U_0 = -\frac{\text{sgn}(e_a).e_a.i_a + \text{sgn}(e_b).e_b.i_b + \text{sgn}(e_c).e_c.i_c}{\text{sgn}(e_a).i_a + \text{sgn}(e_b).i_b + \text{sgn}(e_c).i_c} \tag{6}$$

The neutral point voltage can be regulated by properly adjusting the neutral current. For simplification, the positive sequence modulating signal is divided into six different parts as shown in Fig. 5.

It is clear from the Fig. 5. that only one of the phases has the maximum amplitude during each interval. For instance, Phase A has maximum amplitude during $[-30°, 30°]$, whereas phases B and C has the peak amplitudes during the intervals $[-90°, 150°]$ and $[-210°, 270°]$ respectively. It means there is specific phase current in each interval which influences the neutral point voltage. Each interval further consists of set of small vectors which can be controlled in order to maintain the neutral point potential, as given in Table 2.

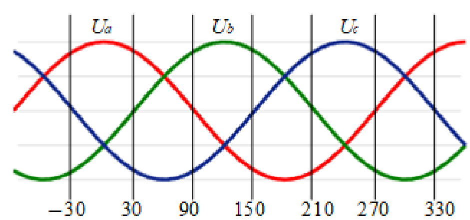

Fig. 5: Six Sectors of Modulation Voltage

Based on multi-carrier modulation method, the appropriate zero-sequence component can be estimated using current direction and difference of the two dc link capacitors. Injection of zero-sequence voltage into modulating voltage actually change the dwell time of the redundant small vectors and NP balance control is achieved. Adding positive zero sequence voltage increases the action time of the small vector type P whereas, the action time of the small vector type N rises by adding negative zero sequence voltage. For instance, during the interval $[-30° \leq \theta \leq 30°]$ if neutral point voltage is greater than the zero and its current direction is towards the neutral point, then by injecting positive sequence voltage the neutral point voltage can be reduced. On the other hand, if neutral point potential is less than zero and current direction

TABLE I: Small Vector and corresponding current in each sector

Sectors	***P-Type Small Vector***	i_{neu}	***N-type small vectors***	i_{neu}
$-30° \leq \theta \leq 30°$	[1 0 0]	$-i_a$	[0 -1 -1]	i_a
$30° \leq \theta \leq 90°$	[1 1 0]	i_c	[0 0 -1]	$-i_c$
$90° \leq \theta \leq 150°$	[0 1 0]	$-i_b$	[-1 0 -1]	i_b
$150° \leq \theta \leq 210°$	[0 1 1]	i_a	[-1 0 0]	$-i_a$
$210° \leq \theta \leq 270°$	[0 0 1]	$-i_c$	[-1 -1 0]	i_c
$270° \leq \theta \leq 330°$	[1 0 1]	$-i_c$	[0 -1 0]	i_c

is into the neutral point, then by adding zero sequence voltage the neutral point voltage can be increased. However, the injection of zero-sequence voltage should follow the constraint given,

$$|e_a + U_0| < M$$

The injection method of zero sequence voltage consists of following steps,

- Conversion of three phase modulation waveform from abc to $\alpha\beta$ plane.
- Find the angle of rotation θ through U_α,U_β
- Finding out the sector using θ
- Add the zero-sequence voltage based on the neutral point voltage and phase current direction.
- Finally, three-phase modulating signal is sent to modulation block to generate the PWM signal for IGBTs

It is observed that the balancing techniques for neutral point voltage use some sort of zero sequence voltage manipulation in case of carrier based PWM. Whereas, all NP balancing schemes in SVM are also based on the same concept of manipulating redundant small vector switching levels. Since the difference between the phase voltage of the positive and negative small vector in the same pair is zero sequence voltage, the small vector manipulation is the zero-sequence voltage manipulation. This appears to be the equivalence between NP balance control systems based on carrier and SVM based PWM schemes.

V. Simulation Results

The simulations of the Shunt APF connected to a three-phase rectifier as non-linear load are performed in MATLAB/SIMULINK environment. The midpoint voltage control is based on a zero-sequence voltage injection using the carrier based PWM modulation scheme is shown in the Fig. 6. It can be seen that the maximum midpoint fluctuation voltage is 5 V, which is reasonable. As the value of the dc side capacitor may not have exactly the same in the actual systems. In order to realize the efficacy of the control of the midpoint potential in extreme scenario, two capacitance values are set at 4000 F and 6000 F, with initial voltages set at 412 V and 338 V respectively while keeping the remaining parameters unchanged. Under these circumstances, the simulation is given in Fig. 7, showing that both capacitors maintain the equal potential in just 0.08s.

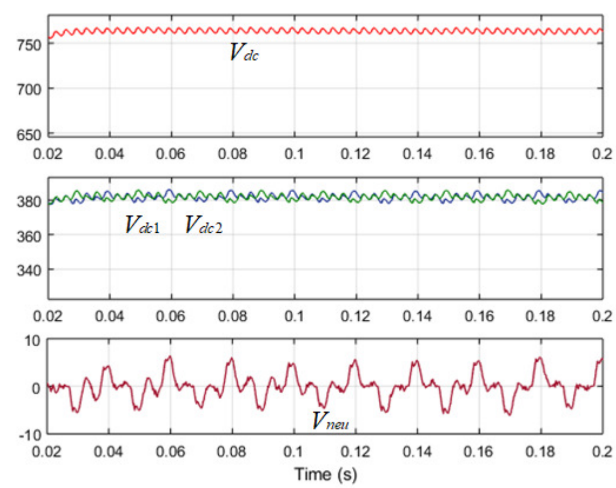

Fig. 6: Midpoint voltage control waveform with same capacitors value

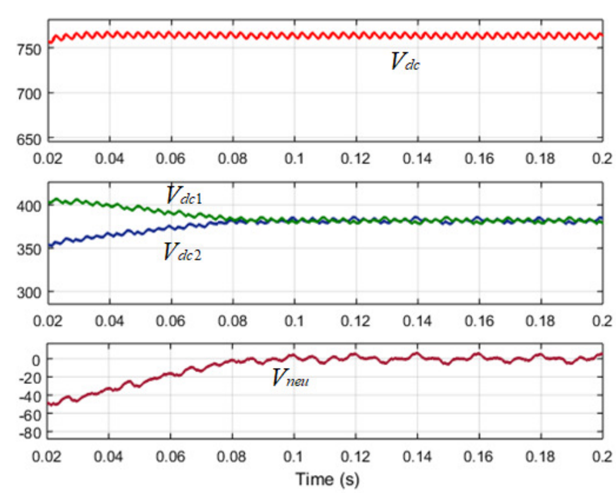

Fig. 7: Midpoint voltage control waveform with different capacitors value

Fig. 8. shows DC-side voltage and the midpoint response during load changes suddenly, which shows the DC-side voltage and the midpoint voltage fluctuations also increase due to the sudden increase in the APF output current. This results in a sudden increase in the neutral current, nevertheless, the dc-side and midpoint potential fluctuations are still less than 5 (RMS). The results of the three-level APF compensation are provided in Fig. 9, which represent the load current, filter and grid currents. Approximately 90% harmonic reduction occurs after compensation can be clearly seen.

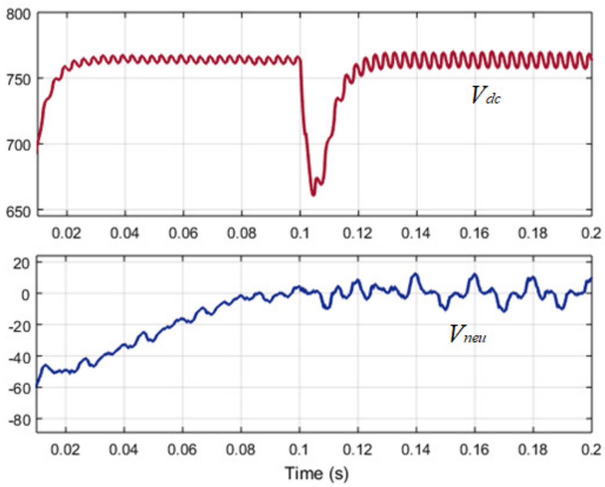

Fig. 8: DC side voltage and neutral point voltage during load change

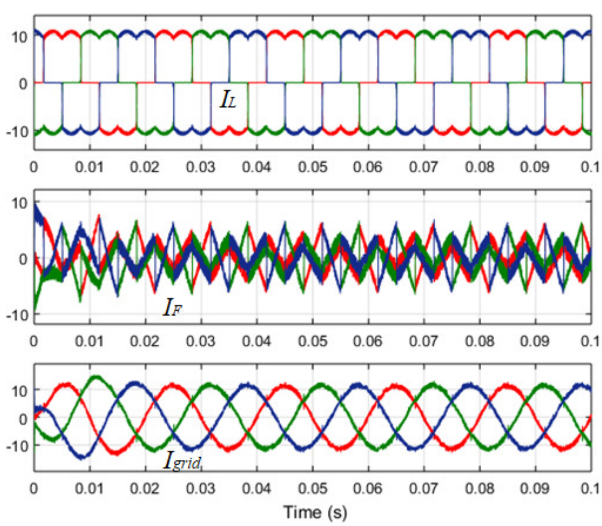

Fig. 9: Compensation effect of three-level APF

VI. CONCLUSIONS

This paper demonstrated the neutral point voltage deviation control in three-level NPC inverter based shunt APF. By using the voltage difference of two DC-link capacitor and the direction of neutral current, a zero sequence component is estimated and added to modulating signal before sending it to carrier-based PWM. This zero-sequence component manipulates the action time of the small vector and hence regulates the neutral point voltage near to zero. Consequently, voltage across each capacitor maintain exactly half of the total DC-link voltage. The simulation results confirms the effectiveness of the presented method in shunt APF compensating the harmonics to mimimum with overall THD reduced to less than 5%.

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