UPGRADING HIGH POWER DC-MOTOR DRIVES USED IN HEAVY INUDSERIES IN EGYPT

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ABSTRACT

Separately excited DC-motors still have a major roll in heavy industries, especially in the already running industrial plants. Concerning the large power demand of these motors and the high level of low order harmonics injected by the conventional converter used, many solutions are tested and implemented. In this paper an upgrading scheme for driving the separately DC-motor in the four quadrants is suggested. The power circuit used is based on PWM voltage source converter (VSC) capable of bidirectional power flow with controllable power factor and pure sinusoidal supply currents. The drive details are presented and its performance is investigated via simulation work. A comparison of performance of the suggested scheme and the conventional scheme shows that the suggested one can economically replace others with valuable contribution to power factor improvement and harmonics reduction in power system.

KEYWORDS: DC-motor drives, Sinusoidal PWM converters, unity power factor converters, microcontroller applications.

1. INTRODUCTION

Steel, aluminum and other heavy industries consume a major part of electrical energy in Egypt. These industries extensively apply thyristorized line-commutated ac–dc variable speed dc-motor drives. DC-motors with power ratings range from few KW to more than 1-MW are used in different industrial processes. The major number of these motors is running at speeds less than 50% of their base speed for the vast operation time and, hence, at armature voltages less than 50% of its rated value. This means that the thyristoriezed ac–dc converters would operate at high values of firing angle, thus consuming

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considerable amounts of reactive power from the supply, and resulting in input PF less than 0.5 for most of the time. Furthermore, they inject significant amounts of low-frequency harmonics such as 5^{th}, 7^{th}, and 11^{th} current harmonic components into the supply. This leads to a great deal of problems in national generation and distribution network. Low power factor wastes network resources and causes large amounts of energy losses. Harmonics have detrimental effects on all loads supplied from network and bring severe interference problems with communication systems. Moreover they cause over-heating and deterioration in network installations such as transformers and alternators. Restrictions on current and voltage harmonics maintained in many countries through IEEE 519-1992 in the USA and IEC 61000-3-2/IEC 61000-3-4 in Europe standards.

The modern variable speed drives, depending on squirrel-cage induction motor with either vector control or direct torque control strategies, nearly replace thyristoriezed DC-motor drives in low and medium ranges of power in newly established industrial plants. However, this is neither a practical nor an economical solution in the present running plants for the following reasons [1];

- The present dc motors are in a good condition, and many spare parts are available in stock, besides experienced personnel for maintenance and repair.
- Significant modifications in the mechanical parts and installation work are needed for the replacement of present dc motors with squirrel-cage induction motors.
- The conventional dc drive continues to play a dominant role when dynamic drives with constant load torque and stringent requirements for overload withstand capability throughout a large speed setting range are involved.
- The use of frequency-controlled variable-speed drives would further necessitate special converter type ac motors, or costly output filter systems in order to get rid of high stresses on motor insulation, causing accelerated aging and insulation failures in the long term [1].
- The global overview on variable-speed induction motor drives shows that they require dual electrical power AC-DC-AC conversion process. A front edge PWM AC-DC converter is required and must comply also with the present harmonic and power factor regulations. This means that variable speed AC drives are double complicated compared to DC-motor drives.

The development of new high power semiconductor devices such as 3.3 kV, 4.5 kV and 6.5 kV insulated gate bipolar transistors (IGBTs) and 4.5 kV, 5.5 kV integrated gate commutated thyristors (IGCTs) have improved converter designs and led to a drastic increase of the market share of PWM controlled unity power factor converters. Meanwhile, these converters ranging from 0.5 MVA to 10 MVA are becoming price competitive against conventional three-phase rectifiers based on thyristors [2].

Based on the above comments it is assured that the most economical and practical solution is to upgrade the old versions of six-pulse line-commutated converters with other schemes based on unity-PF PWM rectifiers.

In this paper a drive system based on a Unity Power Factor (UPF) Voltage Source Converter (VSC) and a 4-quadrant dc chopper as shown in Fig.1 is suggested. This scheme is thoroughly investigated and its performance is compared with the standard conventional 3-phase dual converter drive.

2. UNITY POWER FACTOR CONVERTER TOPOLOGIES

Two main types of unity power factor (UPF) PWM converters topologies are available; the buck or current source (CSC) type and the boost or voltage source (VSC) type. The schematic diagrams of these topologies are shown respectively in Fig.2-a and Fig.2-b. Reference [1], presented application of a buck type UPF converter for low and medium power dc-motor drive. Reference [2] and [3] presented number of configurations of voltage source 2-level and 3-level UPF voltage source converter used in traction applications. There are several works [4]-[7] that presented different models of both topologies and suggested different control schemes.

Generally, both types of converter have their own operational limitations and the one selected depends upon the specified application considered and the designer compromises of several factors. The CSC impresses high voltage stresses in both input and output sides due to the high values of *di/dt* transients. Input and output filters must be used to protect semiconductor devices and motor armature against such unavoidable stresses. The current source nature of the DC-link impairs the speed control dynamic of the drive. This means that CSC is not suitable when fast speed dynamics are required. On the other hand VSC has lower input/output voltage and current stresses and considerable fast dynamics but it must operate as a boost converter for lead or unity power factor. This means that VSC operating at unity power factor cannot directly drive the dc-motor at speed lower than the base speed. The following section describes how VSC can be used in conjunction with DC-chopper to overcome this limitation.

3- DESCRIPTION OF THE DRIVE OPERATION

Referring to Fig.3 to Fig.6 the overall drive system can be considered as two separate sections, the first section constitutes the converter and its feed-back control system and the second section constitutes the 4-quadrant chopper with the motor speed control system. The drive operation can be simply clarified by considering these two sections individually as follows:

3-1 The PWM Voltage Source Converter (VSC).

Figure 3 shows the schematic diagram of the PWM controlled converter and the equivalent single phase representation. The sinusoidal PWM control of the IGBT-bridge brings three phase voltages at terminals A, B and C whose magnitudes depend on value of the DC-link voltage and the modulation index. The three phase supply is connected to converter bridge input via three identical impedances each one consists of the line resistance R and an **intended series reactance** ωL. Normally R is very small compared to ωL and can be safely neglected, while L is a key parameter affecting circuit performance. The simplest way to understand circuit operation is to consider the analogy with the synchronous machine. The fundamental component of the converter terminal voltage relative to the 3-phase supply neutral can be written as:

$$v_{Ta} = V_{T\max}\sin(\omega t + \delta) \tag{1}$$

$$v_{Tb} = V_{T\max}\sin(\omega t + \delta - \frac{2\pi}{3}) \tag{2}$$

$$v_{Tc} = V_{T\max}\sin(\omega t + \delta - \frac{4\pi}{3}) \tag{3}$$

and the supply voltages are:

$$v_{Sa} = V_{S\max}\sin(\omega t) \tag{4}$$

$$v_{Sb} = V_{S\max}\sin(\omega t - \frac{2\pi}{3}) \tag{5}$$

$$v_{Sc} = V_{S\max}\sin(\omega t - \frac{4\pi}{3}) \tag{6}$$

Adjusting magnitude of the converter voltage (V_{Tmax}) analogues to e.m.f. in synchronous machine, and its phase angle δ controls indirectly phase angle and magnitude of the line current. If angle δ is negative, $\underline{V}_T$ lags supply voltage $\underline{V}_S$, electrical power is delivered from the AC supply to DC side and circuit operates as rectifier (synchronous motor analogous). In this case if $\underline{V}_T > \underline{V}_S$ the line current leads supply voltage and circuit operates at leading power factor. Otherwise if $\underline{V}_T \leq \underline{V}_S$ the circuit operates at lagging power factor. On the other hand, if angle δ is positive, $\underline{V}_T$ leads supply voltage $\underline{V}_S$, electrical power is delivered to the AC side from DC link and circuit operates as inverter, (synchronous generator analogous). The average value of DC-link voltage and load current is subjected to control in proportional to active power conducted from the AC side.

In VSC operating at unity or leading power factor, there are two main limiting factors that must be considered; the series inductance L and the DC-link voltage V_{DC}. It can be shown that [8];

$$L < \frac{\sqrt{V_{DC}{}^2 - 3V_{S\max}^2}}{\omega I_{S\max}} \tag{7}$$

The two parameters L and V_{DC} depend on each other and there must be a compromise to select suitable value for each of them. High value of L reduces the current ripples and in the same time requires a higher value of V_{DC} to force converter in unity power factor operation. This high value of V_{DC} introduces higher stresses on the power switches and the dc-link capacitor.

3-2 The 4-quadrant DC Chopper

Referring to Fig.3 the power switches S_A, S_B, S_C and S_D represents a 4-quadrant chopper to accelerate or to brake the motor in either direction of rotation. Each one of these switches consists of an IGBT (Q_A, Q_B, Q_C or Q_D) with anti parallel diode (D_A, D_B, D_C or D_D).

Fig.5 shows the current waveform of each element during first and second quadrant operation. Fig.5c presents simplified circuit diagrams for both quadrants. In 1st quadrant during ON-period current flows from DC-link to motor through IGBT Q_A, Q_B. During Off-period current freewheels through diode D_D and IGBT Q_B.

This IGBT chopper can efficiently operate at switching frequency up to 10-kHz and more. In this case the armature current is continuous and its ripples can be neglected. The armature average voltage, IGBT and diode average currents will be:

$$V_L = k \times V_{dc} \tag{8}$$

$$I_{QA} = I_L \div k \tag{9}$$

$$I_{DD} = I_L \div k \tag{10}$$

Where k is the duty cycle, V_{dc} is the dc-link voltage and $i_{dc}=i_{QA}$. is the dc-link current.

The Circuit will operate as a buck chopper to adjust armature voltage and consequently motor speed.

Figure 5b shows arrangements to operate motor in regenerative brake mode (2nd quadrant). Circuit needs to operate as a boost chopper to step up armature voltage to permit armature current reversal and consequently stored energy recovery to the DC-link. During ON-period IGBT Q_D shorts armature circuit via the series armature inductance L_a, when this switch turns off armature current is forced in DC-link via diode D_A. With the same assumptions stated above the voltage and current relations are;

$$V_{dc} = V_L/(1-k) \tag{11}$$

$$I_{QD} = I_L \times k \tag{12}$$

$$I_{DA} = I_L \times (1-k) \tag{13}$$

There will be similar arrangements to operate the drive in the 3rd and 4th quadrants.

4- THE CLOSED LOOP CONTROL OF THE DC DRIVE

Figure 6 shows the block diagram of the dc-drive feed-back control system. It consists of two separate sections; one to control voltage of the dc-link while maintaining unity power factor of supply current and the other to control the motor speed. When motor accelerates it extends electrical energy from the dc link and there will be a tendency for dc-voltage to decrease. The converter control system reacts to this tendency allowing more electrical power to be converted from the ac-supply. On the other hand when motor decelerates rapidly an appreciable amount of the stored kinetic energy is reflected to the dc-link and the dc-voltage tends to increase. The control system instantaneously reacts to this situation making converter to operate in the inversion mode and returning electrical energy to the ac supply. The above mentioned two sections will be considered with more detail in the following subtitles.

4-1 The Voltage Oriented Control Strategy (VOC) of Converter

As shown in Fig.6 the voltage of DC-link is controlled via a PI feedback controller and hysteresis PWM current controllers. Several control strategies has been effectively used with unity power factor PWM converters [4]-[8]. The control strategy used here is the voltage-oriented control (VOC) [8]. The supply current vector is mapped into the synchronously rotating frame of reference *(dq)* aligned with the supply voltage vector. The d-component of current vector represents the active component while the q-component is the reactive component.

Figure 6 shows the block diagram of the control system where the external loop adjusts value of DC-link voltage to follow the reference input $V_{DC}*$. The internal current controllers adjust both the ***d*** and ***q*** components of supply current to follow their respective reference values. The d-component reference $i_{Sd}*$ is directly related to the power to be conducted to the dc-link through converter and is taken as the output of the outer voltage-control loop. The q-component reference $i_{Sq}*$ is selected according the power factor required.

If unity power factor is required then $i_{Sq}^* = 0$, otherwise $i_{Sq}^* = i_{Sd}^* \tan(\varphi)$, where φ is the power factor angle. The VOC strategy guarantees best control performance both in transient and steady state via the internal current control loops. In present scheme hysteresis current controllers are used. This type of PWM controllers represents the most simply to implement and effective type.

4-2 The Closed Loop Speed Control

The second section of the drive system is the 4-quadrant DC chopper and its accompanied outer speed control loop and internal armature current controller. Such control system had been thoroughly analyzed using different types of conventional PID compensation or Fuzzy controller. *There is no further contribution given here*. In present scheme the conventional PI controllers give acceptable responses in transient and steady state conditions.

5. SIMULATION RESULTS

The suggested drive system is simulated using the *Simulink Power Tools of the Matlab Package*. This software tool represent a ***Virtual Electrical-Power Lab*** containing all machine, power-electronic and control components. Using this package one can obtain a close view of complicated control systems and study critical parameters and variables as well as overall system performance.

This section presented the detailed results of the suggested scheme applied to a medium power dc-motor. Comparison of performance obtained with that of the 3-phase dual converter, used conventionally as the standard dc-drive system, is also presented. The two drive-systems have similar ratings concerning dc motors and ac-supply and are tested under similar loading conditions. The drive system has the following ratings;

Rated output power = *200-hP* Base speed = *1750-rpm*
Rated armature voltage = *500-V* AC supply: *380-V/50-Hz*

Detailed parameters are given in Appendix A.

Test Conditions:

- The drive system is tested by a ramp speed reference with slope ±1750-rpm/s from standstill to 1.0-pu and speed reversal from +1.0-pu to -1.0-pu under a constant full-load torque.
- To test regenerative brake performance a combined fixed load of 0.125-pu and an additional inertial load of 150% of the motor inertia is coupled to the motor shaft and the deceleration ramp is increased to -2500-rpm/s.
- The armature current during speed dynamic changes is restricted to 150% of its rated value.
- The voltage of DC-link is restricted to 700-V (1.36-pu of the output of the uncontrolled 3-phase bridge)

5-1 The speed controller

Figure 7a shows the speed response of the drive system where the motor speed and the armature current exactly track their respective reference signals with negligible overshoot or undershoot.

Figure 8a give a similar response, but due to the high inertial load and fast deceleration ramp the current reverses its direction while speed has the same direction, this means that the drive enters the regenerative brake (2^{nd} quadrant).

5-2- The d-q current controller.

Figure 7b shows 4-traces the upper is that of the voltage of the dc-link which is nearly constant and experience negligible changes at the instants of hard speed changes. The q-current component is fixed at zero value while the d-component traces the power demand required by the drive. The rms line current has the same waveform as d-current component, and this is expected since the two currents are directly related to power demand.

In Fig.8b similar remarks concerning V_{DC} and i_q, but i_d is negative during the range of regenerative brake.

5-3 The supply current.

Figure 7c gives the supply side current and voltage waveform during the steady state drive operation, the line current waveform is nearly sinusoidal with complete phase coincidence with the supply voltage. Quantitative results gives *THD* of current *0.95%* and *PF=.99*.

Figure 8c gives supply voltage and current waveform at instant of quadrant changing (from motoring to regenerative brake) where phase angle is changed from zero to 180^o reversing power to supply.

5-4 Comparison Performance with 3-phase Dual Converter.

Figure 9 compares the overall response of the suggested drive with that of the conventional 3-phse dual converter. Fig.9a shows similar speed and armature current responses in both types. Fig.9b shows the envelopes of line current of both drives where the dual converter shows higher line current during speed transient, this is also clear from Fig.9c. Fig.9d compares the supply voltage and currents at steady state full load operation where the suggested scheme gives superior waveform and phase coincidence. Finally Fig.9e gives the power harmonic spectrum of the previous currents which indicates that the most pronounced harmonic present in line current of the suggested drive is the 5^{th} but its value is below 2.02% compared with 20.21% in the dual converter. The even harmonics and other uncharacteristic harmonics present in case of suggested scheme, due to the variable switching frequency of the hysteresis current controller, have negligible effects since they all have magnitudes less than 1% of the fundamental component.

Figure 10a presented comparative graphs of Power factor and THD of both drives as function of speed where the suggested drive has superior characteristic than that of the dual converter along the full speed range.

Fig.10b compares the magnitudes of supply current as functions of speed, where the suggested scheme has linear dependence of supply current on speed while the dual converter scheme experiences higher current at lower speed. It has a maximum value of line current at nearly 40% of the base speed, this due to the lower power factor and the higher circulating current.

6. COMPARISON OF POWER CIRCUITS OF DIFFERENT SCHEMES

This section compares the power devices required in the suggested scheme with that of the standard dual converter and the current source converter. Comparison is based on similar drive power rating and assumes that accelerating torque is limited to 150% of rated torque. Table 1 summarizes the minimum required ratings of power devices of different converter schemes. This table shows that concerning the total number of power devices there is no effective difference between the three schemes. Due to circulating current the dual converter is expected to have the highest current rating. The chopper part of the suggested scheme has somewhat higher power ratings relative to other devices. However this causes no effective difference on the overall drive cost, taking into account the other distinctive merits gained such as minimized reactive components required and unity power factor operation.

7. CONCULUSION

The simulation results of the suggested dc motor drive based on unity UPF PWM Voltage Source Converter have shown that the resulting system has superior operating characteristics over conventional line commutated dc motor drives. The 4-quadrant chopper provides a good matching between the standard supply voltage levels and the variable dc motor armature voltage thus enabling the VSC to operate at dc-voltage level suitable to force supply power factor to unity. The ac-line currents have sinusoidal waveform and the dc output voltage is nearly level. Relatively smaller size filter can be used to eliminate the high frequency transients and to prevent motor deterioration.

Depending upon the high power ratings of the newly introduced IGBTs and IGCTs, this scheme can be effectively applied to the complete range of dc-motors with small, medium and high power ratings. The unity power factor operation of large motors will eliminate the need of the reactive power compensation capacitors, and greatly enhance electrical power system locally in the industrial plant and globally on national scale.

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10 APPENDIX: DETAILED PARAMETERS OF DRIVES

1- DC-motor ratings and parameters:

Rated output power = *200-hP* Base speed = *1750-rpm*

Rated armature voltage = *500-V* Field circuit voltage = *300-V*

R_a = 0.06727-Ω L_a = 0.001882-*mH* R_f = 30.72-Ω

L_f = 3.166-*mH* L_{af} = 0.2641-*H* J =1.019-kg.m2

B_m = 0.02516-N.m/(rad.S^{-1}) T_f = 26.46-N.m

2- AC supply: *380-V/50-Hz*

3- PWM Converter:

Semiconductor Switches: IGBTs, DC-link capacitance = *4000-μS*

Series line resistance = $0.005\text{-}\Omega$, Series line inductance = $1.0\text{-}mH$

4- Dual Converter parameters

Semiconductors devices: Phase control Thyristors

Circulating current limiting inductance 5-mH

	Power Devices	Number of power Devices	
Suggested Scheme (VSC)	IGBTs or IGCTs	6-Switches	4-Switches
	I_{peak}	450-A	500-A
	I_{rms}	260-A	500-A
	V_{off}	650-V	650-V
Current Source Concverter (CSC)	IGBTs or IGCTs	6-Switches	6-Diodes
	I_{peak}	450-A	450-A
	I_{rms}	260-A	260-A
	V_{off}	650-V	650-V
Dual Converter	SCRs	12-SCRs	
	I_{peak}	500-A	
	I_{rms}	287-A	
	V_{off}	540-V	

Table 1 Comparison of power devices in different Schemes

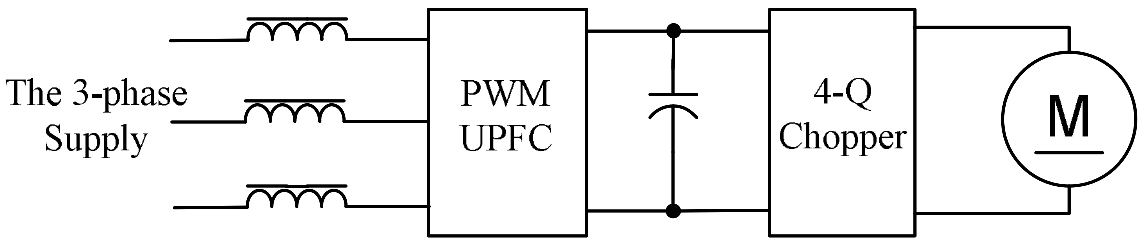


Fig.1 Simple Block diagram of The Suggested DC Motor Drive

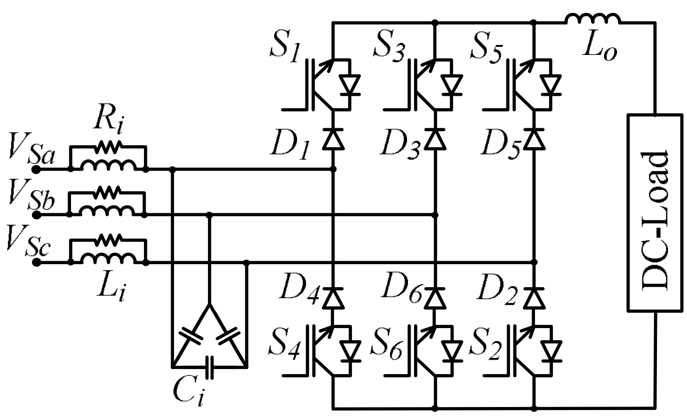


Fig.2a PWM Current Source Converter

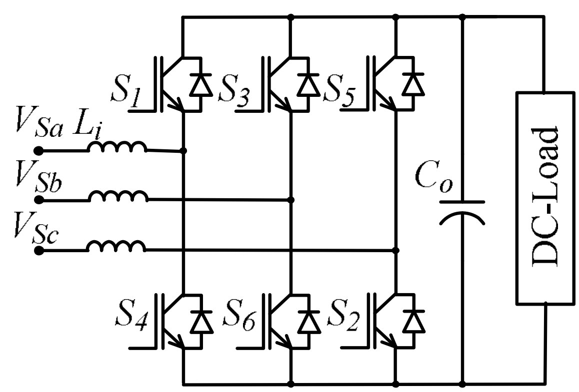


Fig.2b PWM Voltage Source Converter

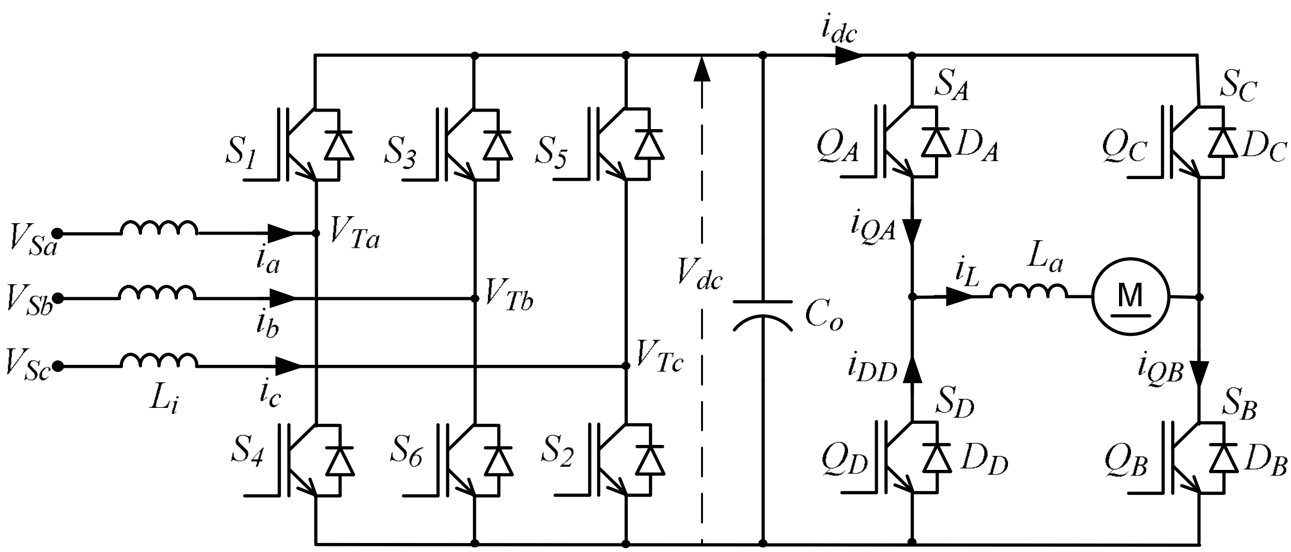
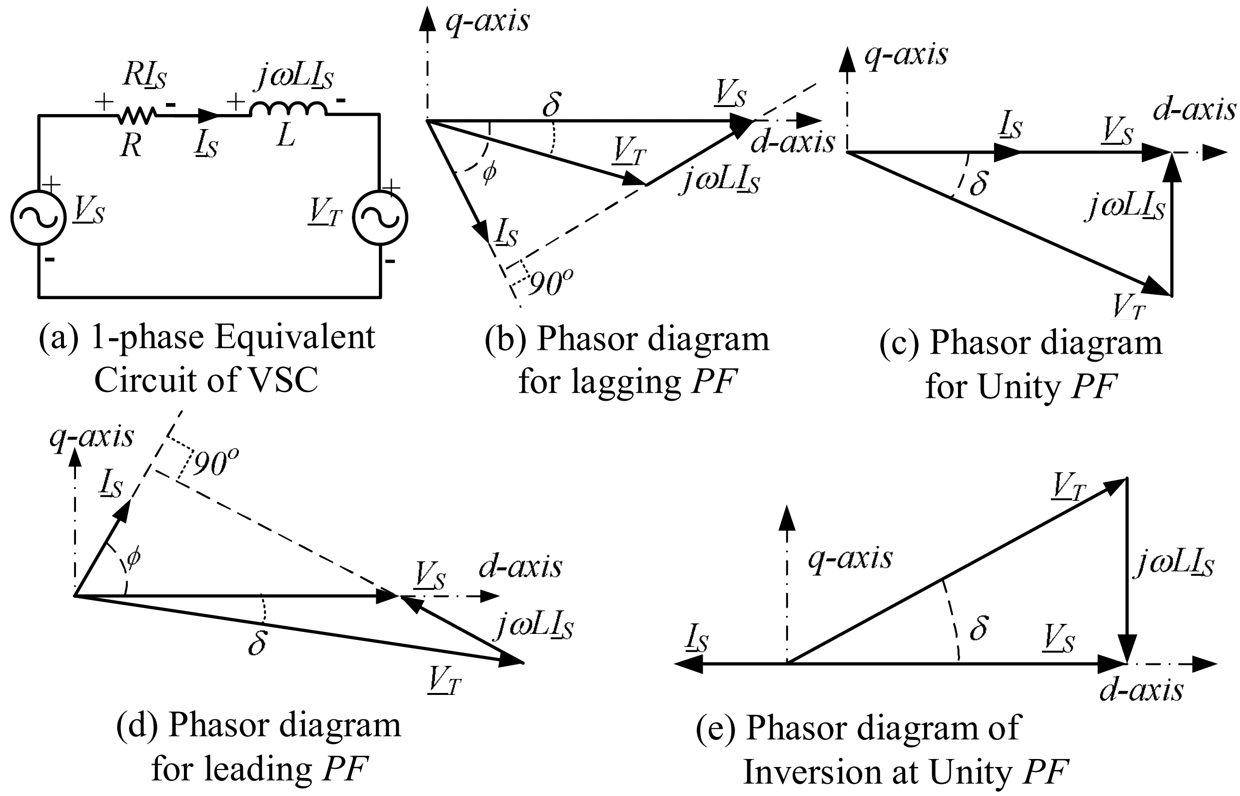
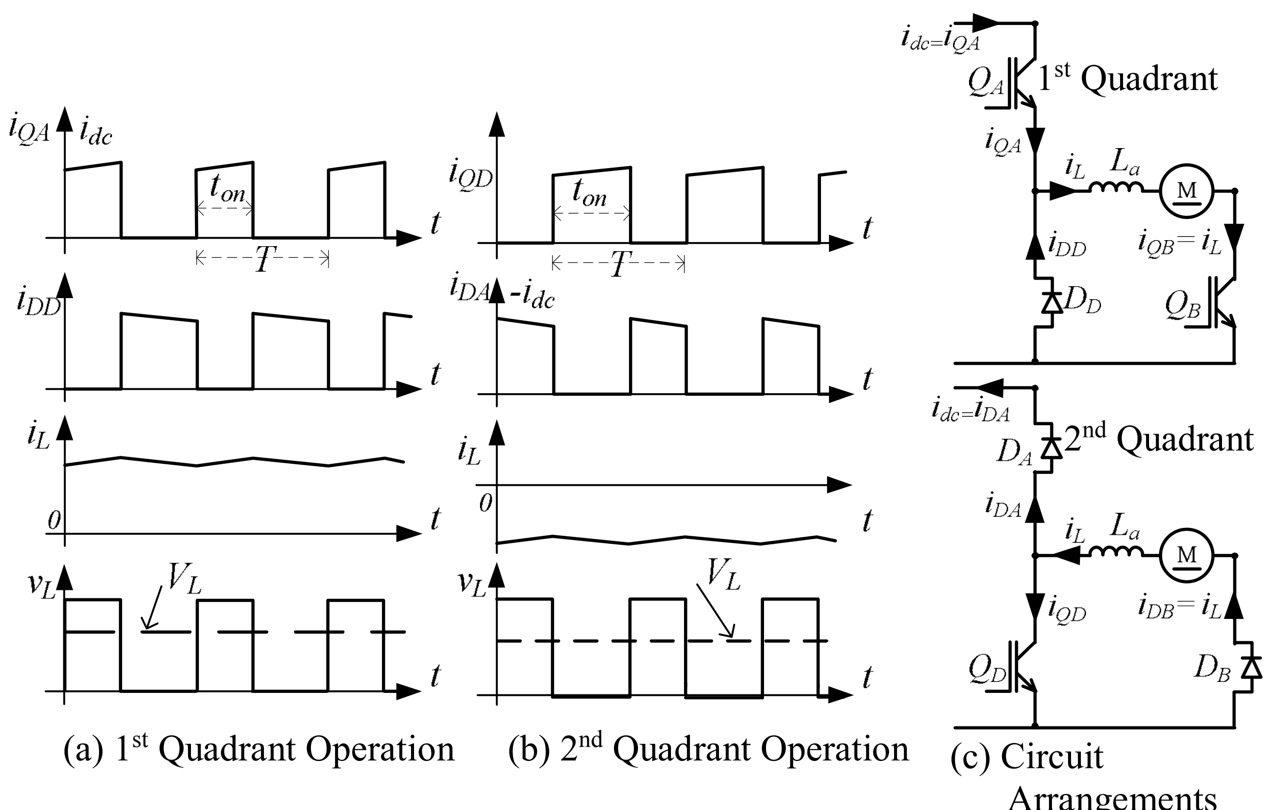


Fig.3 Suggested DC Motor Drive



(a) 1-phase Equivalent Circuit of VSC
(b) Phasor diagram for lagging *PF*
(c) Phasor diagram for Unity *PF*
(d) Phasor diagram for leading *PF*
(e) Phasor diagram of Inversion at Unity *PF*

Fig.4 Clarifications of Different Modes of Operations VSC



(a) 1st Quadrant Operation
(b) 2nd Quadrant Operation
(c) Circuit Arrangements

Fig.5 Chopper Current & Voltage Waveforms

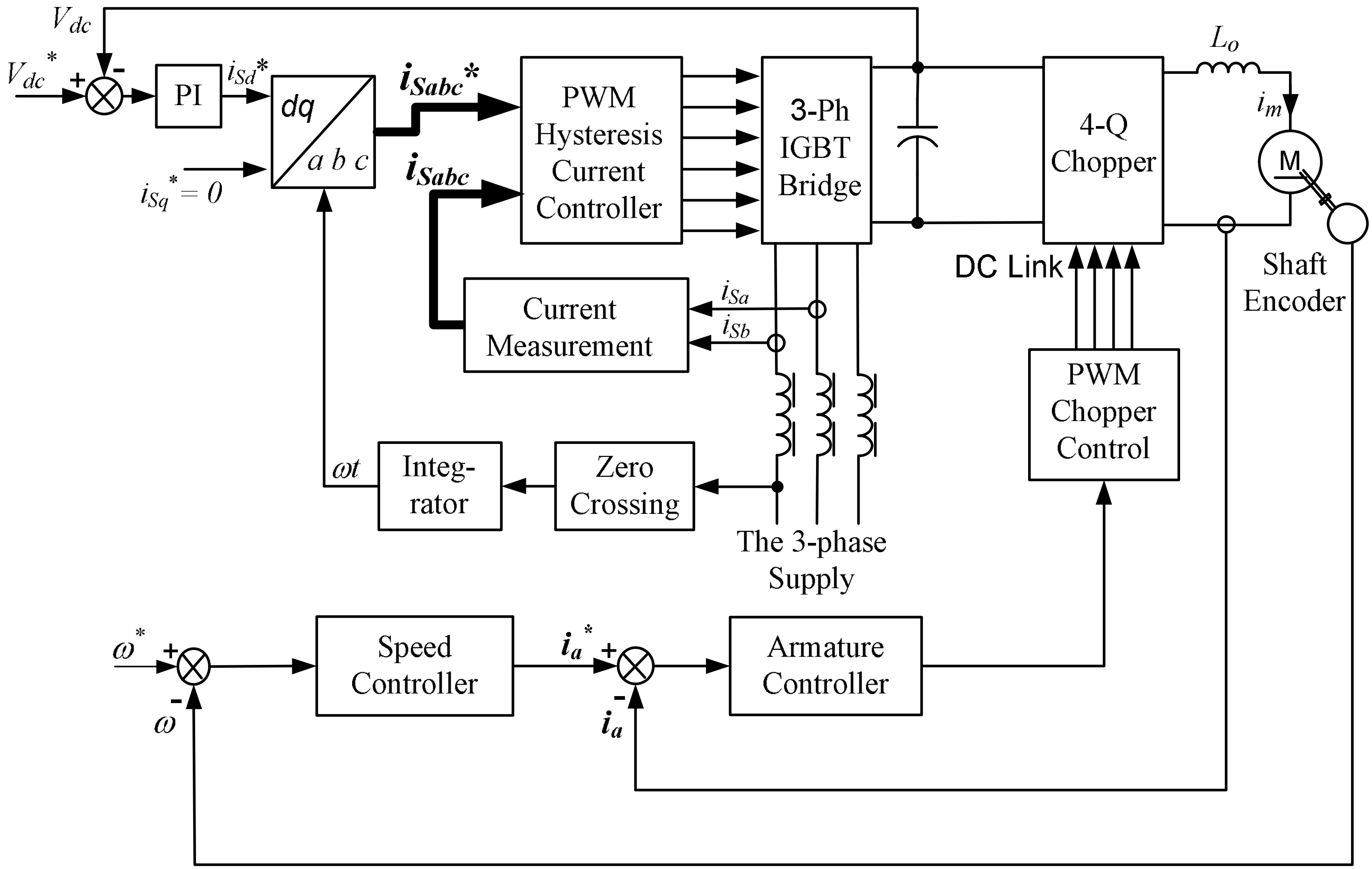


Fig.6 Feedback Control System of The Suggested Scheme

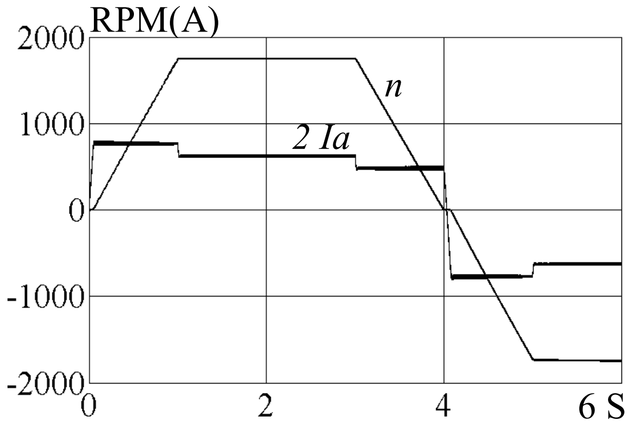


Fig.7a Speed and Current Response for a ramp speed reference.

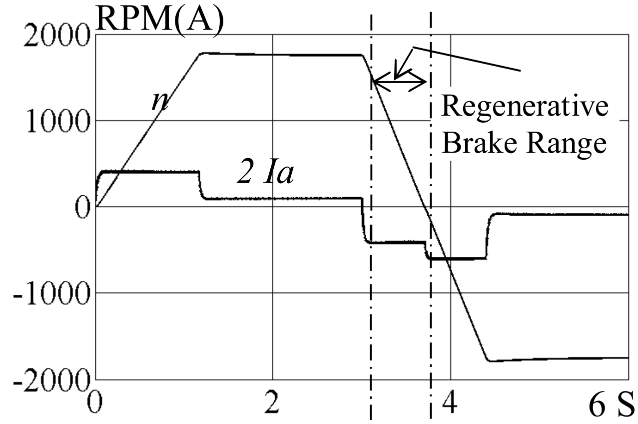


Fig.8a Speed and Current Response for a ramp speed reference.

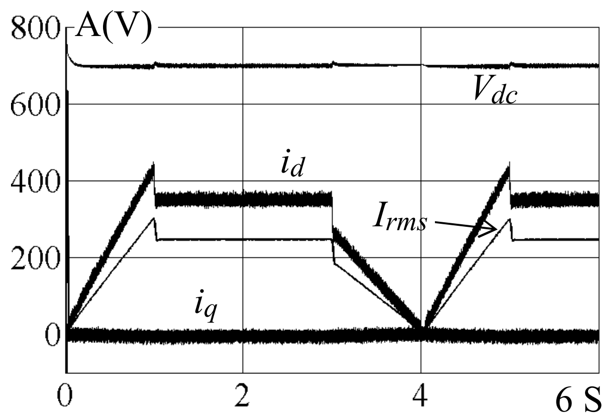


Fig.7b Converter VOC Response for a ± 1.0 pu ramp speed reference.

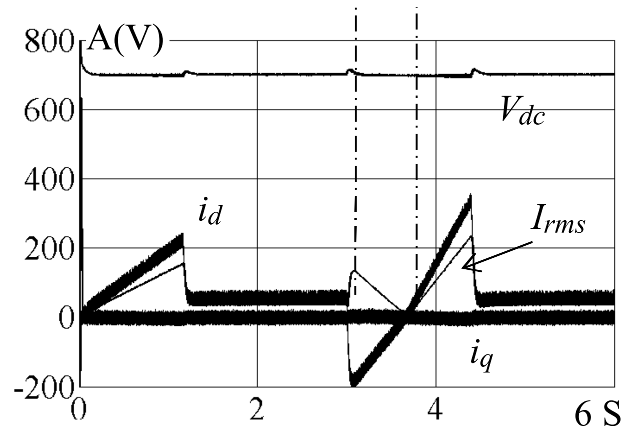


Fig.8b Converter VOC Response for a ± 1.0 pu ramp speed reference.

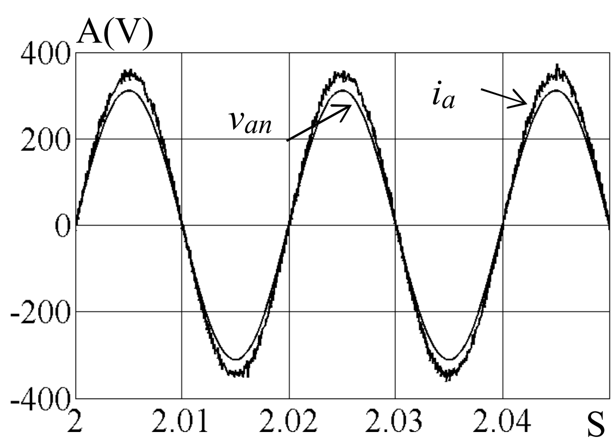


Fig.7c Steady-State ***i/v*** of Supply at Full Load

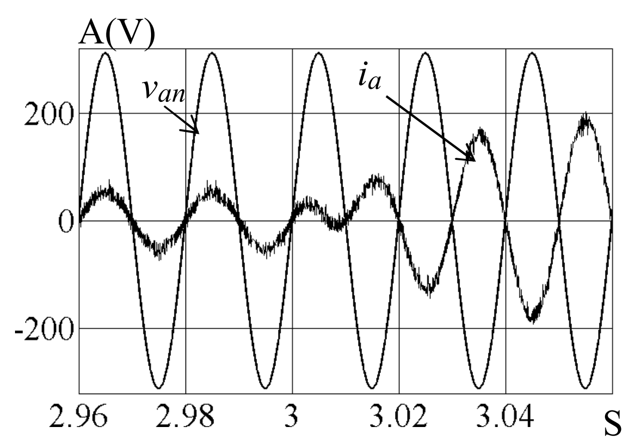


Fig.8c Supply Current during Speed Reversal

Fig.7 Drive Response for ± 1.0-pu speed input at Rated Constant-Torque Load.

Fig.8 Drive Response for ± 1.0-pu speed input with High Inertial-Load.

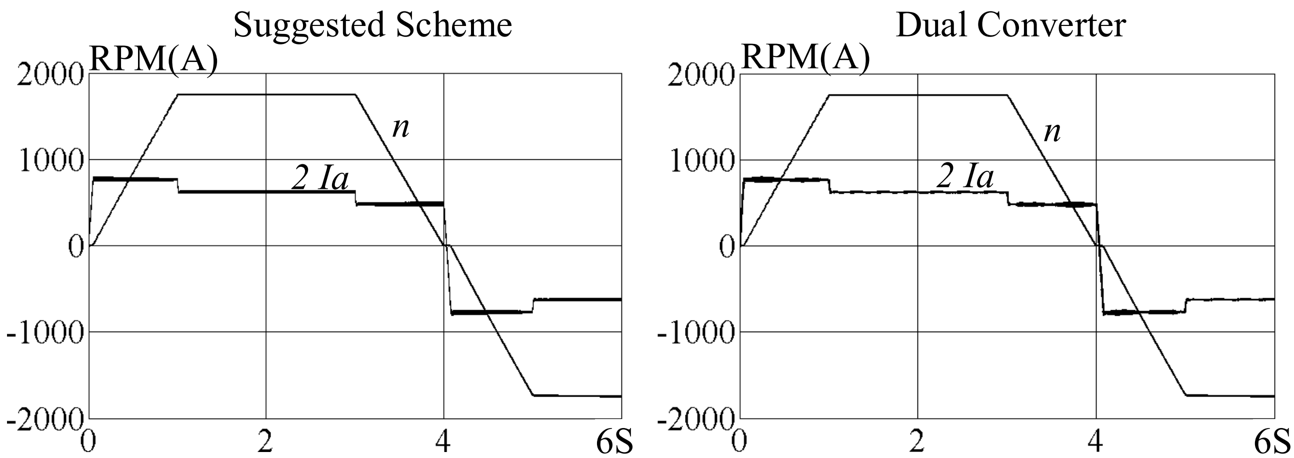


Fig.9a Comparison of Speed Response.

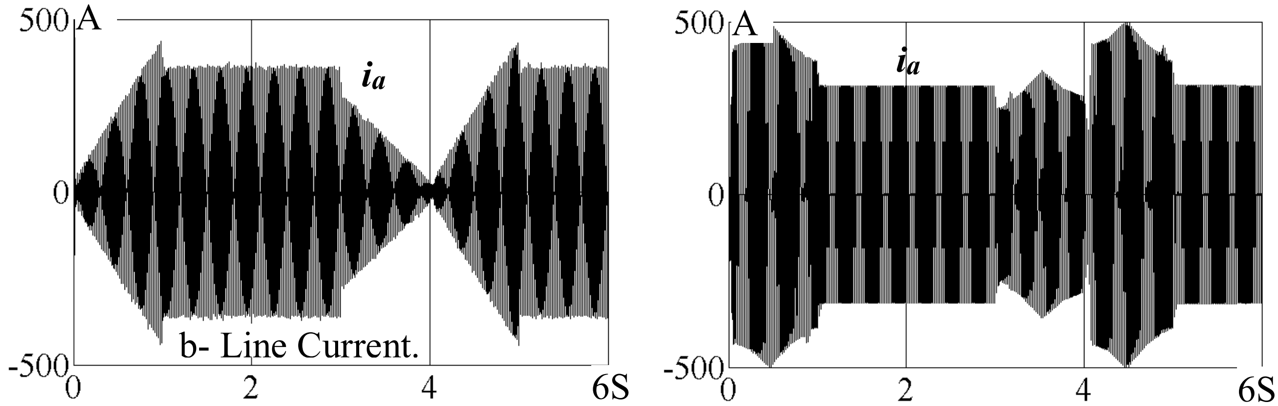


Fig.9b Comparison of envelope of the Line Current.

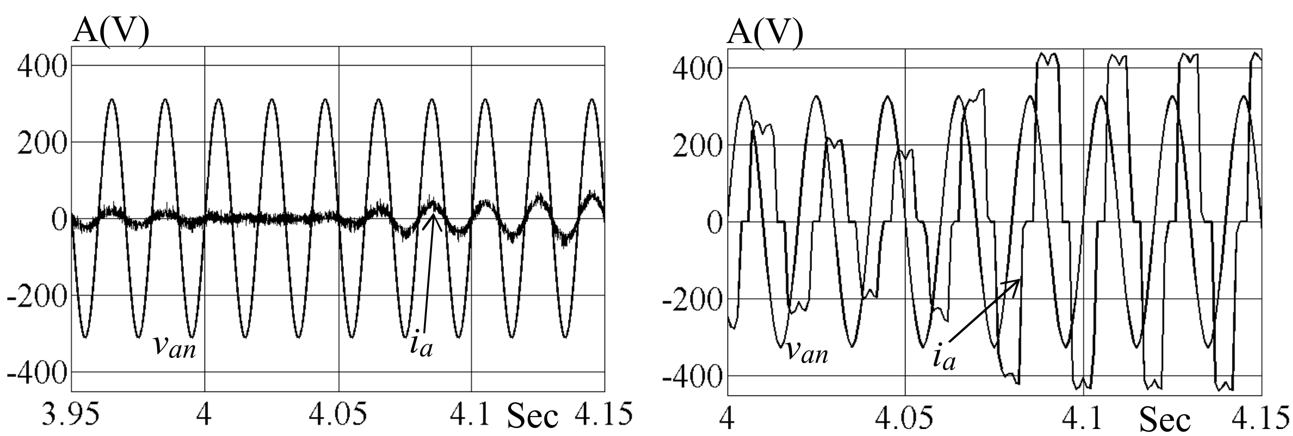


Fig.9c Supply Voltage & Line Current During Speed Reversal

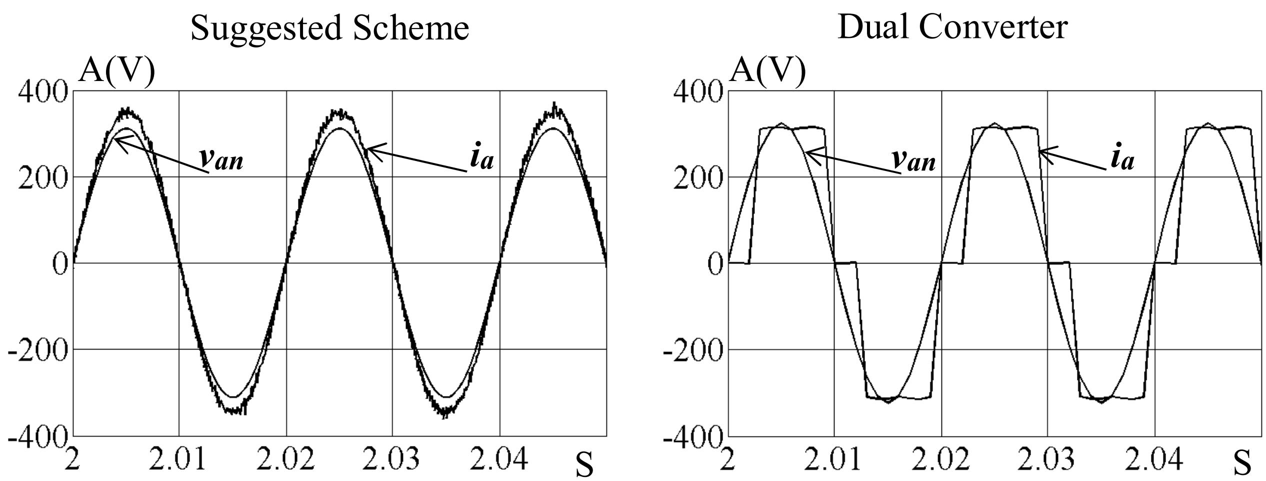
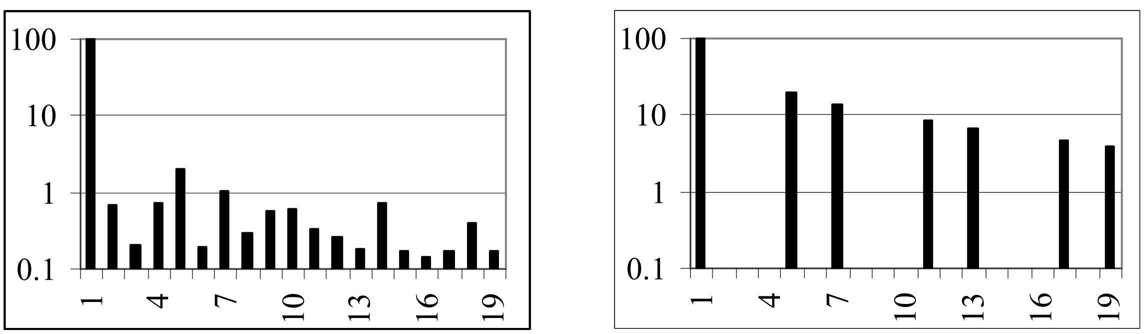


Fig.9d Comparison of Supply Current During Steady State Speed

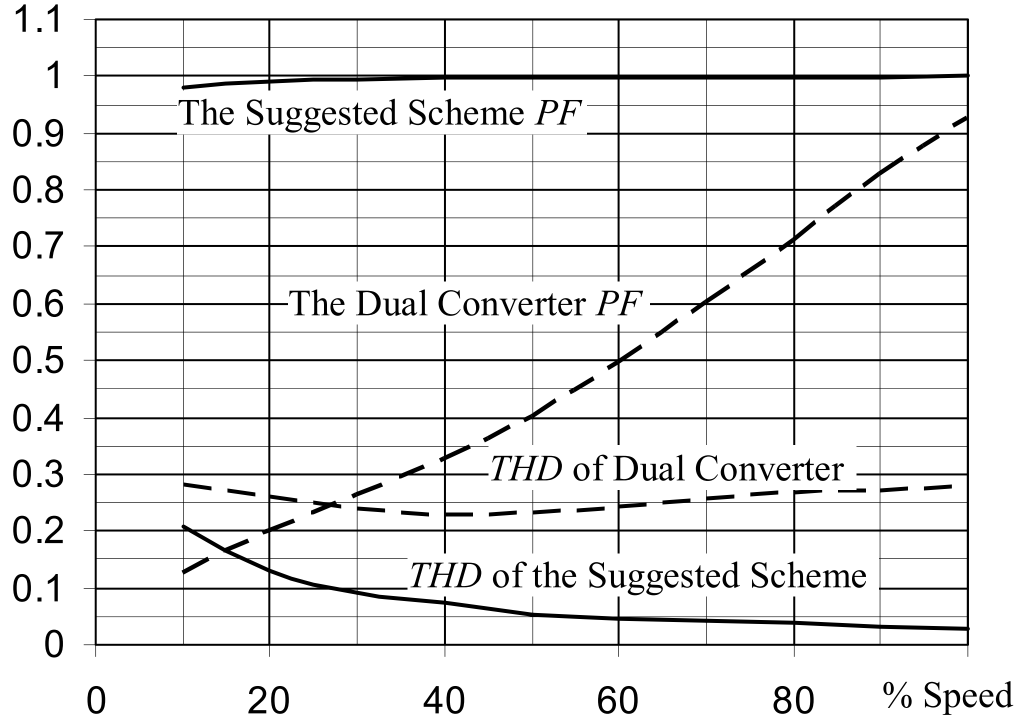


Fundamental = 348.6-A peak,
(246.5 rms),(THD) = 0.95%

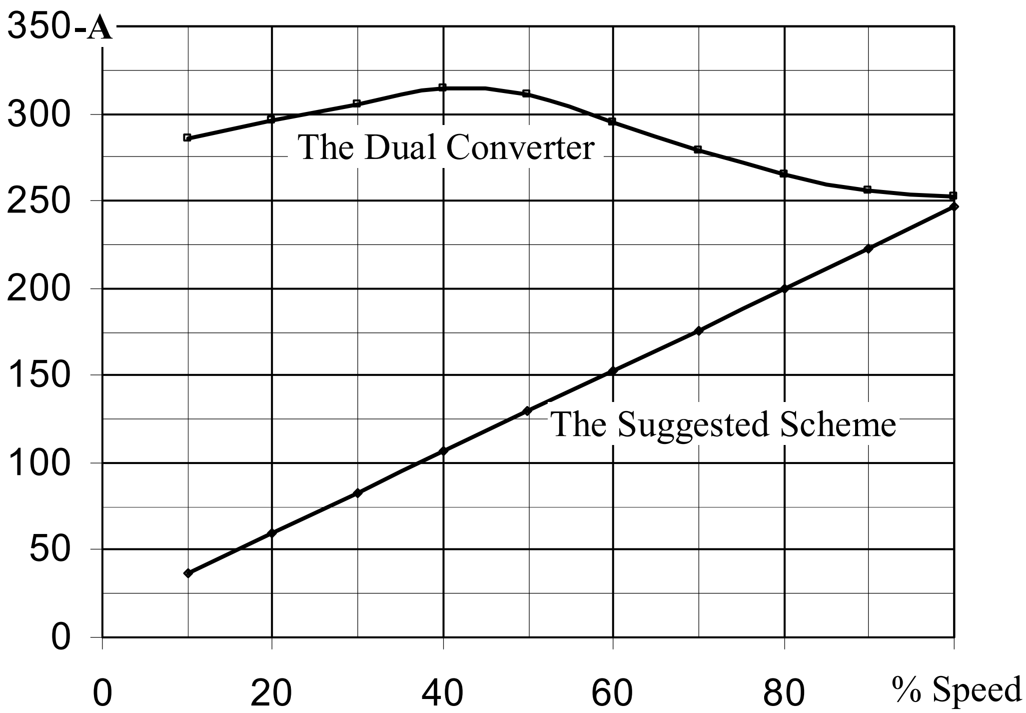
Fundamental = 343.9 peak,
(243.2 rms), THD = 27.25%

Fig.9e Comparison of Harmonic Spectrum of line Current

Fig.9 Comparison of Performance of the Suggested Scheme and the Dual Converter at Full Load, Steady State and Dynamic Speed Change.



a- Comparison of the THD and Power Factor



b- Comparison of the RMS Value of Line Current

Fig.10 Comparison of Performance of the Suggested Scheme and the Dual Converter over the Full Range of Speed.