6-1-2021

AC-DC Converter Operation for Active Sinusoidal Line Converter.

Ibrahim El-Sayed
Faculty of Engineering and Technology., Helwan University., Cairo., Egypt.

Follow this and additional works at: https://mej.researchcommons.org/home

Recommended Citation

El-Sayed, Ibrahim (2021) "AC-DC Converter Operation for Active Sinusoidal Line Converter.," *Mansoura Engineering Journal*: Vol. 20 : Iss. 2 , Article 5.
Available at: https://doi.org/10.21608/bfemu.2021.161267

AC-DC Converter Operation for Active Sinusoidal Line Current

Ibrahim Fatouh El-Sayed
Faculty of Engineering and Technology, Helwan Univrsity, Cairo, Egypt

'محول التيار المتردد الى مستمر والذى يتطلب تيارا فعالا فقط وجيبيا الشكل من الشبكه الكهربائيه'

ألخلاصـــه :

يتناول هذا البحث كيفية بناء محكوم لتوحيد التيار المتردد والذى يعمل بطريقه تضمين عرض النبضات بترددات عاليه, ويعمل النظام بحيث يؤدى الى مصدر تيارى مستمر مـن جانب وفى نفس الوقت بسحب من الشبكه الكهربيه تيارا فعالا فقط وجيبا الشكل.

فى بداية البحث تم استعراض أهمية هذا الموضوع فى التطبيقات الصناعيه, حيث أن نظم توحيد التيار العاديه الشائعة الأستخدام حاليا فى معظم التطبيقـات الصناعيه تسبب مشـاكل عديده لشبكة الكهرباء الرئيسيه من أهمها معامل القدره المنخفض والعشوائى, ثم تم شرح النظـام الجديد الذى يتطلب من الشبكه تيارا فعالا فقط وجيبيا الشكل فى التطبيقات المختلفه مثل التحكم فى ألات التيار المستمر والمرحله السابقه للعواكس التى تغذى الألات الحثيه والمتزامنه. كما تنـاول البحث استعراض البحوث السابقه فى هذا المجال حيث لم يتطرق أحد الى وضـع معـالات ولفيه تسـاعد الباحثين فى دراسة هذا النظام أوتصميمه أومعرفة حدود تشغيله.

فهذا البحث يعطى لأول مره طريقه تحليليه لفهم متغيرات نظام توحيد التيار الحديث, كمـا يستنبط المعادلات اللازمه لربط المتغيرات ببعضها فى صوره جليه لفهم تأثير متغيرات التحكم على الأداء المقيد بمعامل القدره المطلوب. وتم هذا التحليل لنظام التوحيد فى حالـة كل مـن حمل مقاومى وحمل ديناميكى, ولقد تم التركيز فى هذا البحث على التوصـل الى خواص هذا النظـام الجديد لتوحيد التيار وذلك فى حالة معامل قدره مساو للوحده. وبدراسة المعـادلات والمنحنيات تمت مناقشة كيفيـة الأستفاده من متغيرات التحكم الخاصـه بدائرة القدره للحصـول على الأداء المتميز والذى يحقق أكثر من هدف فى وقت واحد. ويرجع ذلك الـى التحكـم فـى تشـغيل ترانزستورات القدره بنموذج نبضات محكوم للقوه والزاويه فى نفس الوقت. ولتحقيق ذلك تم استنباط طريقة التحكم المناسبه والتى لاتعتمد على بارامترات دائرة القوى، وتم التحقق من امكانية تنفيذ الطريقه الجديده المقترحه من حيث الأداء المتميز المطلوب والـذى يتلخص فـى تيار مستمر محكوم ويناظره تيارا مترددا جيبا الشكل له نفس طور (وجه) جهد المصدر.

ABSTRACT. The paper describes and implements a stand-alone, unity power factor, controllable current source converter system. It is based on high frequency PWM technique. The converter topology is chosen to operate for both inverter and rectifier modes. Firstly, the principle of operation is discussed. Then, the presented AC-DC converter that demands only sinusoidal active current is studied. Most features of the converter are clearly interpreted for resistive and dynamic loads. On the basis of the given analysis, the paper provides PWM converter design guidelines for unity power factor operation. Also, a novel control strategy is proposed, which allows to fulfill all the specifications; in particular zero reactive power demand and very low distorted line currents have been guaranteed. The proposed method in this paper utilizes simultaneously the control variables: modulation index D (variable PWM pattern) and power angle δ (position of the PWM pattern). The instantaneous control for both achieves high-dynamic response and insensitiveness to parameter variations and disturbances. Also, the presented control structure employs power factor adjustment capability. This development provides a low cost solution, where no digital signal processors or large memories for the PWM generation are required. Results from device level PSPICE confirm the validity of the proposed method and the performed analysis. The proposed system can be utilized for power conditioning, DC and AC drive applications.

1. INTRODUCTION

Traditional power electronic systems are the main reason for harmonic pollution. This pollution may lead to destructive resonance beside many other drawbacks for the electrical distribution systems. Most variable speed drive applications get its power via AC to DC converters. Normally phase-controlled thyristors converters have been extensively used because of there control simplicity. However, the line currents drawn by such converters have distorted waves those posses harmonic and reactive power. On the other hand, the harmonic contents and the reactive power are load dependent. Many attempts were introduced to reduce such drawbacks. For example input filters are used to reduce input harmonics, also a compensating system can be used for power factor improvement. Another approaches uses an additional power electronic schemes such as active filters [1]-[5] and reactive power compensators [6]-[8] that adapt itself with the AC-DC converters to overcome its drawbacks. For these approaches, it is difficult to eliminate all harmonics. Also, the load transients may cause difficulties for compensation process. Moreover, the required additional components increase system complexity that reduces its use as a low-cost option.

With the recent developed power electronic devices, a better rectifier approach can be proposed in which the requirements are not only the output magnitude and shape but also the input current. The controller modulates the converter switching devices with high frequency instead of a single turn-on and turn-off per half cycle.

The old approach makes eye only on the output state (current or voltage) and thereby the converter satisfies the output requirement with non sinusoidal line currents. The recent developed approach uses PWM technique for rectifier schemes. It can offer several advanced features such as sinusoidal input current at unity power factor and simultaneous high quality DC output. This in turn results in reduced current ripple and reduced AC voltage distortion in

the grid and thereby contributes to overall improved performance. The grid sinusoidal active current reduces the losses and magnetic noise in the power transformers. The size of the passive elements in the AC side is considerably reduced due to PWM operation. Also, this approach can preserve its high performance features even under unbalance in the input supply that may be frequent, particularly in weak AC systems. Thus both input and output control capability of such PWM controlled AC-DC converters make it very suitable for applications such as magnet power supplies, DC motor drives, controlled voltage and current inverters, reactive power control, and utility interactive wind and photo voltaic systems. The new generation of pulse width modulated controlled rectifiers has been widely studied. The expected converter is the one that stand alone with good performance level in terms of low harmonic distortion, power factor adjustment capability, power reversal, and good dynamic response.

Fig. 1 shows the general schematic circuit for PWM converter. The common factor of the PWM controlled converters is the method used in controlling the output state which is kept close to the desired value. The error either controls the AC input current or the converter back modulated voltage Vm. In general, the optimal PWM pattern is being adjusted to satisfy the system requirements.
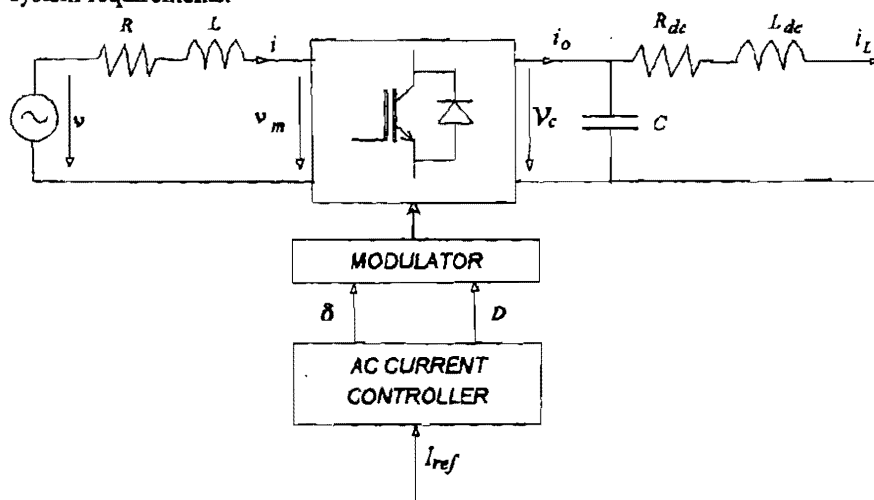

Figure 1: PWM controlled current converter.

Regarding the switching pattern generation and positioning, related research papers have been continuously appearing which signifies the importance and complexity of this subject [9]. Previous recent works [7], [10]-[13] are so much focused on system linearization or solving nonlinear dynamic equations on-line. These require multi-DSP system operating in parallel. However, up to the present, these control strategies are of the static type.

In this work, the proposed controlled current converter that draws sinusoidal active current is analysed and implemented. The analyses is focused on unity power factor operation for resistive and dynamic loads. The presented method can be used to understand clearly the system capability and the relations between the control variables. Where it can be used for developing different control strategies. Also, the paper presents a new simple control strategy that satisfies unity power factor, and sinusoidal current in addition to output DC-current control. Finally, the real control method and power circuit have been implemented using Pspice for verification.

2. PRINCIPLE OF OPERATION

Assuming that the high-order switching harmonics do not contribute much to the fundamental components, the equivalent power circuit for AC and DC sides is shown in Fig. 2. In this figure, V is the fundamental rms source voltage. Vm is rms value of the fundamental wave generated by pulse width modulation for the capacitor DC voltage. R and L are the resistance and inductance inserted between the converter circuit and the AC source. The inductance L is necessary to filter the high frequency switching of the used PWM pattern. The current source i_o impresses current segments of the AC side current i to the DC circuit. Therefore, the DC capacitor C is necessary for decoupling the instantaneous reaction between the DC load current i_L and the current source i_o.
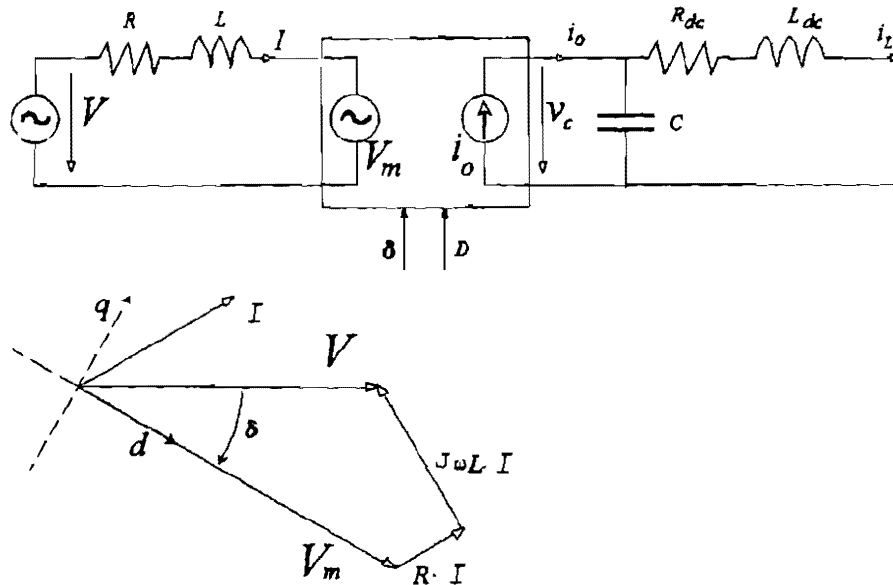

Figure 2: Equivalent circuit and phasor diagram.

The magnitude Vm depends on the capacitor average DC voltage Vc and the modulation ratio m. Assuming full utilization of the power circuit where over modulation range can be used, then the value of Vm can be expressed as:

$$Vm = D \cdot Vc \tag{1}$$

The control variable D (modulation index) has a nonlinear relation with the modulation ratio m.

As shown in Fig. 1, and 2, the switching PWM pattern generated by the modulator controls the voltage phasor Vm. Where, the modulation index D, results by the used PWM switching pattern, affects the magnitude Vm. While its position relative to the supply voltage defines the power angle δ. Hence the modulator with the power scheme shown in Fig. 1 controls the amount and direction of the power flow transferred between AC and DC sides. For negative power angle (Vm lags V), the power flow goes from the AC to the DC side and for positive power angle the power flows in the opposite direction.

A system control method that is based on the unchangeable predetermined PWM switching pattern is proposed in [14], where the modulation index D is held constant to achieve linear relation between the average capacitor voltage Vc and Vm. However, there are still nonlinear relations that should be processed. Also, the non-utilization of control variable D limits the system control capability, where the power factor is load dependent and, hence, is not constant.

It is important to state here that the presented control method in this paper utilizes simultaneously the control variables: modulation index D (variable PWM pattern) and power angle δ (position of the PWM pattern). The main task for the presented controller is to control the phasor Vm referred to the source voltage through the AC current and source waveform template to satisfy the requirements: controlling the DC load current with zero reactive power. The presented analysis shows that the relations between the above mentioned control variables and different DC load current for unity power factor are nonlinear. With these characteristics, it is difficult to achieve the requirements using on line computations. This problem is solved here by using an intelligent hysteresis controller for the input AC current. It can force the desired AC current efficiently and instantaneously to follow the reference wave by the proposed hysteresis controller in [15]. Then, without computations for PWM patterns and with only building the desired AC current wave that has the source voltage template, the DC load current can be controlled with input sinusoidal active current. The amplitude of the reference sinusoidal current is generated by the DC current controller. This control structure can drive the power circuit for both rectifier and inverter operations. When the sign of the current error signal is positive, the controller builds a reference AC current wave that be in phase with the source voltage forcing the power circuit for rectifier operation. But when the error sign is negative, the reference AC current wave will be inverted for inverter operation.

3. ANALYSIS OF THE CONVERTER

For AC side, the phasor diagram shown in Fig. 2 establishes operating conditions between the source phasor V and the converter terminal phasor Vm . Also this phasor diagram can be expressed in d-q frame as:

$$R \, Id - X \, Iq = Vd - Vmd \qquad (2)$$
$$X \, Id + R \, Iq = Vq - Vmq \qquad (3)$$
where
$$Vd = V \cos (\delta) \qquad (4)$$
$$Vq = V \sin (-\delta) \qquad (5)$$
$$Vmd = Vm \qquad (6)$$
$$Vmq = 0 \qquad (7)$$

Clearly, the DC-side converter output current io controls the capacitor voltage level and the load current iL. This current satisfies the instantaneous power balance equation between the AC side and the DC side of the converter circuit that can be written as follows:

$$Vc \, io = Vmd \, id + Vmq \, iq \qquad (8)$$

For steady state operation, the average DC capacitor voltage reaches a particular equilibrium value, which means that the average DC load current IL becomes equal to the average value Io. Then, the power balance equation (8) can be written for steady state as:

$$Vc \, IL = Vmd \, Id + Vmq \, Iq \qquad (9)$$

For simplicity, the parasitic resistance Rs and Rdc are omitted for the following analysis. By using Eq. (1), (2)-(9), it is possible to derive the relations between DC output current I_L and the input control variables (D, δ).

$$I_L = D . Id = (D . V/X) . \sin (- \delta) \tag{10}$$

3.1. Resistive load characteristics

The relation between the DC output voltage Vc and the input control variables (D, δ) for resistive load can be obtained using Eq.(10).

$$Vc = (D . V . RL/X) . \sin (-\delta) \tag{11}$$

Also, the active and reactive powers drawn from the AC source are:

$$P = Vd . Id + Vq . Iq$$
$$= (a . V^2 /X) . \sin^2 (\delta) \tag{12}$$

$$Q = Vq . Id - Vd . Iq$$
$$= (V^2/X) . [1 - a . \sin (\delta) . \cos (\delta)] \tag{13}$$
where
$$a = (RL / X) . D^2 \tag{14}$$

Fig. 3 shows the $P - \delta$ and $Q - \delta$ relations for different a 's. It can be seen that the constant a should be greater than 2 for zero reactive power operation.
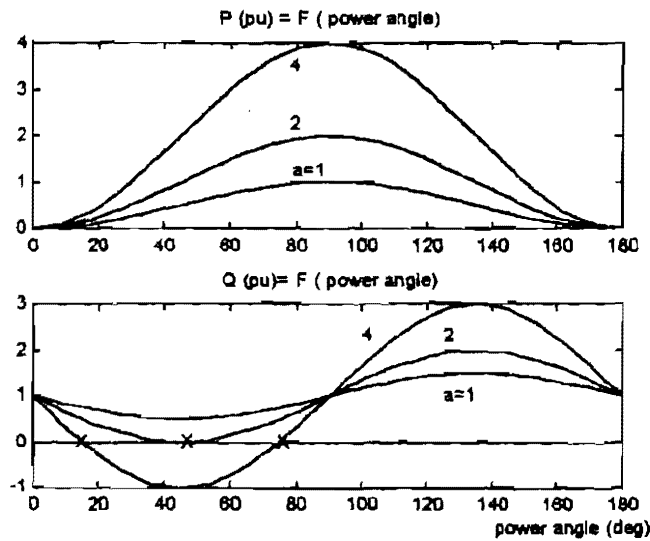

Figure 3: Active and reactive power (resistive load).

There are two possible power angles ($\delta1$, $\delta2$) for unity power factor operation. These power angles can be obtained from Eq.(13) when $Q = 0$.

$$\delta1 = 0.5 . \arcsin (2/ a) \tag{15}$$

$$\delta_2 = 90^\circ - 0.5 \ . \ \arcsin (2/ a) \tag{16}$$

The DC load power of (12) for unity power factor conditions of (15), and (16) becomes

$$P_{1,2} = (a \ . \ V^2 /X) . \sin^2 (\delta_{1,2}) \tag{17}$$

It is clear that the relation between the control variables are nonlinear. For the same value of the constant a , there are two possible values for output power P and two possible values for the control variable δ. Equations (14)-(16) allow us to plot the relations between the control variables δ, and D required for unity power factor condition.

Fig. 4 shows D - δ curves for different values of RL/X. Clearly, the control range of the modulation index D and power angle δ depend on the ratio between the load resistance RL and the AC side inductor impedance X. The possible ranges for these control variables determine the control capability of the PWM converter for unity power factor operation.
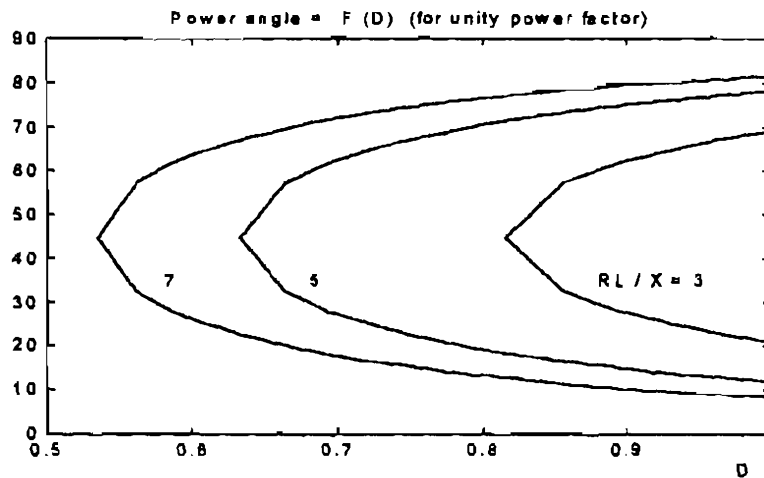

Figure 4: Control variables relation (resistive load).

Considering V and V/X as base values for voltage and current, the perunit load current and capacitor voltage using Eq. (10), (11), (15), and (16) are shown in Fig. 5. It can be seen that for given RL, the source inductance determines the DC load current range that can be provided under unity power factor operation. Note that it is possible to get operations outside this range but on the expense of power factor different from unity.

3.2. Controlled current characteristics

The PWM converter can operate as ideal controlled current with unity power factor independent of the DC voltage level. The control variables determined by the PWM switching function forces the system to satisfy the requirements. The system capability depends on the circuit parameters. In case of dynamic load, the power circuit also allows negative DC current flow (inverter operation) when the reference current is negative. This regeneration occurs while the DC capacitor voltage is kept positive. Hence the transient response for the DC current is determined mainly by the DC smoothing inductor.
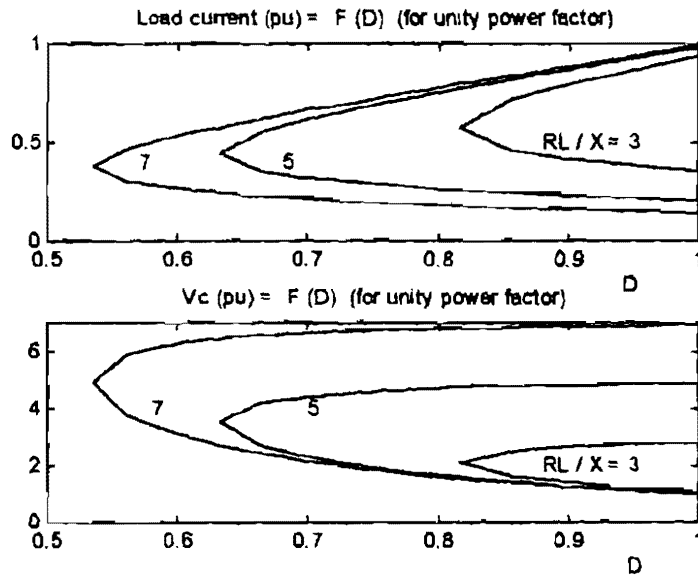
Figure 5: Load current and voltage capability (resistive load).

If the load has a voltage level of V_{co}, the perunit reactive power Q becomes

$$Q = 1 - b \cdot \cos(\delta) \tag{18}$$

where

$$b = (V_{co} / V) \cdot D \tag{19}$$

Clearly, for constant power angle, the reactive power is linearly dependent with b or equivalently D. To control the load current and the reactive power at the same time, both control variables δ and D should be used as shown in Eq. (10), (18), and (19).
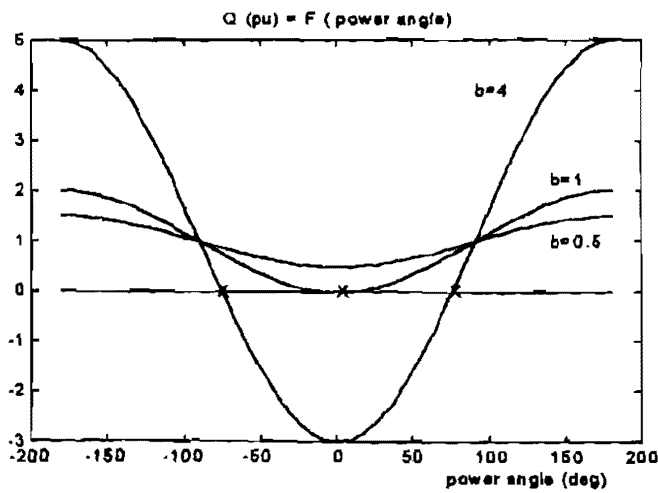

Figure 6: Reactive power (dynamic load).

Fig. 6 shows the perunit reactive power for different values of b. For zero reactive power operation, b should be greater than 1. There are two possible power angles ($\delta 1$, $\delta 2$) for unity power factor operation. The positive power angle δ is for regenerative operation, while the negative value for rectifier operation.

The constraint equation for zero reactive power is obtained from eq. (18), and (19) to be

$$D = (Vco / V) . \cos (\delta) \tag{20}$$

If the constraint equation (20) is considered during operation, the DC load current will take a particular and well-defined value for each load voltage $Vc0$. By using Eq. (10), and (20), it is possible to derive the relation between the load current and the control variables D or δ.

$$I_L = (V/X) . (V / Vco) . \tan (\delta) \tag{21}$$

$$I_L = D . (V/X) . \sin [\arccos (V /(D . Vco))] \tag{22}$$

Fig. 7 shows the constraint relation between the control variables δ and D for different DC voltages. It can be seen that, for low values of DC load voltage $Vc0$, the system can not satisfy unity power factor operation, where the modulation index D is limited by the nature of the power circuit.

Also, Fig. 8 shows the system capability for controlled current operation under unity power factor condition. To increase the absolute DC load current capability under unity power factor and certain DC voltage $Vc0$, the AC side inductance should be decreased.

This analysis is helpful for understanding easily the converter capability and its relations with the parameters that are necessary for system design stage.
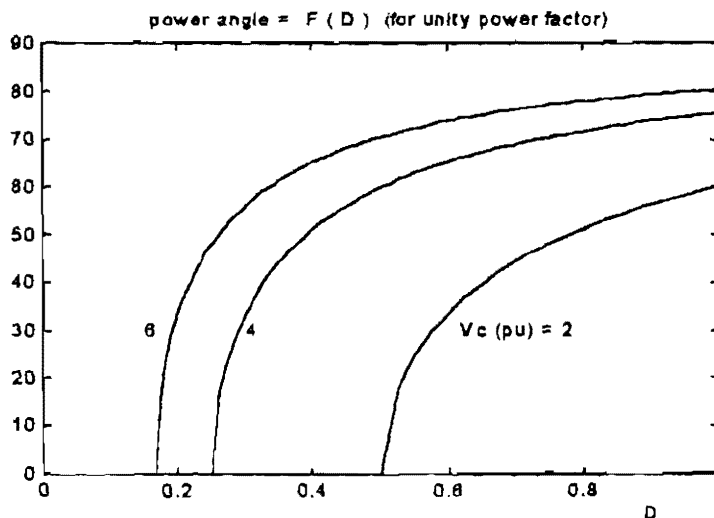

power angle = F (D) (for unity power factor)

Figure 7: Control variables relation (dynamic load).

Load current (pu) = F (D) (for unity power factor)

Load current (pu) = F (power angle) (for unity power factor)
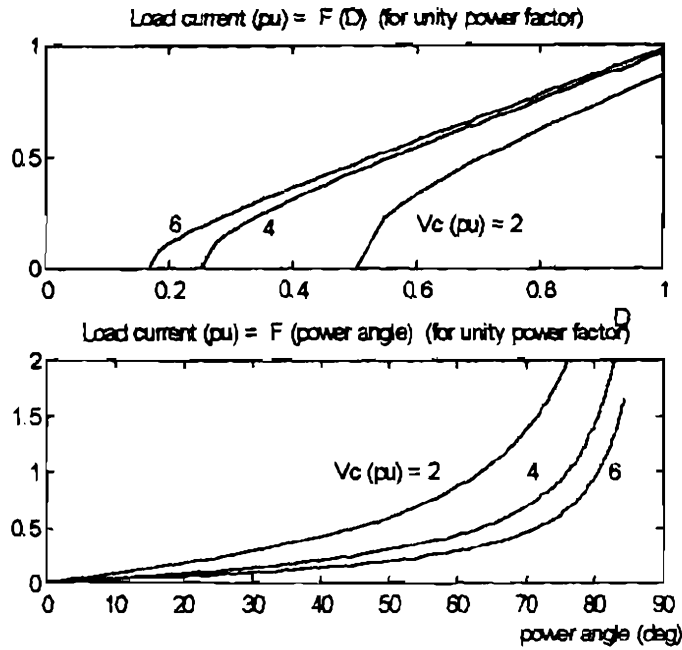

Figure 8: Load current and voltage capability of the converter (dynamic load).

4. ZERO REACTIVE POWER CONTROLLER

Using the characteristics explained before, different control method can be proposed to achieve the desired requirements as shown in Fig. 9 and 10. The DC load current can be kept close to the reference by using the error signal between that current and the reference. This error either controls directly the AC input currents or the converter terminal modulated voltage Vm. In both cases, the control variables D and δ are used to satisfy the operation requirements.
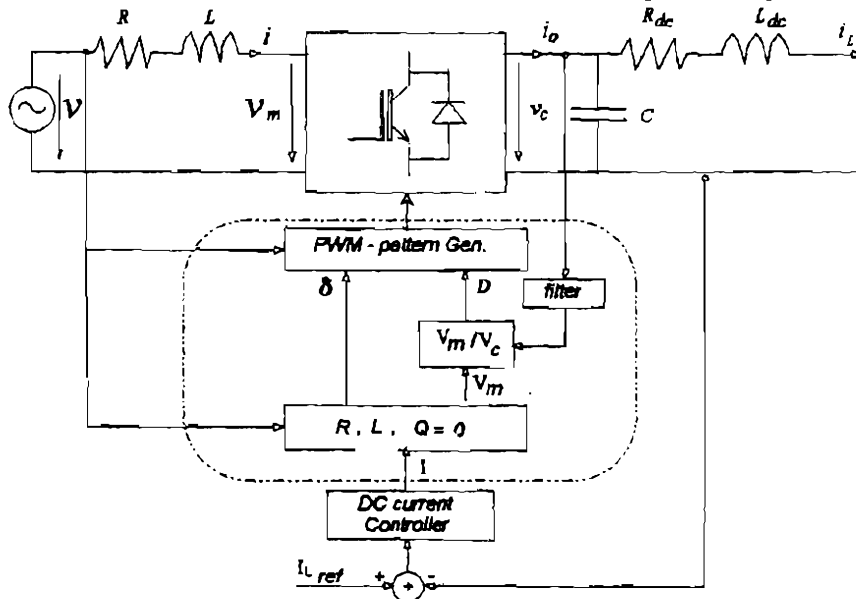

Figure 9: Indirect control scheme.

Fig. 9 shows a controller structure that can control the output DC current indirectly. For the indirect control method, the reference input AC current is calculated and then the required Vm. The control variable D is determined according to the average DC voltage V_{c0}. The modulator uses these values to generate the PWM switching pattern that satisfies the requirements. This method needs on-line calculation that leads to time delay. Moreover it requires accurate values of the system parameters that may changes with time.

The direct method shown in Fig. 10 uses an AC current controller that forces the power circuit to draw a current close to the reference one. This AC current controller generates automatically the required PWM pattern. In this work an intelligent simple hysteresis current controller proposed in [15] is used. This controller is based on the so called freepolar modulation method. It can control the current ripple by efficient switching frequency and has excellent dynamic performance. The reference current is generated according to the source voltage template and the amplitude produced by the DC current controller. This method is very simple because there are no complex on-line computations. Beside that there are no need for system parameters where the system adapts itself for any parameter changes.
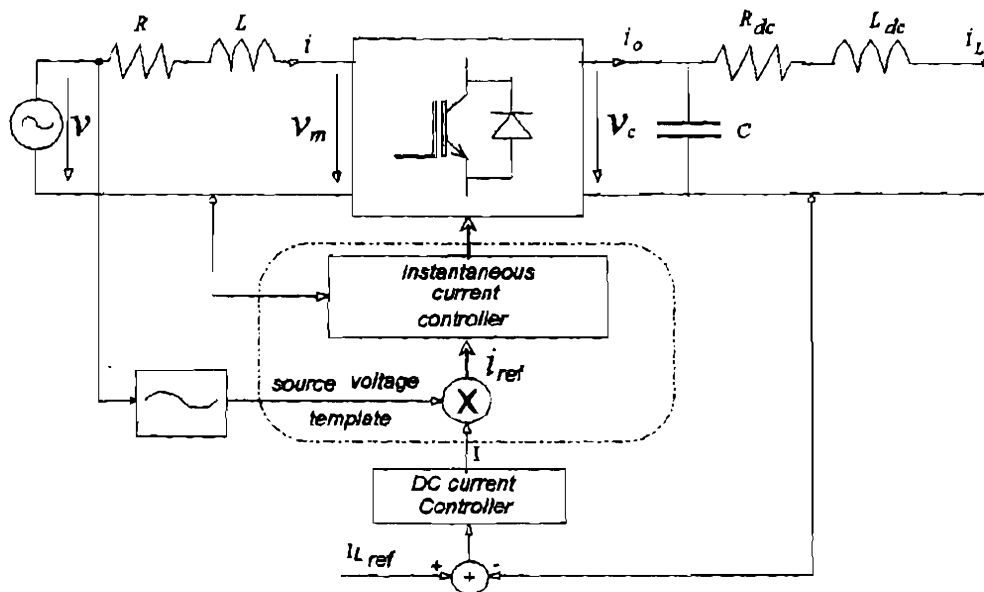

Figure 10: Proposed direct control scheme.

5. VERIFICATION

The system is verified in time domain by means of a widely used industry standard device level Pspice program. The proposed PWM converter scheme in Fig. 10 is implemented including real control circuit, drivers, snubber circuit with the following main parameters.

$V = 65$ v, $50Hz$, $R = 1$ ohm, $L=10$ mH,

$V_{c0} = 220$ v, $R_{dc} = 0.5$ ohm, $L_{dc} = 0.2$ H, $C = 2000$ uF

Fig. 11-a and b show the behavior of the system in case of rectifier and inverter operations for the same parameters. It can be observed that the AC input current is an active sinusoidal

current with very low amplitude of ripples in both operations. Also, the control system adapts the power angle and the switching pattern automatically to keep the AC line current close to the reference for both cases. Regarding the DC side, it is clear that the current source i_o is a unidirectional pulse width modulated segments of the AC current i .
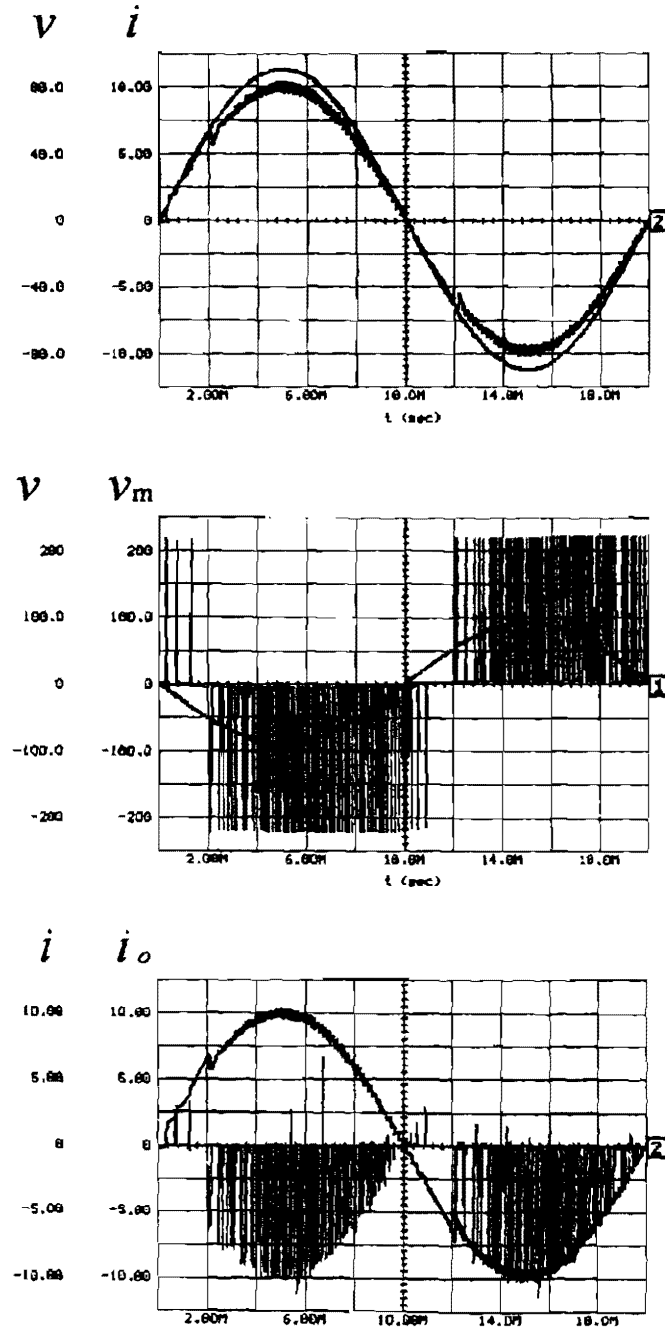

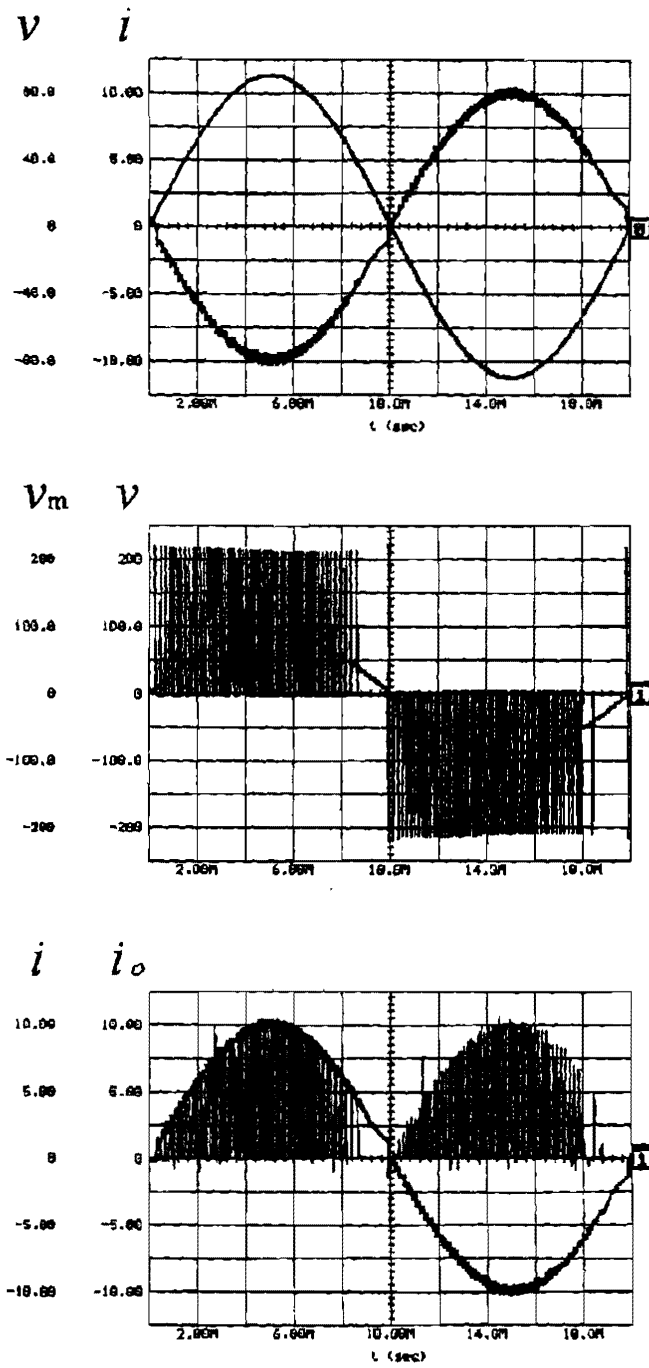Figure 11-(a): Rectifier performance.

Figure 11-(b): Inverter performance.

6. CONCLUSION

A novel AC/DC PWM controlled converter, controlled instantaneously, is developed and implemented. A high degree of controllability is obtained by using a simple control strategy. The principles of operation are described, and design expressions are derived. Several new facts are identified and contributed. The DC current can be controlled in a certain range that depends on the system design parameters. The unity power factor operation can be obtained when the constant $a = (RL/X)$. D^2max is larger than 2 in case of resistive loads, and when the constant $b = (Vco/V)$. $Dmax$ is larger than 1 in case of dynamic loads.

The presented analysis shows that the relations between the control variables D, δ and DC load current for unity power factor are nonlinear. Therefore it is difficult to achieve the requirements using on line computations. This problem is solved here by using a self adaptive instantaneous current controller for AC current. Then, without computations for PWM patterns and with only building the desired AC current wave that has the source voltage template, the DC load current can be controlled with input sinusoidal active current. With simple control structure, the converter achieves high performance such as: unity power factor operation for rectifier and inverter operation, controlled ripple for the demanded sinusoidal line current, and output controlled DC current source as well as minimum converter loss. Other interesting characteristics are: 1) the robustness to parametric variations and disturbances; 2) the input power factor can be arbitrarily controlled; 3) full utilization of the power circuit through simultaneous control of the modulation index D and the power angle δ.

Further research is required to handle the remaining step in perfecting the stand-alone PWM converter. Which allows the converter to operate under maximum power factor when it is beyond the unity power factor range.

REFERENCES

[1] Duke, R.M., and Round, S. D., "The Steady -State Performance of a Controlled Current Active Filter" IEEE Trans. Power Electron., 1993, vol. 8, no. 2, pp. 140-146

[2] Harmens, G.L., and Enslin, J.H.R., "Real-time Dynamic Control of Dynamic Power Filter in Supplies with High Contamination" IEEE Trans.Power Electron. Vol. 8, No. 3, 301-308, 1993.

[3] Bhavaraju, V.B., and Enjeti, P.N., "Analysis and Design of an Active Power Filter for Balancing Unbalanced Loads" IEEE Trans.Power Electron. Vol. 8, No. 4, 640-647, 1993.

[4] Chicharo, J.F., Dejsakulrit, D., and Perera, S.P., "A Centroid Based Switching Strategy for Active Power Filters" IEEE Trans.Power Electron. Vol. 8, No. 4, 648-653, 1993.

[5] Nastran, J., Cajhen, R., Seliger, M., and Jereb, P., "Active Power Filter for Nonlinear AC Loads" IEEE Trans.Power Electron. Vol. 9, No. 1, 92-96, 1994.

[6] Ooi, B.T., and Dai, S.Z., "Series-Type Solid-State Static VAR Compensator" IEEE Trans.Power Electron. Vol. 8, No. 2, 164-169, 1993.

[7] Enjeti, P.N., and Choudhury, S.A.," A New Control Strategy to Improve the Performance of a PWM AC to DC Converter under Unbalanced Operating Conditions" IEEE Trans.Power Electron. Vol. 8, No. 4, 495-500, 1993.

[8] Shirahama, H., Sakurai, Y., Matsuda, Y., Ishigaki, Y., and Murai, K., "Instantaneous Control Method with a GTO Converter for Active and Reactive Powers in Superconducting Magnetic Energy Storage" IEEE Trans.Power Electron. Vol. 9, No. 1, 1-6, 1994.

[9] Trzynadlowski, A. M., and Legowski, S., "Application of Neural Networks to the Optimal Control of Three-Phase Voltage-Controlled Inverters" IEEE Trans.Power Electron. Vol. 9, No. 4, 397-404, 1994.

[10] Wang, X., Ooi, B.T., "Unity PF Current-Source Rectifier Based on Dynamic Trilogic PWM" IEEE Trans.Power Electron. Vol. 8, No. 3, 288-294, 1993.

[11] Wang, X., Ooi, B.T., "Real-Time Multi-DSP Control of Three-Phase Current-Source Unity Power Factor PWM Rectifier" IEEE Trans.Power Electron. Vol. 8, No. 3, 295-300, 1993.

[12] Zhang, Z.C., and Ooi, B.T. "Multimodulator Current-Source SPWM Converters for Superconducting a Magnetic Energy Storage System" IEEE Trans.Power Electron. Vol. 8, No. 3, 250-256, 1993.

[13] Bertini, S., Ghiara, T. and Marchesoni, M., "AC/DC/AC High Voltage Traction Drives with Quasi-Zero Reactive Power Demand" IEEE Trans.Power Electron. Vol. 8, No. 4, 632-649, 1993.

[14] Veas, D.R., Dixon, J.W., and Ooi, B.T.."A Novel Load Current Control Method for a Leading Power Factor Voltage Source PWM Rectifier." IEEE Trans.Power Electron. Vol. 9, No. 2, 153-159, 1994.

[15] EL-Sayed, Ib.F., "A powerful and efficient hysteresis PWM controlled inverter" EPE Journal, Vol. 4, no. 4, PP. 27-33, 1994.