Using Four – Quadrant Chopper with Variable Speed Drive System Dc-Link to Improve the Quality of Supplied Power for Industrial Facilities

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ABSTRACT:
This outcome of this research paper improves the quality and performance of the power system by using a four-quadrant chopper circuit in the DC –LINK of the variable speed drive systems (VSDS). In addition, the effects on reducing the ripple factor for both the current and voltage in DC-LINK are illustrated. In this study, a variable speed drive system is simulated and designed with the proposed chopper. Furthermore, the control system of pulses for the transistors is determined. Finally, a discussion of the results is introduced. The given results show the advantages of using the proposed chopper circuit with variable speed drive systems. Likewise, the superiority of the proposed method over other newly suggested techniques is verified by several simulation scenarios.

KEYWORDS: Four- Quadrant Chopper, Variable Speed Drive Systems (VSD_S), Power Quality, DC-LINK, Crest Factor, Ripple Factor, Total Harmonic Distortions Factor, Active Filters, Passive Filters, PI Controller Tuning.

1. INTRODUCTION

Recently, the amount of nonlinear loads in electrical grid has increased. These loads cause the harmonics in the electrical grid and lead to non-sinusoidal currents, as well as these are the main causes of electromagnetic compatibility (EMI), distortion of voltage and current waves, and reduce the grid power factor and their efficiency [1-3].

The voltage waves that feed industrial facilities are non-sinusoidal and have many undesirable harmonics [2]. One of the main sources of compatibility in the industrial grids is that the variable speed drive systems can be simplified as nonlinear loads. This kind of loads can be a source of problems with the quality of provided power.

The total harmonic distortion factor (THD %) of the current wave in these systems is about 60% and of the voltage wave is about 5.6%. The permissible value of the total harmonic distortion for voltage wave according to the international standard IEEE519-1992 is 5% [4].

IEC61000-3-2 and IEEE519 set the permissible values of the total harmonic distortion in voltages and currents because of their harmful effects, where they may cause power quality issues in the electrical grid [5-7].

Several methods have been used to improve the quality characteristics of variable speed drive systems, the most common method is using passive filters, but they were limited spread because of their size, weight, and the potential of capacitor explosion [8].

Active filters were used in various types such as serial, shunt, multi- level [9-10]. Subsequently, the research had directed to the DC-LINK circuit. Literature, all components of the conventional DC-LINK circuit were replaced with a small film capacitor. This method was called the alternating drive with a small DC-LINK circuit and used in closed loop control applications in the speed of fans for ventilation as well as pumps used in heating and cooling systems. This method has provided a total harmonic distortion of the grid current between 30% and 35%, but the problem of this type of drive is that it is compact and cannot be added to a system already existed system[11-13].

Different types of choppers were used in the DC-LINK. Boost chopper was used with a new technology for regulating the fundamental input current and eliminating of high harmonics. In this method, the value of the fundamental current is constant according to the working condition. In addition, the boost chopper raises the voltage which is suitable for motor driving applications [14]. DC-LINK currents for variable-speed drive systems might have constant values and have no oscillations. However, all the harmonic mitigation methods used previously did not give currents with constant values. These currents were distorted, containing oscillations and have variable values, which had a negative effect on the inverter, performance of the connected motor, the grid, and the consumers connected to the point of common coupling [15-16]. In [17], the buck-boost chopper was applied in dc-link. This method reduced the size of the smoothing inductor. Higher losses were founded because load current goes through more than two electronic elements.

In Ref. [18], buck-boost chopper introduced the best results to reduce current oscillations and maintain a constant value in the DC-LINK circuit, but the current of the DC current through the electronic elements in the chopper caused the breakdown of these elements [19].

The choice of modulation techniques plays an important role in switching losses. In addition, high values of the capacitor voltage lead to its failure. The failure of the dc-link capacitor is a very serious issue, especially if the motor is operating at high speeds. It effects on the inverter, the connected motor, and the electrical grid.

The variable-speed drive system with buck-boost chopper in DC-LINK has a total harmonic distortion of the grid current 28.8%, input voltage 2.71%, ripple factor for dc-link current RF 1.95, crest factor for grid current CF 1.4, for DC-LINK current 1.12, and power factor for active load PF 0.956, while the DC-LINK capacitor voltage has a fluctuating value up to 30V.

In this paper, a novel technique is proposed to achieve a good performance of the variable speed drive systems (VSDS) in the industrial facilities by reducing the THD % for both voltage and current waves and increasing the power factor. THD % reduction of the voltage and current waves is positively reflected on the work in the industrial facilities, where these distortions cause a voltage drop on the facility inputs, leading to larger currents by loads. This leads to a loss of stability in the facility. The main contribution of this work is by achieving the basic requirements of the automated operations required for high performance. Small size and low weight of the drive and control circuits with chopper circuit are very suitable for integration with variable speed drive systems. This integration does not require major changes in both power and control circuits. Allowing it to be integrated with any existing system by adding some simple modifications. Some of the main contributions in this paper are as follows:

1- Proposing a novel four-chopper for variable speed drive systems.
2- Introducing a new VSDS method able to highly reducing THD.
3- The ripple effects on the current and voltage of DC-LINK are diminished.
4- A new method for determining the control signals is proposed

The rest of this paper is organized as follows. The research methodology is given in section 2. Section 3 presents the buck-boost chopper. The four-quadrant chopper technology is introduced in section 4. An overview of the proposed variable speed drive system is highlighted in section 5. Section 6 introduces the needed VSDS components and technologies. Section 7 introduces the parameters calculation of the studied system. Section 8 presents the simulation results and discussions and section 9 concludes and provides future research trends.

2. RESEARCH METHODOLOGY

The Research Methodology Suggest developing DC – LINK buck –boost chopper and use four – quadrant chopper. The work investigates in finding appropriate control strategy to apply the bias voltages to operate the transistors of four - quadrant chopper. The proposed strategy aims to reduce the harmonics and increase the overall power factor of the variable speed drive system.

To achieve this strategy, we have taken the following steps:

- ❖ Modeling variable speed drive system with four – quadrant chopper added to DC-LINK using MATLAB / SIMULINK.
- ❖ Evaluating the performance of the variable speed drive system by comparing the results of the total harmonic distortion factor THD% for both voltage and current waves with and without using the controlled chopper circuit.
- ❖ Comparing the results with the standard values IEC standard by comparing the results before and after using the proposed chopper and comparing results with international standard limits found in IEEE 519-1992.

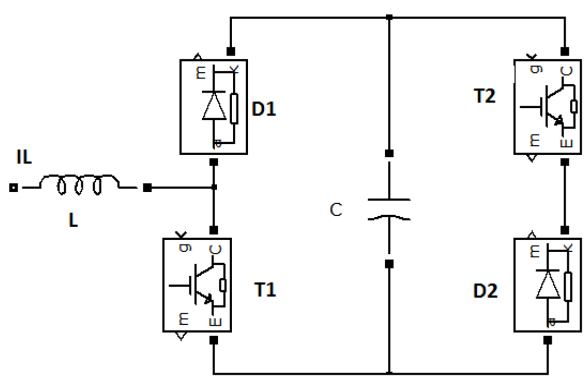


Fig. 1. Buck- Boost Chopper.

3. BUCK- BOOST CHOPPER

Buck- Boost chopper described in Fig. 1, consists of smoothing inductor L, transistors (T1, T2), diodes (D1, D2), and capacitor C.

The current I_L is controlled by using different values of the duty cycle to the transistors T_1, T_2. The advantage of this circuit is the ability to control the output current of the diode bridge to have a constant value, which causes reducing the current harmonics, oscillations of both output voltage and current, and the size of the DC-LINK filter.

Reduction of the passive filters size is necessary to achieve high energy density by maintaining high-quality input currents from the grid. In spite of high switching frequencies, the switching losses are very few as long as switching voltages are relatively small and the losses associated with each switch are very small. In addition, the high energy density of power switches enables integration with electrical machines and provides an optimized condition for integrating the motor with variable speed drive systems, which is suitable in various industrial applications such as pumps, capacitors, etc. [20-21].

In this paper, DC-link is developed by using four-quadrant chopper instead of buck-boost chopper.

4. FUOR – QUADRANT CHOPPER

Four quadrant chopper consists of four semiconductor switches and four diodes arranged in antiparallel. The four – quadrant choppers are numbered according to which quadrant they belong. Their operation will be in each quadrant and the corresponding chopper is only active in its quadrant.

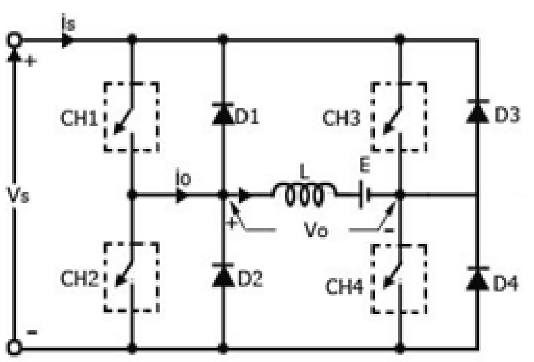


Fig.2. Four quadrant Chopper.

When CH_1 and CH_4 are trigged, output current io flows in a positive direction through CH_1 and CH_4, with output voltage V_o=V, this gives the first quadrant operation which acts as a step- down chopper.

When both CH_2 and CH_3 are OFF, the load current io continues to flow in the same direction D_1 and D_4 and the output voltage V_o=V. Therefore, the chopper operates in the second quadrant as V_o is positive, but I_o is negative.

The chopper will act as a step-up chopper as the power is fed back from load to source.

When CH_2 and CH_3 are trigged the load current I_o flows in the opposite direction, and the output voltage V_o = -V. Since both I_o and V_o are negative, the chopper operates in the third quadrant, acts as a step-down chopper. When both CH_1 and CH_4 are OFF, the energy stored in the inductor L drives I_o through D_2 and D_3 in the same direction, but output voltage V_o = -V. Therefore, the chopper operates in the fourth quadrant acts as a step up chopper as the power is fed back from load to source.

5. VARIABLE SPEED DRIVE SYSTEM

There are different types of drives used to control the speed of motors, including:

- Variable Frequency Drives (VFD).
- Variable Speed Drives (VSD).
- Adjustable Speed drives (ASD).

According to IEEESTD.1566, the term variable speed drive (VSD) is defined as a correlated set of equipment that controls the speed of both motor and its equipment which is driven by it such as mechanical loads (fans, pumps, compressors) [22].

Variable speed drive systems have a wide range of potential applications in electric driving, due to their ability to drive different types of loads including [23]:

- Static torque loads.
- Variable torque loads.

The technology used to change speed depends deeply on the quality of the driving load.

6. PROPOSED SPEED SYSTEM COMPONENTS

Variable speed drive systems consist of three basic components: an electrical motor, direct and indirect power converter, and control system. Fig. 2, shows the basic structure of the variable speed system with an indirect power converter.

Converter schemes for medium-power industrial driving are located in two basic plans direct and indirect. Speed control methods used in the industry are classified into three main sections: electric, electrolytic, mechanical [24-33].

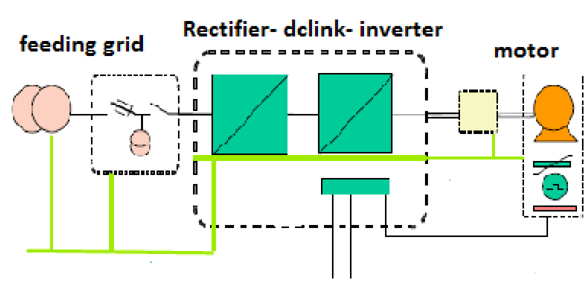


Fig. 3. Variable Speed Drive System.

The following advantages of VSDS have given it significant importance in industrial facilities:

1. Control starting current.
2. Reducing disturbances in the grid.
3. Ability to control the torque.
4. Saving electricity.
5. Restore energy.
6. Dispose of some additional mechanical parts.
7. Smooth regulation of motor speed.

To use VSDS in industrial facilities, a choice must be made between designing nonlinear devices that provide low levels of THD%, or installing substation compensation equipment at the substations. Recently, buck-boost chopper has been used in DC-LINK for variable-speed drive systems.

7. PARAMETERS OF THE EQUIVALENT CIRCUIT

To perform the simulated process, we must choose the parameters of this system:

1. input line impedance:
   Input line impedance depends on various factors such as distribution connected transformer in line or other equipment connected at the point of common coupling (PCC). Grid inductance varies from a few hundreds of μH to some mH, depending on the numbers of transformers connected in transmission and distribution system and their leakage inductances.
2. The capacitor output:
   Output capacitor of 10 μF is obtained by putting two film capacitor of 5μF in parallel; these capacitors are purposed to operate at 800V 70 ° C and 700 ° F at 80 ° C
3. The inductor of four-quadrants chopper circuit: Required value for the inductance value of four-quadrant chopper is found by the following equation:

$$L_{DC} = \frac{\left(\frac{3}{2}\right).V_i - (V_o - V_c)}{0.4\ I_L * 2f_s} \tag{1}$$

Where, Vi, Vo, Vc, I_L and fs are three phase diode bridge output voltage, inverter voltage, chopper capacitor voltage, load current, and cutting off frequency respectively.

The average value of duty cycle is 0.5. Therefore, the current ripples on active switches and diodes equal to half of the rated current. For output power 4 KW, dc inductor is chosen to be 40 μH, depended on 20% ripple current is allowed.

4. Capacitor of four-quadrant chopper circuit: Chopper capacitor C stores energy corresponding to changes of the output voltage of diode bridge output voltage which has a sixteen ripple of the mains frequency. In three levels of operation, rms value of capacitor current depends on the ratio of peak value rectified voltage to chopper capacitor voltage.

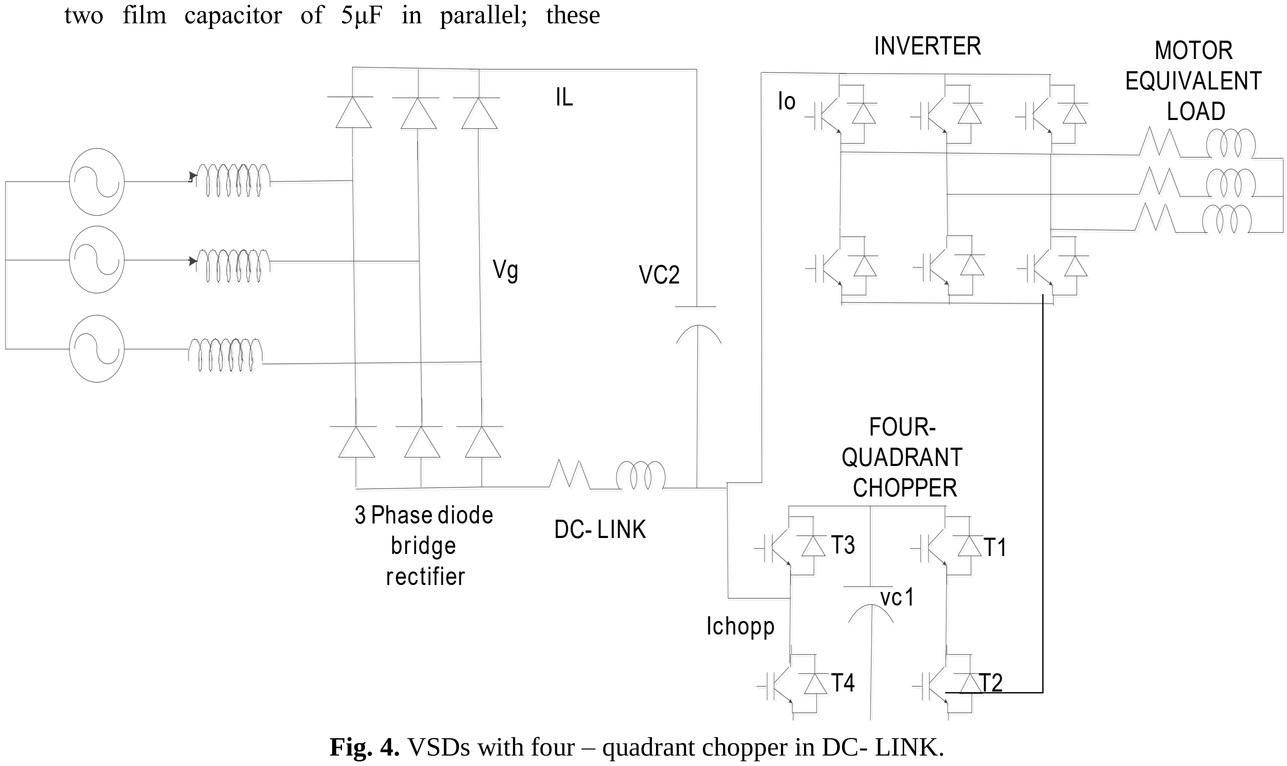


Fig. 4. VSDs with four – quadrant chopper in DC- LINK.

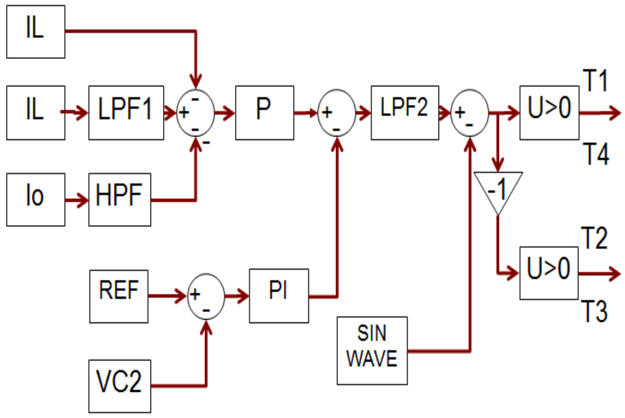


Fig. 5. The proposed control Scheme for variable speed drive system.

In order to improve the performance grid, we used the four-quadrant chopper in the DC-LINK instead of buck –boost chopper, as shown in Fig. 4.

In this scheme, current i_L does not pass through the active elements of the chopper, four-quadrant chopper works as a hybrid filter passes only high-frequency currents. Charging and discharging of capacitor C_1 is determined by chopper current signal i_{CHOPP}, so it is necessary to control the bi-directional chopper current $i_{CHOPP} = i_L - i_O$, where i_o is the inverter current.

Three level voltage modulations $v_{c2} - v_{c1}$, v_{c2} , $v_{c2} + v_{c1}$ are available on the inverter input. The current i_L increases at $v_o = v_{c2} - v_{c1}$, decreases at $v_o = v_{c2} + v_{c1}$. Besides, the current has an individual pass regarding capacitor C. The current I_o passing to the positive side of inverter is shown in Fig. 15 , thus the current passes to the chopper, i_{CHOPP}, different from inverter current i_o and inductor current i_L as shown in Fig. 15.

When Inverter operates without chopper circuit, the inverter input voltage V_o is equal to V_{c2}. In the case of the chopper is bypassed, V_o is always equal to V_{c2}, when only one of T_1 and T_4 is on, then the chopper capacitor is bypassed. As well as, one of T_2 and T_3 will be on during this time.

The control scheme illustrating in Fig. 5 similar to buck-boost chopper control adding some modifications, SPWM block has to generate four signals.

Four- quadrant chopper has to deliver the required high frequency current to the inverter, the current Io flowing from positive rail of DC-LINK to inverter wont flow through the chopper circuit, also current flowing in the chopper is bidirectional. Therefore, the duty-cycle of the switch is determined by an inner current control loop and the constant dc output voltage vc2.

The inductor current I_L is controlled to have a constant value by four transistors operation T_1, T_2, T_3 and T_4.

Both (T_1,T_2) and (T_3,T_4) operate by complementary signals for gates, also Operate by complementary gate signals.

- In the turn-on period of both T1 and T4, inverter voltage V_o is $V_{c2} - V_{c1}$.
- When both T2 and T3 are turned on inverter voltage V_o is $V_{c2} + V_{c1}$.

Low-pass filter LPF_1 is used to reduce the high-frequency components in pulse load currents. The proportional control P is used to control the shape of the current I_L, where high P-value produces a current with ripples lower by six times from the main frequency in the DC- LINK.

The high pass filter, HPF, is used to detect the resonant currents and block the low frequency components of e rectified current. To reduce the equivalent switching ripple, a low pass filter LPF_2 should be employed in the main control loop. The cut-off frequency is selected around 500Hz, which should be higher than the six times than the main frequency and enough to reduce the equivalent switching frequency ripple to a sufficient level.

For controlling DC-LINK voltage V_c, a PI-type controller is used and connected in parallel to the main control loop. This allows offset adjusting of the control signal. This scheme has many advantages over buck-boost chopper, but the controlling of four-quadrant chopper is much more complex and has many problems.

8. RESULTS AND DISCUSSION

The input currents of the VSD_S suffer from a THD% factor 45% and for voltage wave up to 5.6%, ripple factor (RF) of the output rectified current 3.2, crest factor (CF) 1.74 and power factor (PF) 0.951 while improving VSD_S power quality characteristics. The main goal of this paper is reducing both ripple and crest factors of DC-LINK current. This will affect positively on the input current total harmonic distortion factor of input currents in the VSD_S.

Grid currents of VSD_S with the buck-boost chopper and with four quadrant chopper circuit are shown in Fig. 6, we note that grid currents distortion is clearly reduced. The total harmonic distortion factor of grid currents VSD_S has decreased from 28.81% to 25.53% as shown in Fig.6.

Fig. 8, shows the maximum and effective value of this current and the amount of distortion in each harmonic in this wave.

Fig. 9, shows the phase – phase input voltage of studied variable speed drive system with the buck-boost chopper and with four quadrant chopper circuit. Fig. 10, shows that the total harmonic distortion of output voltage decreased from 2.72% to 2.53% that reflex advantages of using four-quadrant chopper in DC-LINK.

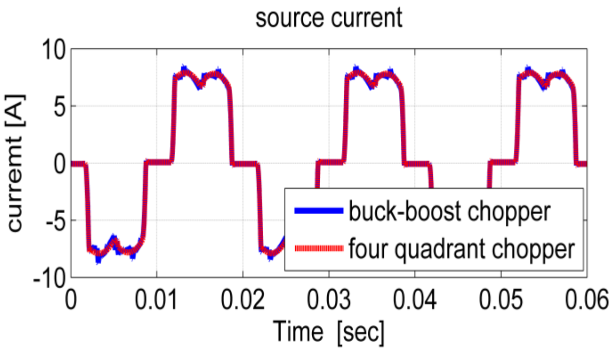


Fig. 6. Grid Current for VSDs.

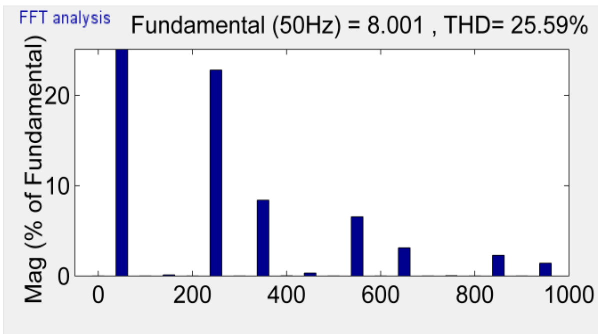
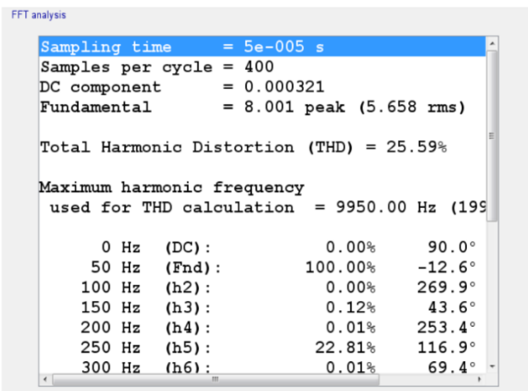


Fig. 7. Total harmonic distortion factor of VSDS.


FFT analysis

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Sampling time          = 5e-005 s
Samples per cycle = 400
DC component           = 0.000321
Fundamental            = 8.001 peak (5.658 rms)

Total Harmonic Distortion (THD) = 25.59%

Maximum harmonic frequency
 used for THD calculation  = 9950.00 Hz (199

    0 Hz  (DC):            0.00%      90.0°
   50 Hz  (Fnd):         100.00%     -12.6°
  100 Hz  (h2):            0.00%     269.9°
  150 Hz  (h3):            0.12%      43.6°
  200 Hz  (h4):            0.01%     253.4°
  250 Hz  (h5):           22.81%     116.9°
  300 Hz  (h6):            0.01%      69.4°
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Fig. 8. FFT analysis of grid currents for proposed VSDs,

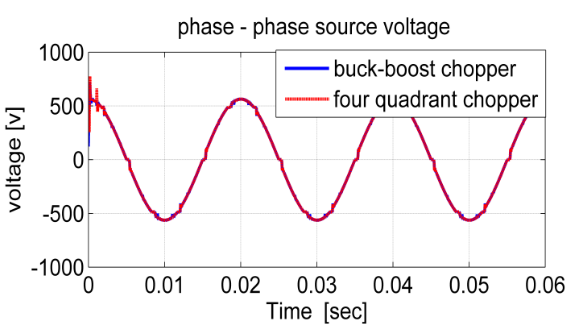

Fig. 9. Phase to phase for the input voltage of proposed VSDs.

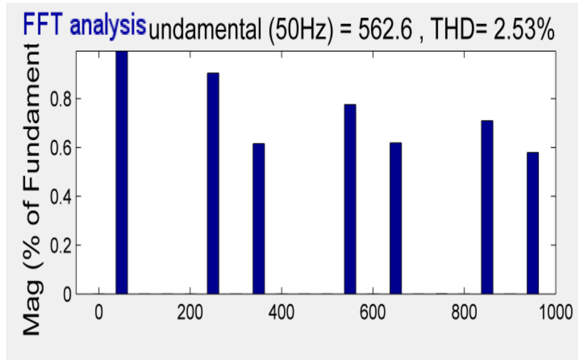

Fig. 10. FFT analysis of phase – phase grid voltage for proposed VSDs.

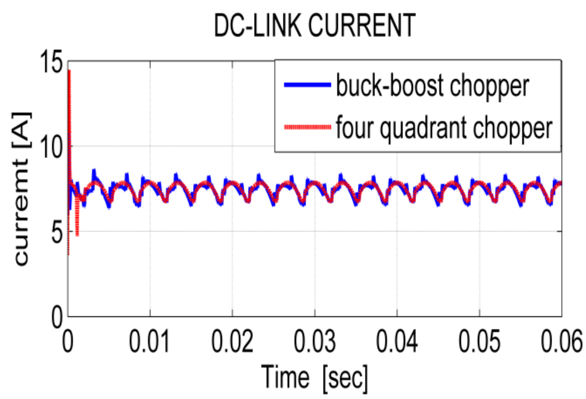

Fig. 11. DC-LINK Current.

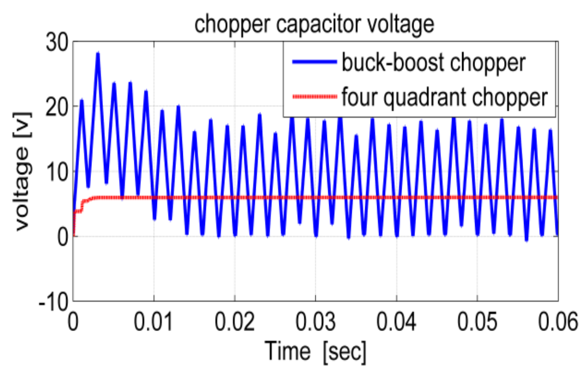

Fig. 12. Chopper capacitor voltage.

Fig. 11, shows DC-LINK current in both cases mentioned previously, ripple factor has been reduced from the value 1.95 to 1.105 when using the four-quadrant section. The conventional VSD_S has a ripple factor of the continuous vehicle current about 4.9.

Crest Factor calculation is intended to give an idea about the effect of the waveform. Crest factor is defined as the ratio of peak value to an effective one.

The Crest factor of grid current is reduced from 1.4 when using buck – boost chopper to 1.30 with four quadrant chopper. In addition, the crest factor for dc-link current is reduced from 1.12 to 1.05 with four-quadrant chopper.

Grid currents of conventional VSD_S have crest factor 1.74 and DC-LINK current 1.40.

Power factor is increased from 0.951 in conventional drive system to 0.953 when using buck-boost chopper in DC-LINK, and to 0.956 when using four-quadrant chopper in this paper.

Fig. 12, shows that chopper capacitor voltage is reduced to 6 V when using the four-quadrant chopper. Also this figure shows that the voltage of the capacitor is a varying pulse; the peak of these pulses is reached to 24 V, while its effective value is 12 V.

The output voltage has lower oscillations as shown in Fig. 13. Therefore, the use of the four-quadrant chopper in dc-link gives lower oscillations in output voltage.

Constant dc-link voltage is achieved after using four-quadrant chopper in DC-LINK, but the effective value of the voltage in both cases remained 540 V as shown in Fig. 14.

The aforementioned results validate the proposed method for implementing in engineering applications. It is clear that the proposed method has the ability of diminishing the voltage oscillations and ensure constant voltage in the DC-LINK. Likewise, the THD is highly reduced using the proposed method. Furthermore, the ripple factor is highly reduced by implementing the proposed variable speed drive system.

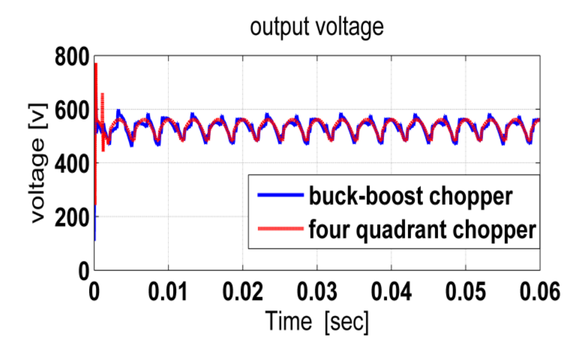

Fig. 13. Output voltage.

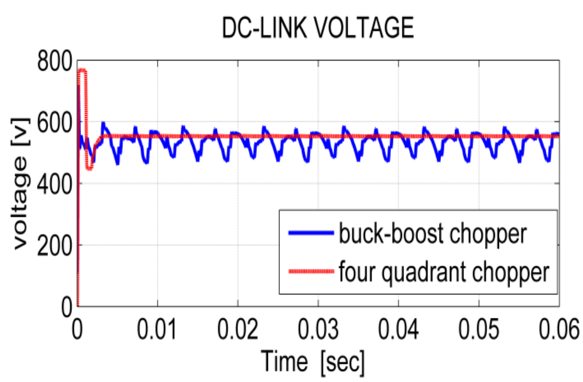

Fig. 14. DC-LINK voltage.

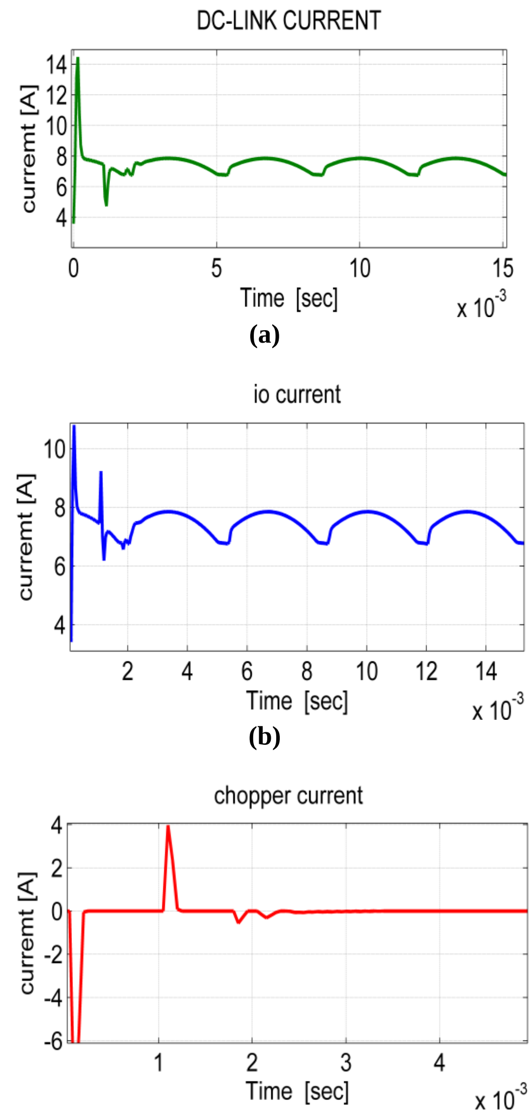

Fig. 15. Currents of the different components: a) inverter current, b) DC-LINK current, and c) chopper current.

9. CONCLUSIONS

From the theoretical and practical study, it could be concluded that the power quality of input current for these systems has improved by reducing total harmonic distortion factor (THDs) while increasing the power factor (PF), in addition, in the dc-link both ripple factor and the crest factor have reduced to acceptable values. The capacitor voltage is reduced to an acceptable value which does not lead to the failure of the capacitor besides canceling the oscillations in dc-link voltage. Finally, for future works continuing this topic is recommended; by using SVPWM to generate biases voltages for chopper transistors, and using this chopper with a 12-pulse rectifier variable speed drive system to determine the suitability and adaptability of this chopper with different types of rectifier schemes used in variable speed drive systems. As a future work, the proposed method can be investigated for different types of industrial systems. Likewise, intelligent methods might be combined with the proposed method with the potential of presenting comprehensive assessment results.

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