Grid Connected WECS with Multi-Level NPC Shunt Active Power Filter

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Abstract— This paper presents the efficient operation of three-level Neutral Point Clamped (NPC) Shunt Active Power Filter (SAPF) for interconnecting the WECS (Wind Energy Conversion System) to the utility grid using an extended reference signal generation scheme. The proposed topology provides wind power generation in addition to the current compensation function. The SAPF wants a supply of energy for compensate the current based disturbances in the load current, which utilizes the WECS with DC-DC converter like a DC power source. The shunt connected inverter controls the DC-link voltage along with the active and reactive power transferred from the renewable energy sources to grid with improved power quality. The modified p-q theory is used for reference current generations. To maintain the DC link voltage as constant and compensate the power losses of the Voltage Source Inverter (VSI) a PI controller is used in the outer control loop. The gating signals for the switches are generated from the carrier based Sinusoidal PWM (SPWM) technique. The main features of the proposed system are that it will provide the continuous current based compensation for throughout the day and recompense the voltage interruption. These systems make use of the wind energy and accordingly save the electrical energy and offer uninterruptable power supply to important/sensitive load. The simulation results are presented to verify the effectiveness of the proposed configuration.

Key words: Wind Energy Conversion, High Step-Up DC-DC Boost Converter, Three-Level NPC Voltage Source Inverter, Reference Current Generation, Total Harmonic Distortion (THD)

I. INTRODUCTION

Wind energy has massive potential to offer energy with minimal impact on the environmental surroundings, because it is hygienic and pollution free. On the other hand, severe regulations have already been applied to the apparatus connected to the utility grid. A number of these rules and regulations are related to harmonics disturbances and power factor. However, with the growth of power electronic converters are increasing in the meting out of electrical energy in the industrial applications like as adjustable speed drives, digital power supplies, direct current (DC) motor drives, battery chargers, etc. These units are non-linear loads which receive nonlinear currents from the source and despoiled the power quality (PQ) in the power distribution system [1]. The cruel power quality problems issues in the distribution systems are for example flicker, resonance and electromagnetic interference with electronic equipment, power losses and heating in transmission lines, vibrations and noise in motors, malfunction of metering/sensitive apparatus. The numerous Custom power devices have been utilized to improve the power quality and stability of electrical power system. Primarily, passive filters with tuned *LC* components normally used to control the voltage and current harmonics because it is low cost, simple in configuration and high efficiency [2, 3].

However, the passive filters have large numbers of disadvantages such as fixed compensation, large size, parallel and series resonance with load and utility grid impedances [4]. All the above mentioned disadvantages of passive filters can be prevail over by using active power filters (APFs) [5, 6] for the compensation of harmonics and reactive power. The APFs can be classified into two types based on their system configuration such as series and shunt active filters. The combined configuration of series and shunt APFs is named the unified power quality conditioner (UPQC). The shunt active filter is the most vital corrective measure to eliminate the source current harmonic issues [7].

The SAPF is connected in parallel to the load that produces the compensation current to eliminate the harmonics in the load current. Nowadays, multilevel Neutral Point Clamped (NPC) inverter has become progressively more splendid in the active power filter application scenario. This is due to the superior compensation capability procured from this topology, besides it requires smaller size of filter elements. In addition to that it yields the higher efficiency, low dv/dt, diminished common-mode voltages and low electromagnetic interferences [8]. The reference current generation methods decide the performance of active filter topology. Hence, any incorrectness in the reference currents gives up to wrong compensation [9]. The different methods have been proposed to determine the reference current of the SAPF [10]. The conventional instantaneous reactive power theory or p-q theory is the generally used method to generate reference current [11]. This p-q theory requires numerous transformations and assumes the system as balanced one that will be not the real condition of electric power system [12]. To overcome this complexity the proposed control scheme utilized the modified p-q theory. In this method, the High Selectivity Filter (HSF) has been employed as an alternative of classical harmonic extraction filters. After the well-organized generation of the reference current, suitable SAPF currents controller is used to keep up the active power filter currents at the required reference value [13, 14].

Numerous controllers such as PI, PID, etc. are utilized by many authors to achieve the efficient compensation. But, the PI controller desires a precise linear mathematical model, which is difficult to acquire and can not give better results under different conditions for example parameter variations, unbalanced or distorted voltages, etc.. The fuzzy logic controllers have unique features over the PI controller such as: it does not necessitate a defined mathematical model; it is capable to work with incorrect inputs, it is able to handle nonlinearity and it is potent than the PI controller [15, 16]. This paper extends the use of the HSF within the SAPF based on a three-level inverter for a three-phase distribution system under the unbalanced conditions. The objectives of this paper are to sustain the DC link voltage of the three-level NPC shunt connected inverter to afford endless compensation, make use of the green energy and offer the uninterruptable power to the load. The WECS interfaced DC-DC boost converter used to maintain the DC-link voltage as constant. The simulation results are presented to confirm effectiveness of the proposed method.

II. WECS SUPPORTED THREE-LEVEL NPC SHUNT ACTIVE POWER FILTER

The SAPF provide the current harmonics reduction by injecting the current which is equal but is achieved in the shunt active power filter by the injection of equal but opposite phase of the harmonic current components at the PCC, consequently it formulates the source current in phase with the source voltage.

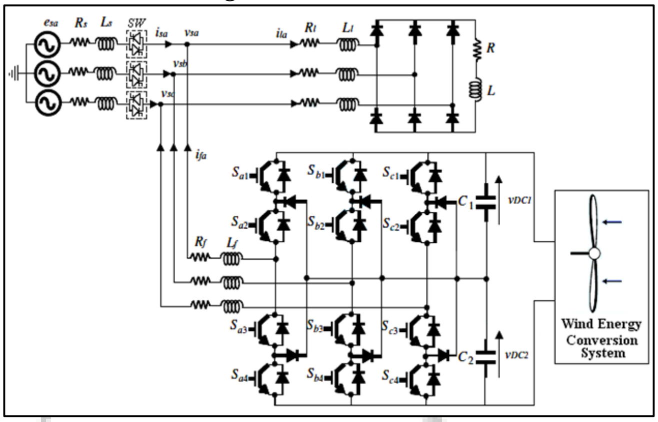


Fig. 1: WECS based Neutral Point Clamped shunt active power filter configuration

The wind energy conversion based SAPF topology is shown in Fig.1 For 3-level NPC inverter, each leg is composed by four controllable switches ($S_{x1} - S_{x4}$) , where x is specified phase(a , b , or c), with the two clamping diodes[17,18]. If we think about that two capacitor voltages v_{DC1} and v_{DC2} in the DC link are equal, three voltage levels (0, $v_{DC}/2$ and $-v_{DC}/2$) are created on the AC terminal output of the anticipated inverter. It is contained that the upper-leg and lower-leg capacitor voltages are impossible to differentiate, with the value $v_{DC}/2$ each. The phase-to-midpoint voltage of every phase can be defined as:

$$v_{fx} = C_x v_{DC} / 2 \qquad (1)$$

Where x is the phase index, x = a,b, c ; C_x is the state variable, C_x = 1, 0, -1 and corresponding to the 3-levels are $v_{DC}/2$, 0 and $-v_{DC}/2$.

C_x	S_{x1}	S_{x2}	S_{x3}	S_{x4}	v_{fx}
1	1	1	0	0	$v_{DC}/2$
0	0	1	1	0	0
-1	0	0	1	1	$-v_{DC}/2$

Table 1: Switching states of 3 level NPC inverter

Then, the phase to neutral voltage of the inverter can be noted as:

$$v_{fa} = \frac{v_{DC}}{3}\left(C_a - \frac{C_b}{2} - \frac{C_c}{2}\right) \qquad (2)$$

$$v_{fb} = \frac{v_{DC}}{3}\left(C_b - \frac{C_a}{2} - \frac{C_c}{2}\right) \qquad (3)$$

$$v_{fc} = \frac{v_{DC}}{3}\left(C_c - \frac{C_a}{2} - \frac{C_b}{2}\right) \qquad (4)$$

At the voltage interruption time, the WECS-SAPF affords the uninterruptable power to the load, through the WECS with DC-DC converter throughout the day and night time respectively. The grid power supply source is disengaged through the semiconductor switches (S_1 & S_2), once a rare power interruption happens in the received power supply. The schematic diagram of the WECS is shown Fig.2. It includes wind turbine, PMSG, 3-phase diode bridge rectifier and low step-up DC-DC boost converter [19, 20]. The wind generator is used to supply the DC power source for DC link of the SAPF for the purpose of providing compensation of harmonics and voltage interruption.

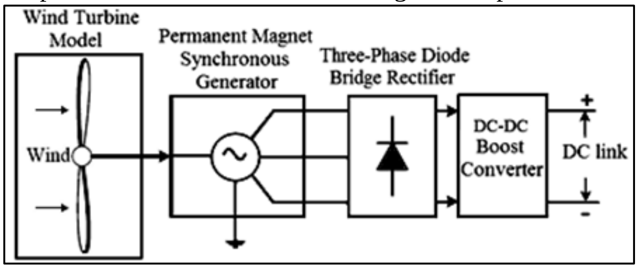


Fig. 2: Block diagram of WECS

III. CONTROL SCHEME OF SAPF

The proposed control scheme of the three-level NPC SAPF involves the following sections: find the harmonic content in the load current and work out a synchronised reference, generation of the gate signal of the switches, provide the closed-loop control to compel the filter current to track the reference valus and to maintain the DC link voltage of SAPF to sustain the DC voltage at a invariable value.

A. Calculation of Reference Currents

To achieve the control function of SAPF, current should be injected to the line that is equal in the amplitude and opposite in direction of the load harmonics current. Thus, a reference current was essential to calculate the injected current magnitude. In this control strategy the reference current is obtained through the sensed magnitude by the use of the instantaneous reactive power theory with 2 HSFs. The main functions of this approach are concised in the block diagram shown in Fig. 3. The reference currents are determined by using modified p-q theory. The HSFs are used in place of classical harmonic removal filter such as High Pass Filters (HPF) or low pass filters (LPF).

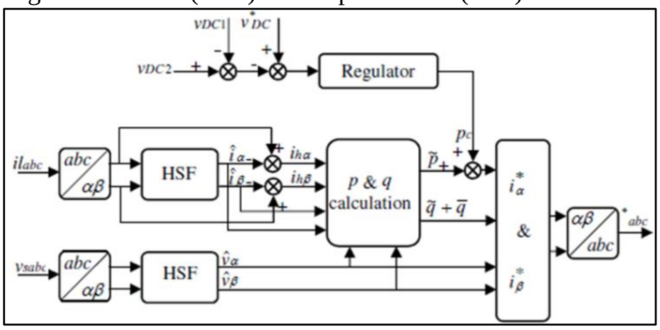


Fig. 3: Block diagram of proposed controller

With the use of instantaneous reactive power theory, the system voltage and the load current are transformed from a- b- c coordinates into α-β coordinates using the transformations (5) [21-24]:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{la} \\ i_{lb} \\ i_{lc} \end{bmatrix} \qquad (5)$$

The alternating components of the instantaneous real and imaginary power are given by

$$\begin{bmatrix} \tilde{p} \\ \tilde{q} \end{bmatrix} = \begin{bmatrix} \hat{v}_\alpha & \hat{v}_\beta \\ -\hat{v}_\beta & \hat{v}_\alpha \end{bmatrix} \begin{bmatrix} i_{h\alpha} \\ i_{h\beta} \end{bmatrix} \qquad (6)$$

Basic component of the instantaneous imaginary power is given as in the Equation (7)

$$\bar{q} = \hat{v}_\beta \, \tilde{i}_\alpha - \hat{v}_\alpha \, \tilde{i}_\beta \qquad (7)$$

When the active power is added for regulating the DC link voltage, p_c, to the alternative component of the instantaneous real power, $\tilde{p}$, the current references in the α - β reference frame are calculated as follows:

$$i^*_\alpha = \frac{\hat{v}_\alpha}{\hat{v}^2_\alpha + \hat{v}^2_\beta}(\tilde{p} + p_c) - \frac{\hat{v}_\beta}{\hat{v}^2_\alpha + \hat{v}^2_\beta}(\tilde{q} + \bar{q}) \qquad (8)$$

$$i^*_\beta = \frac{\hat{v}_\beta}{\hat{v}^2_\alpha + \hat{v}^2_\beta}(\tilde{p} + p_c) - \frac{\hat{v}_\alpha}{\hat{v}^2_\alpha + \hat{v}^2_\beta}(\tilde{q} + \bar{q}) \qquad (9)$$

To obtain the reference compensation current in the *a-b-c* co-ordinates, the inverse of the transformation given in expression (10) is used as follows:

$$\begin{bmatrix} i^*_a \\ i^*_b \\ i^*_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i^*_\alpha \\ i^*_\beta \end{bmatrix} \qquad (10)$$

B. SAPF Gating Signals Generation

The performances of SAPF will depend in actual fact on the type of modulation and implemented control scheme. The different types of modulation techniques have been proposed for multilevel converters in three-phase system. In this control scheme, the carrier-based Sinusoidal Pulse Width Modulation is employed to generate the suitable switching signals of the power switches, because it has the advantage of making appreciably simpler the calculation procedure and due to their operation at fixed switching frequency [25-28].

The switching SPWM pulses are generated by subtracting the filter currents (i_{fa} ,i_{fb} ,i_{fc}) with the reference currents(ia^* , ib^* , ic^*). The resulting error (e) ($e = i^* - i_f$) is sent to a fuzzy logic controller.

Then the output signal of the fuzzy logic controller is compared with a two triangular carrier bipolar signals shown in Fig. 4.

The comparison result is sent to the combinational logic circuit for the switching devices. Here, the gating signals generator has three inputs: $\Delta i_f = i^* - i_f$ (corresponding to Δi_{fa}, Δi_{fb} and Δi_{fc}), the first carrier-signal C_{s1}, and the second carrier-signal C_{s2}.

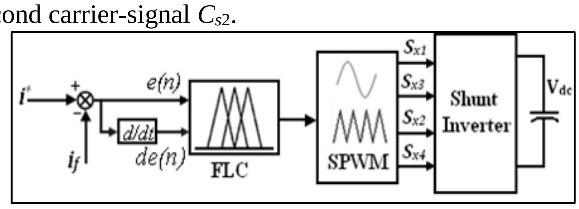


Fig. 4: Gate Signal Generating Scheme

Initially, we have to determine the intermediate signals $T_{1,}$ T_2 and T_3 as follows:

- if $\Delta if \geq Cs_1$, then $T_1 = 1$, else $T_1 = 0$;
- if $\Delta if \geq Cs_2$, then $T_2 = 0$, else $T_2 = -1$;
- $T_3 = T_1 + T_2$.

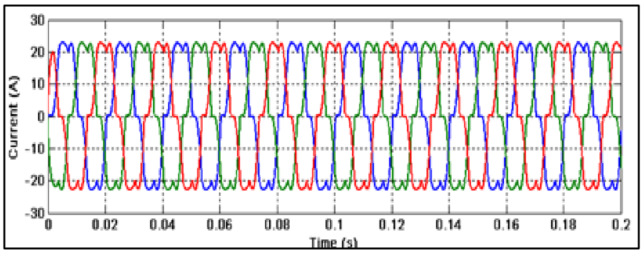
After that, we obtain the switching function of the two switches S_{x1} and S_{x2} of the upper leg x ($x = a,b,c$), the two other legs have switching signals delayed of 120° compared to the first one, and the lower half bridge contains the complementary switches. The WECS connected with DC-DC boost converter supervises the DC-link to offer continuity of compensation effectively. In the present control scheme, PI voltage controller is used to keep the DC-bus voltage constant.

IV. Simulation Results

In this paper, the proposed control method based on a modified version of p-q theory using a HSF for the WECS based SAPF is estimated utilizing Matlab/Simulink. In the simulation studies, the results are precise before and after the function of the WECS based three-level SAPF system. The simulation study was conducted under three different conditions are balanced voltages with balanced loads, balanced voltages with unbalanced loads and unbalanced voltages with unbalanced loads. The comprehensive simulation results are presented below.

A. Balanced Voltages with Balanced Loads

Fig. 5 Shows the simulation results of load currents($\boldsymbol{i}_{labc}$), source currents($\boldsymbol{i}_{sabc}$),active filter currents($\boldsymbol{i}_{fabc}$), inverter output line voltage, and source voltage($\boldsymbol{e}_{sa}$) superimposed by the source current($\boldsymbol{i}_{sa}$) of the proposed system for the case of balanced condition. Fig. 5(e) shows the source current ($\boldsymbol{i}_{sa}$) after the compensation, from this result examined that the source current is in phase with source voltage ($\boldsymbol{e}_{sa}$) confirming that the compensation is being done correctly. The harmonic analysis of the source current before and after compensation in phase "*a*" are shown in Fig. 6(a) and 6(b) respectively. Prior to compensation, the measured THD level of the source current in phase "*a*" was 25.65% ; after compensation, the THD level of the source current is about 1.54% , which is well within the limit specified by IEEE Std. 519-1992.



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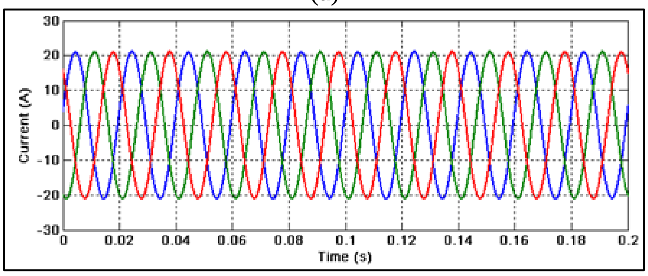

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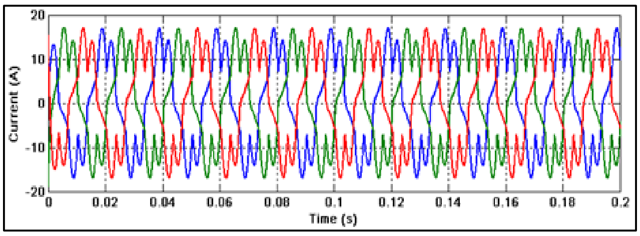

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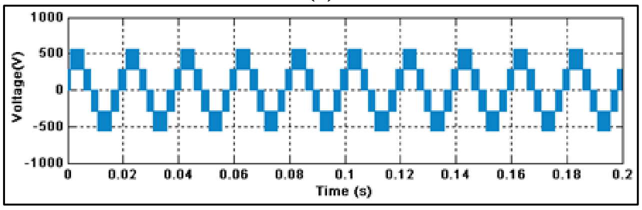

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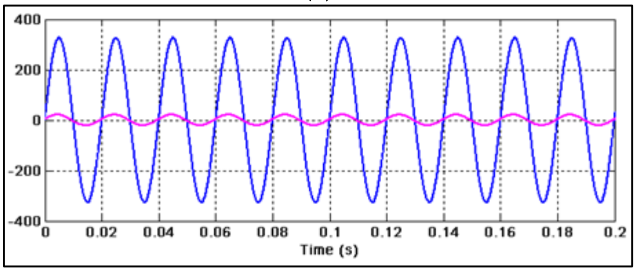
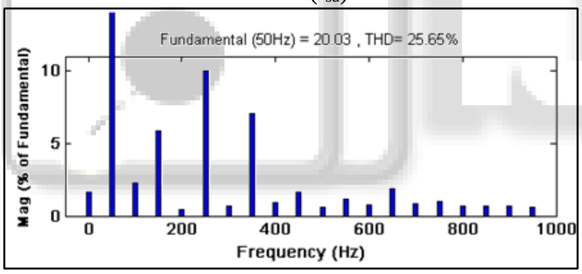


(e)

Fig. 5: Simulation results under balanced voltages with balanced loads: (a) load currents (i_{labc}) (b) source currents (i_{sabc}) (c) active filter currents (i_{fabc}) (d) inverter output line voltage (e) source voltage (e_{sa}) superimposed by the source current (i_{sa}).



(a)

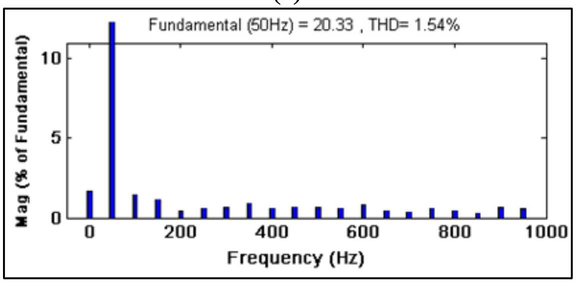


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Fig. 6: THD levels of source current (a) THD level of source current before compensation in phase '*a*' (b) THD level of source current after compensation in phase '*a*'.

Fig.7 shows the DC–DC converter output voltage. A control circuit is incorporated with the proposed step-up DC-DC converter to regulate the output voltage at 180V. The DC-link voltages, v_{DC1} and v_{DC2} must be maintained almost as a constant value within certain limits in order to provide energy to generate the required harmonic compensation current from the shunt active filter.

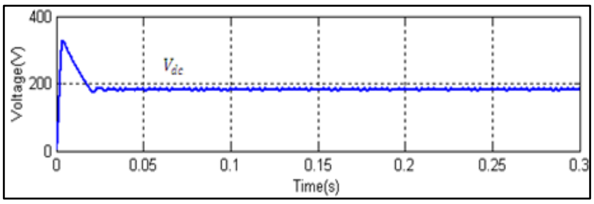
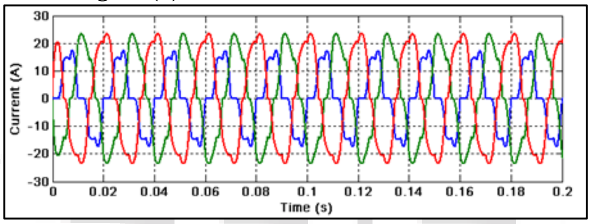


Fig. 7: DC–DC converter output voltage.

B. Balanced Voltages with Unbalanced Loads

In this case, the load currents are unbalanced by connecting a single phase diode rectifier connected between two phases. Fig.8 illustrated the simulation results of load currents(i_{labc}), source currents(i_{sabc}),active filter currents(i_{fabc}), and source voltage(e_{sa}) superimposed by the source current(i_{sa}). THD level of the three phase currents before installing the active power filter are 25.7%, 27.64% and 25.61% respectively. The harmonic spectrum of the source current in phase "a" after installing the active power filter with modified p-q theory is shown in Fig. 9. The THD level has reduced to 2.02%, 1.97% and 2.04% in phase "a", "b" and "c" respectively. In addition, the source current is in phase with the source voltage so that the power factor is equal to one as shown in Fig. 16(d).



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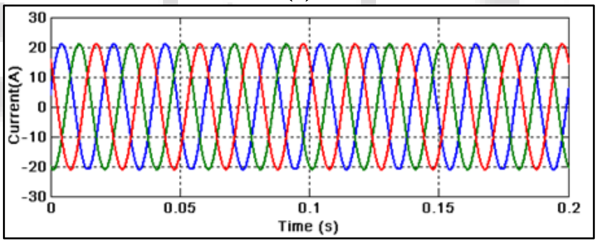

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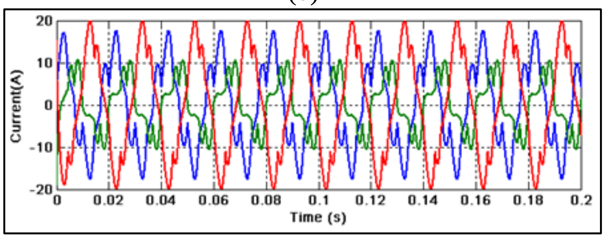

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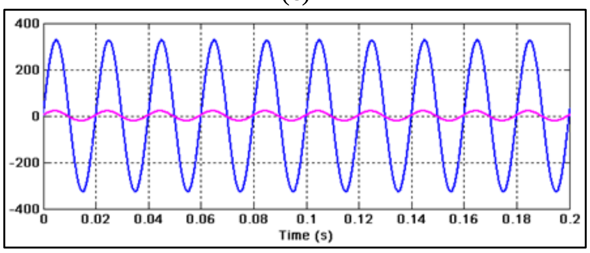


(d)

Fig. 8: Simulation results under balanced voltages with unbalanced loads: (a) load currents (***i_{labc}***) (b) source currents (***i_{sabc}***) (c) active filter currents (***i_{fabc}***) (d) source voltage (***e_{sa}***) superimposed by the source current (***i_{sa}***).

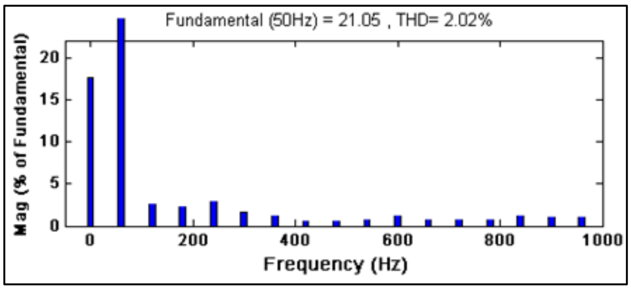
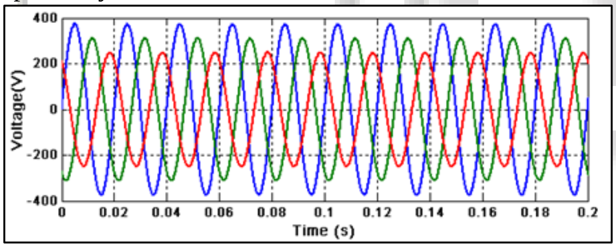


Fig. 9: THD level of source current after compensation in phase ‘a’.

C. Unbalanced Voltages with Unbalanced Loads

For evaluating the performance of the SAPF under the unbalanced voltages with unbalanced loads, the preceding unbalanced non-linear load is supplied by unbalanced AC voltages. The unbalanced source voltages(e_{sabc}), unbalanced load currents(i_{labc}), source currents(i_{sabc}),active filter currents(i_{fabc}) and source voltage(e_{sa}) superimposed by the source current(i_{sa}) are depicted in Fig. 10. The results shown in Fig.10 confirm that the WECS based SAPF system is able to improve the power quality. As shown in Fig. 10(c), it is evident that three phase source currents are balanced and sinusoidal after compensation, with power factor close to the unity, as can be observed in Fig. 10(e). The frequency analyses of the source current after compensation in phase “a” is shown in Fig.11. The THD of the source currents before compensation are 22.53%, 25.71% and 28.54%; and are reduced to 2.12%, 2.07% and 2.05% after compensation respectively.



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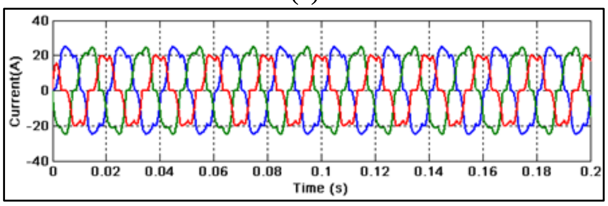

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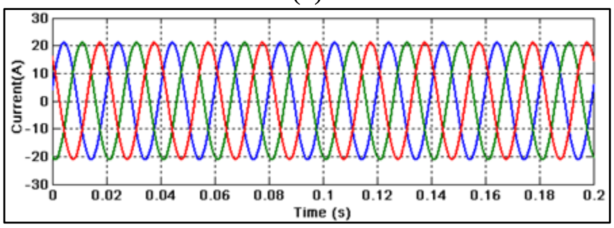

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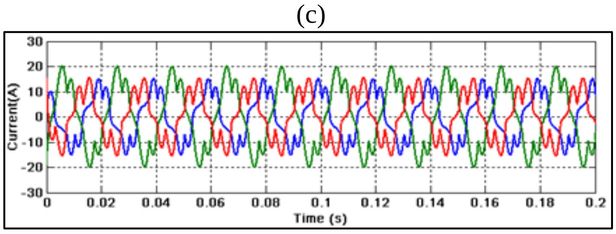

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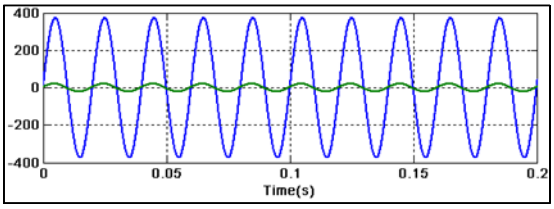

(e)

Fig. 10: Simulation results under unbalanced voltages with unbalanced loads: (a) unbalanced source voltages (e_{sabc}) (b) load currents (i_{labc}) (c) source currents (i_{sabc}) (d) active filter currents (i_{fabc}) (e) source voltage (e_{sa}) superimposed by the source current (i_{sa}).

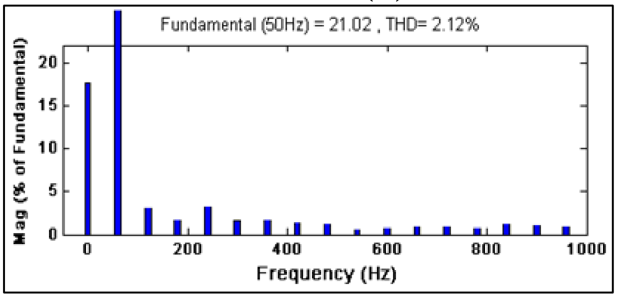

Fig. 11: Frequency analyses of the source current after compensation in phase “a”

V. Conclusion

This paper examined a new reference current generation scheme with the use of modified *p-q* theory. This approach is proposed in the WECS based 3-level SAPF for current based disturbances and voltage interruption compensation. A DC–DC boost converter with MPPT algorithm is utilized to obtain the maximum power point of the wind energy. Furthermore, fuzzy logic controller is used for enhancing the compensation capability of the SAPF. This WECS supported 3-level shunt active power filter is employed to diminish the energy using up from the utility grid, when the WECS generates mandatory real power to meet the load demand. The simulation results show that the proposed control scheme reduces the impact of distortion and unbalance of the load current on the power system.

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