RETROFITTING THE ACCELERATING MAGNET OF THE MGC-20 CYCLOTRON

G. M. Sarhan[1]   A. A. Hagras[2]   Sh. M. Saad[3]

ABSTRACT

This paper suggests a retrofitting scheme for the accelerating magnet of the MGC-20 cyclotron owned by the Egyptian Atomic Energy Authority AEAEG. The main coil of this magnet and the accompanied corrector coils are to be equipped with new better quality power supplies based on a high performance Digital Signal Processor and highly efficient PWM converters. This paper can represent a partial proposal of an overall project to modernize and upgrade the replaceable cyclotron systems aiming at improving its performance and maximizing its economical and research profit. Digital simulation presented proves effectiveness and quality expected from the suggested scheme in adjusting magnet currents and consequently obtaining better results in final beam extraction and pointing to irradiated target.

KEYWORDS: MGC-20 cyclotron, Sinusoidal PWM converters, unity power factor converters, DSP applications.

يعتبر معجل السيكلوترون MGC-20 والذي يستخدم لأغراض البحث وإنتاج النظائر المشعة أحد أهم إمكانات هيئة الطاقة الذرية في مصر وقد تم بناءه بواسطة معهد NIIEFA في سان بطرسبرج في روسيا ودخل العمل الفعلي منذ العام 1999 في إطار برنامج التعاون مع الوكالة الدولية للطاقة الذرية. ويستخدم لتعجيل البروتونات والديوترونات وأيونات الهليوم وجسيمات ألفا، ويخدم هذا المعجل مدى واسع من التطبيقات من تحليل الطيف النووي إلى إنتاج النظائر المشعة ذات العمر القصير المستخدمة في الأغراض الطبية. ونظراً لأن تصميم هذا المعجل وتنفيذه قد تم في مرحلة مبكرة قبل الثورة التكنولوجية الهائلة الحالية فإن أجزاءه المختلفةتعمل بكفاءة متدنية نسبياً كما أنها قد قاربت نهاية عمرها الافتراضي وأصبح استخدامه يعاني الكثير من فترات التوقف بما يضيع الكثير من الإمكانيات البحثية والاقتصادية

[1] Lecturer of Elect. Eng., Benha Higher Institute of Technology.

[2] Electronic Engineer in AEAEG.

[3] Professor of Nuclear Physics AEAEG.

ومن ثم تحتم القيام ببرنامج تحديث لأنظمته المختلفة بما يدعم اعتمادية أدائه ويحسن من إنتاجيته. ويقدم هذا البحث مقترح لتحديث مصادر تغذية ملفات مغناطيس التعّجيل يعتمد على معالج العمليات الرقمي DSP كوحدة تحكم مركزية للقيام بأعمال التحكم والمراقبة والاتصال، ودوائر تحويل حديثة قائمة على طريقة تعديل عرض النبضة، ودوائر قياس عالية الدقة بما يحسن الأداء في عملية استخلاص الشعاع الأيوني بأكبر قيمة ممكنة وتوجيهه بصورة دقيقة. وعلى الرغم أن هذا المقترح جزئي ويختص فقط بأحد الأنظمة المتعددة الموجودة بالمعجل فإن إمكانية تكامله مع أي مشروع عام لتحديث باقي أنظمة السيكلوترون متاحة من خلال القدرات المتعددة لمعالج العمليات الرقمي. كما أن هذه القدرات تعطي إمكانية مستقبلية لاستبدال نظام ضبط وتشغيل أوتوماتيكي بنظام الضبط والتشغيل اليدوي القائم حالياً وذلك عند استكمال تحديث باقي الأنظمة مثل نظام التردد العالي ونظام التبريد ونظام تفريغ الهواء ونظام الإمداد بالغاز المؤين.

1. INTRODUCTION

The MGC-20 cyclotron is one of the main departments of the Egyptian Atomic Energy Authority. This cyclotron has been established with the help of International Atomic Energy Agency (IAEA) according the cooperation protocol with Egypt. It has entered service since year 1999. This cyclotron is used to accelerate different charged particles such as protons, deuterons, Helium ions and Alfa particles. This cyclotron is used to produce radioisotopes used in different research, medical and other applications. This cyclotron represents a medium complicated process and comprises a number of subsystems that can be briefly described in the following [1];

1- The accelerating system consisting of the main magnet, the accelerating chamber, the high voltage RF generator and the resonance system.
2- The ion source including the gas supply and the hot filament and other components of ionizing system.
3- The vacuum system used to evacuate all the internal parts prior to accelerating-irradiation process.
4- The cooling system that secures limited temperature of all critical parts irrespective of quantities of heat dissipated.
5- The beam extraction system consisting of the electrostatic deflector and the magnetic channel including the diagnostic probe, the switching magnet, quadruples lens doublets, the magnetic correctors and the ion-beam guides.

Efficient operation of cyclotron means obtaining the highest possible beam current at the required beam energy. This efficient duty depends on correct operation of all the above systems and components. Since all systems of this cyclotron are constructed with technology of the early eighties of the last century. None of these systems lend itself for automation and all approach end of their useful age. An overall retrofitting project of its replaceable parts and systems can extend the useful usage age of this cyclotron and maximize the profit of the capital has been invested in it.

One of the critical parameters to be taken into account of any retrofitting scheme is to minimize out-of-service periods required to execute it. So a step by step schedule is preferable in such situation. Based on this fact this paper gives a retrofitting scheme for the most troublesome system. That is the system of power supplies feeding coils of the accelerating magnet.

2- COMPONENTS OF THE ACCELERATING MAGNET

Establishing a uniform magnetic field in cyclotron is one of the main important factors affecting its operation. Actually, stability of the acceleration process, attainment of the final energy of the accelerated beam and efficiency of the beam extraction system depend on uniformity of the magnetic field and controllability of magnitude of its low order harmonics. Error in these low order harmonics can reduce the efficiency of the beam extraction resulting in complete disappearance of the ion beam. Magnetizing coils of the main magnet consists of the following:

1- The main magnet coil rated at 500-A and 240-V, this coil provides the main mmf required to establish main pole flux.
2- The 11-corrector coils each is rated at 20-A, 30-V. Each of these coils must be fed by a high accuracy power supply equipped with a high resolution current measurement and control scheme. These coils are used to fine adjust uniformity of the magnetic flux distribution under the main pole and are arranged in 3-groupes as follows:
    a- 3-Internal harmonic coils established near centre of the main magnet and are displaced 120^{o} apart.
    b- 3-External harmonic coils established near outer periphery of the main magnet and are also displaced 120^{o} apart.
    c- 5-Concentric coils established concentrically with the main magnet.

In the original scheme the above coils are fed with power supplies based on conventional phase controlled SCR rectifiers cascaded with linear current regulators and analog feed-back control strategies. Each of these power supplies consists of a large number of bulky modules to perform different processes required such as measurements, feed-back control, communication with the host computer, firing delay and power circuits. These supplies suffer from inherent low frequency ripples in the order of 6 of power frequency and must be fitted with large smoothing inductances to filter such harmonic. Operation of these power supplies is subjected to frequent malfunctions due to components aging and there is inherent difficulty in precise current setting. Since the periods of operation can extend to more than 10 hours continually, interruption of operation leads to drastic economical losses and research-effort wasting.

3. AN OVERVIEW OF THE SUGGESTED SCHEME

Figure 1 shows the outline of the suggested scheme. The DSP resources are effectively utilized to control number of power converter supplying different coils of the accelerating magnet. Each of these coils is supplied with a power converter suitable for its current and voltage ratings. Figs.2 and 3 show these power converters, where the main coil is supplied with a unity power factor (UPF) pulse width modulated (PWM) current source converter (CSC). Each of corrector coils is supplied with a 4-quadrant chopper operating in quadrants 1 and 3. The dc-bus supplying these choppers is energized by a UPF voltage source converter (VSC). The following subsections describe each of these circuits in more detail. How the DSP controls different converters and obtains the required measurements of feed back signals will be described in the later subsections.

3. 1 Power Circuit of the Main Coil

The main magnet coil with the previously stated ratings has a large time constant (more than 40-mS) and it is to be operated at constant current without any abrupt changes. Excluding the initial setting adjustments at start of operation, current of this coil must be fixed during the full irradiation period. In such case a UPF CSC is the most suitable choice. This type of converter greatly reduces impact on ac-supply since it can operate at unity power factor with nearly sinusoidal line current. As shown in the schematic diagram Fig.2 the circuit consists of a 3-phase current source converter bridge supplied by a step down 3-phase transformer. An input filter consisting of *0.05-mH* series inductance and a delta connected *50-μF* capacitor bank is used to filter out the high switching transients and reduce high voltage stresses on circuit components. Details of power circuit design taking into account a 20% overload capacity are:

1- Input Transformer		*125-kVA, 380/208-V*, Δ/Y
2- Switches;	IGBT:	I_{DC}= *600-A* maximum current rating.
		I_{RMS}= *350-A* RMS, V_{CE0}= *600-V*.
	Series Diodes:	Fast Recovery.
		I_F= *600-A* maximum current rating.
		I_{RMS}= *350-A* RMS, V_{RB}= *600-V*.
3- Input Filter:	Three phase delta	*C=50-μF, 250-VAC*
	Series inductor	*L=50-μH*

3. 2 Power Circuits of the Corrector Coils

Although the corrector coils, consisting of the 6-harmonic coils and the 5 concentric coils, have approximately equal current and voltage ratings each of them needs to be adjusted to a different current setting depending on each operation-cycle adjustments. As shown in Fig.3a and Fig.3b all these coils are supplied form a common dc supply via individual 4-quadrant choppers. These 4-quadrant choppers are needed taken into account that current setting of individual coils can be either positive or negative according to operation requirements. The voltage rating of corrector coils is 30-V then a suitable value of bus voltage is about 60-V giving enough voltage margin for individual current controllers and devices voltage drop. For this low voltage level power MOSFETs are the best choice for switching devices. MOSFET has the highest switching speed among power semiconductor devices and the lowest ON-state voltage drop giving rise to high efficiency operation. Power MOSFET has an integral reverse diode of comparable power ratings and switching frequency, so there is no further external diodes required. Further more power MOSFET can be easily operated in parallel to fulfill current requirements. Based on current and voltage ratings of each chopper and the voltage ratings of dc-bus the following ratings per switch are required:

Switches:	MOSFET	$I = 30\text{-}A\ Max$
		$I_{RMS} = 20\text{-}A$
		$V_{DS} = 100\text{-}V$

3. 3 VSC Converter Supplying DC-Bus of the Corrector Coils

Making reference to Fig.1 and Fig.3a the sum of input currents of individual choppers feeding the corrector coils, represents the total load of the dc-bus. This load current is variable and depends on the actual currents of individual coils. Unlike the case of the main coil, load current here is not constant and load circuit has small inductance, the most suitable converter here is the UPF voltage source converter. As stated above, the suitable voltage level of the dc bus is about 60-V. To determine the maximum power ratings of the VSC assume that all choppers are operated at their full load current then output voltage is 30-V, the duty cycle $k = 0.5$, chopper input current $I_{Ch} = 10\text{-}A$ and the total load on dc-bus $I_{DC\text{-}Bus}=110\text{-}A$.

For the voltage source converter to be operated at UPF the 3-phase supply peak voltage V_{smax}, the dc-voltage V_{DC} and the series input inductance L_{i2} are dependent on each other [6]. A suitable value of input inductance is around *0.1 pu* then the value of supply voltage per phase will be $V_{smax} \leq 35\text{-}V$, *taken* $V_s = 24\text{-}V\ (rms)$.

Details of power circuit design are as follows;

1- Input transformer:	*5-kVA, 380/24-V, Δ/Y*
Series Impedance including Transformer:	$R_S=0.005\text{-}\Omega$, $L_S=0.15\text{-}mH$
2- Switches: IGBT	$I_{DC} = 110\text{-}A$
	$I_{RMS} = 64\text{-}A$
	$V_{CE0} = 200\text{-}V$
3- Output smoothing capacitor:	*C=560-mF/100-V*

3.4 Capabilities of the DSP Used

The DSP 56F807 is used as a master processor to perform different control and communication duties in this scheme. This DSP is a hybrid controller that combines, on a single chip, the processing power of a DSP and the functionality of a microcontroller. It has a flexible set of peripherals making it an extremely compact solution for the present project. The most important features and peripherals are [8]:

- Its core has 40-Million Instruction Per Second (MIPS) and allows as many as six operations per instruction cycle with an optimized instruction set allowing straightforward generation of efficient, compact DSP and control code. Programming can be directly with assembly-language or C/C++ to enable rapid development of optimized control applications.
- Two external dedicated interrupt lines and up to 32 General Purpose Input/Output (GPIO) lines, depending on peripheral configuration.
- 60K, 16-bit words of Program Flash and 8K words of Data Flash (each programmable through the JTAG port) with 2K words of Program RAM and 4K words of Data RAM.
- Two PWM modules. Each of these modules can be either programmed to control a 3-phase bridge or to support six independent PWM functions, for a total of 12 PWM outputs.
- Four 12-bit, Analog-to-Digital Converters (ADCs), which support four simultaneous conversions with quad, 4-pin multiplexed inputs.
- Two separate quadrature Decoders capable of capturing all four transitions on two input lines.
- A full set of standard programmable peripherals that include two Serial Communications Interfaces (SCI), one Serial Peripheral Interface (SPI), and four Quad Timers. Any of these interfaces can be used as General-Purpose Input/Outputs (GPIO) if that function is not required. A Controller Area Network interface (CAN Version 2.0 A/B-compliant), an internal interrupt controller, and 14 dedicated GPIO lines.
- JTAG/On-Chip Emulation (OnCETM) for unobtrusive, processor speed-independent debugging

3.4 Allocation of DSP Resources

Figure 1 shows the out line of the control system of the suggested scheme. The DSP resources are effectively allocated to minimize the peripheral components required. In the following, details of these allocations are presented:

- The PWM port A is used to control the current source converter of the main coil. Here each of the 6 PWM lines is used to drive one of the converter-switches.
- PWM port B is used to control the unity power factor voltage source converter used as a main dc supply for harmonic and concentric coils. The individual of the 6-harmonic coils and 5-concentric coils is supplied from this dc-bus via a 4-quadrant dc chopper. PWM control of these 11-choppers is implemented by the DSP via a single FPGA chip. This configuration enables operating at a high switching frequency (up to 100-kHz) and high resolution. This high frequency leads to very smaller current ripples with less bulky small smoothing inductances. The high resolution in PWM signals enables accurate current setting.
- All the current feed-back signals are measured via the 16-lines, 12-bit ADC of the DSP.
- Port JTAG of the DSP is used to download control software into internal memory and to communicate with the monitoring computer. Other communication-ports of the DSP are reserved for future communication with other cyclotron systems that will be available in the final retrofitting stage.

3.5 Current Measurement Circuits

There are two main requirements in current measuring circuits; the high accuracy and the galvanic isolation of output signals from the power side. There are two methods commonly used in such cases;

1- The Hall-effect current measuring circuits which introduce the required galvanic isolation via magnetic field and hall-effect sensor. The commercial measuring modules based on this method have accuracy not better than ±1%. This accuracy is less than that required in present application. Fortunately, some vendors introduce new special products with accuracy better than 0.005% which can best fit present application.

2- The other method is to use a series current-shunt of low TCR alloy (constantan) with additional temperature compensation. The galvanic isolation in this case is obtained via a modulation and demodulation circuit. The current signal is obtained from the power circuit without isolation. This measured signal modulates a high frequency carrier signal and a coupling transformer is used to transmit this signal to the other circuit while introducing the required galvanic isolation. On the other side of the coupling transformer a demodulation circuit extracts the intended signal. The overall accuracy largely depends upon modulation and the demodulation scheme used.

The current sensors to be used here are of the first type based on their less complicated circuitry securing more reliable operation and less maintenance effort.

4. THE CLOSED LOOPE CONTROL SYSTEM

The 4-quadrant dc choppers, the voltage source and the current source PWM converters used here are analyzed in several papers and textbooks [3-7]. There is no contribution to repeat such analysis here. The loads supplied from these converters are simple *RL* type without back-emfs. They have relatively long time constants (40-ms of main coil, 0.5-ms for correction coils). In this case the feed-back controller design and parameter tuning represent no challenge problem, and the conventional PI compensations give adequate response. All these controllers are to be implemented via software programs in the DSP without additional external hardware.

5. SIMULATION RESULTS

The suggested scheme is simulated using the ***Simulink Power Tools*** to check how it can satisfy requirements imposed by the cyclotron operating instructions.

5.1 The PWM UPF Current Source Converter of the main magnet

The Simulink model of the PWM UPF CSC, feeding the main magnet coil, is simulated at 10-kHz switching frequency. This is a typical switching frequency of practical IGBT power circuits. Figure 4 shows the current response for a unit-step reference input of 80% of the rated current. The transient response is adequately good with considerable fast rise and settling times and negligible overshoot. The most important response is the steady state response including the steady state error and the percentage ripple content. Fig.4b expands the plot of current in steady state to measure the above quantities. From this figure the steady state error is zero while the ripple content is limited to 0.025%.

The impact of converter on ac side is clarified in Figs.4c and 4d where supply current has nearly sinusoidal waveform with unity power factor. The low order harmonics have negligible magnitudes and the THD is less than 0.27%.

5-2 The PWM UPF Voltage Source Converter feeding the DC-bus

The Simulink model of the PWM UPF VSC, feeding the dc-bus of the corrector coils, is simulated at conditions similar to those stated above. Fig.5a shows a combined input consisting of a step change in voltage reference from

60-V to 70-V and a load current disturbance from 60 to 120-A. Fig.5b presents the effect of this input on dc-bus voltage showing tracking of actual voltage to its reference with adequate fast response. Effect of load disturbance is very small. The impact of converter on ac-supply is clarified in Fig.5c to Fig.5f. Fig.5c and Fig.5e expand current and voltage waveforms to examine the phase coincidence and quality of current waveform during light and heavy loading condition. Fig.5d and 5f present the harmonic spectrum of supply current during both heavy and light loading conditions. Generally THD is lower than 1.3% and the lowest order harmonic is the 5^{th} and its magnitude is smaller than 1.25%. The higher loading condition gives better results.

5.3 The DC Choppers Feeding Correction Coils

The model of dc-chopper feeding one of the harmonic coils is tested at 50-kHz switching frequency with a step input from 50% to 100% of its rated current. Here since the time constant of load is small (0.5-mS), an additional series inductance of 10-mH is required in series with each coil to reduce the ripple content to an acceptable value. Results illustrated in Fig.6a shows a considerably fast critically damped response. Fig.6b expands the vertical scale in the steady state to examine the ripple content in load current. It is smaller than 0.025%.

6. CONCULUSION

The simulation results of the suggested scheme are adequately fitting cyclotron accurate-operation requirement. The main coil current and correcting coils currents have the sufficient accuracy and their ripple contents lie within the limits stated by the cyclotron users. The DSP implementation of various controllers and communication modules will drastically reduce system complexity and diminishes its volumetric bulkiness. DSP computing, storing, peripherals and communication capabilities will facilitate introduction of several automated and optimized operation schemes when other cyclotron systems are renewed as well.

7. REFERENCES

[1] A. Azzam "Factory Tests of the Physical Parameters of the MGC-20 Egyptian Cyclotron" *AEAEG Local report no. 306,1999.*

[2] Z. Kormány, I. Ander, P. Kovács, T. Lakatos , I. Szûcs " Renewal and Automation of the Atomki MGC-20 Cyclotron", *Proceedings of EPAC 2000, pp1844-1846, Vienna, Austria*

[3] Y. Ye, M. Kazerani, V. H. Quintana "Modeling, Control and Implementation of Three-Phase PWM Converters" *IEEE Trans. Power Electron, vol. 18, No. 3, May 2003.*
[4] J. Espinoza and G. Joos, "State variable decoupling and power flow control in PWM current-source rectifiers," *IEEE Trans. Ind. Electron., vol. 45, Feb. 1998.*
[5] D.C. Lee, G.M. Lee, and K. Lee "DC-Bus Voltage Control of Three-Phase AC/DC PWM Converters Using Feedback Linearization" *IEEE Trans. Indust. Applicat., vol. 36, NO. 3, MAY/JUNE 2000.*
[6] M. P. Kamierkowski "Control Strategies for PWM Rectifier inverter-Fed Induction Motors", *in Proc. IEEE-APEC Conf., vol. 2, pp. 832-839, 2000.*
[7] M. H. Rashid "Power Electronics; Circuits Devices and Applications" *3rd Edition Prentice-Hall, Inc., Englewood Cliffs 2003.*
[8] Motorola "Technical Data of DSP 56F807/D" *Rev. 12.0, 02/2004*.

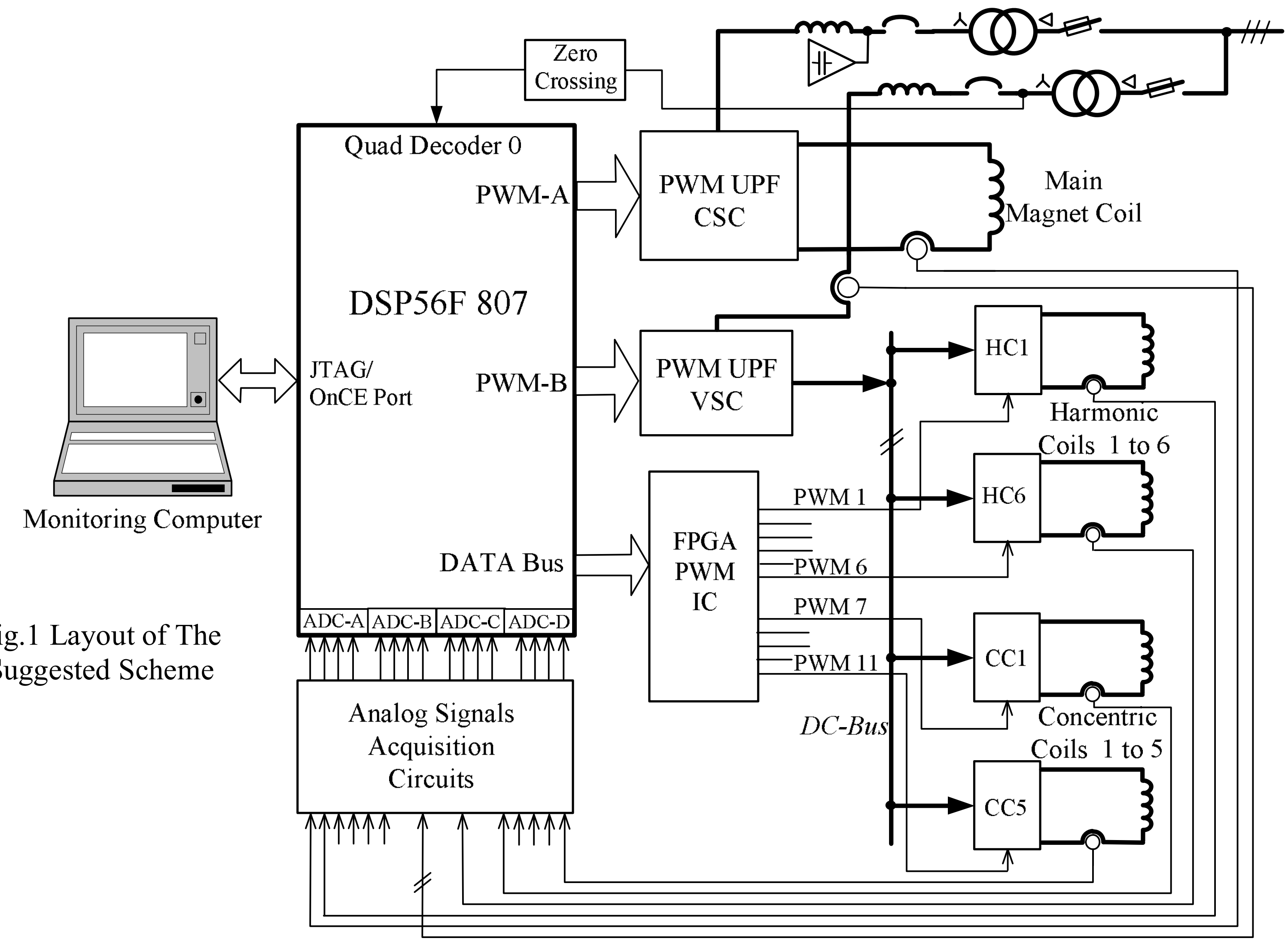


Fig.1 Layout of The Suggested Scheme

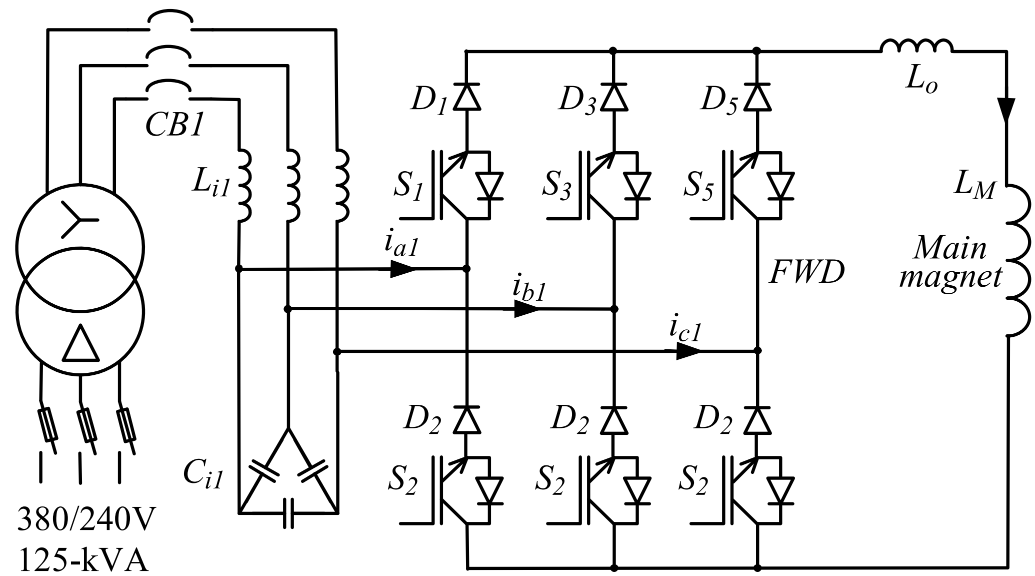


Fig.2 PWM Unity Power Factor Current Source Converter
to Supply Main Magnet Coil

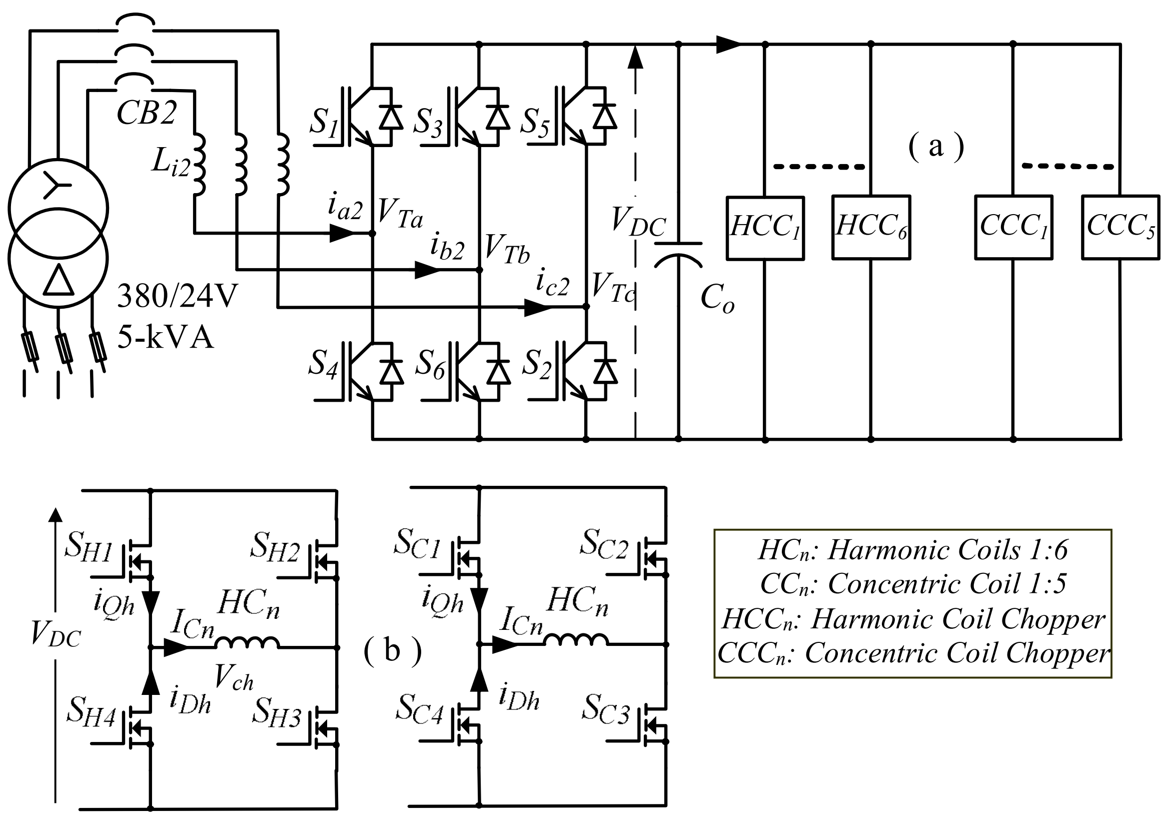
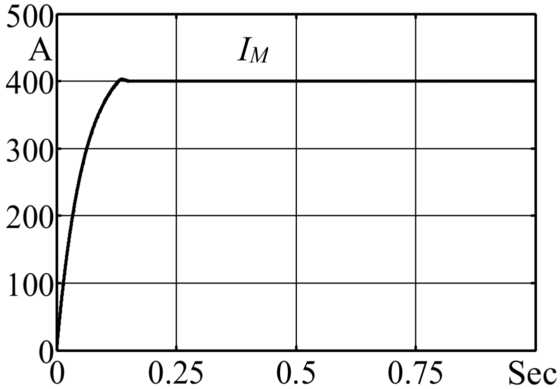


Fig.2 Power Circuits of Harmonic and Concentric Coils
(a) The PWM unity power factor voltage source
converter used as the main DC supply.
(b) Choppers for each individual harmonic and concentric coils.



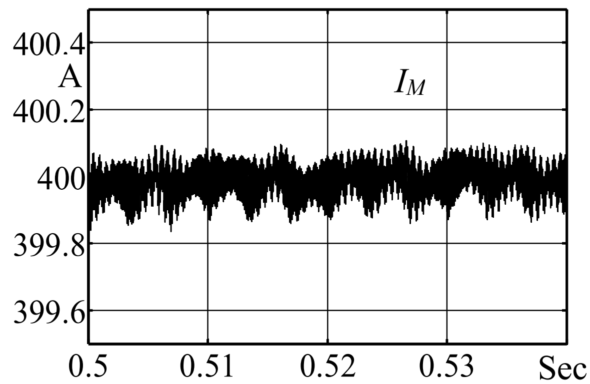
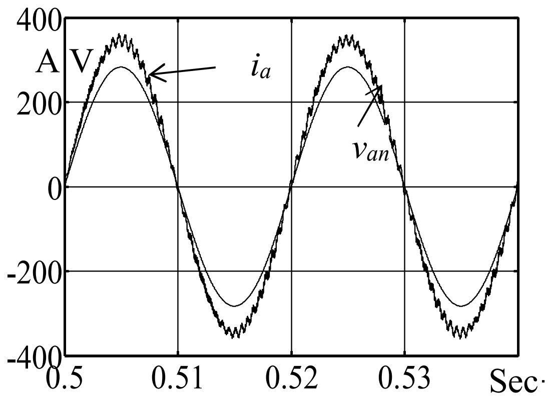


Fig.4a Step Response of CSC Controller Feeding the Main Coil

Fig.4b Expanded View of Fig.6a to show the Ripple Content



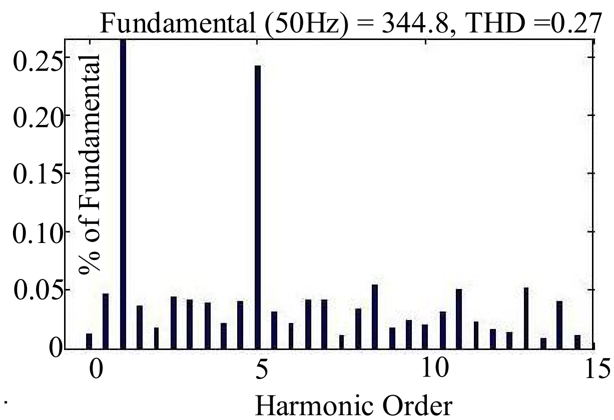
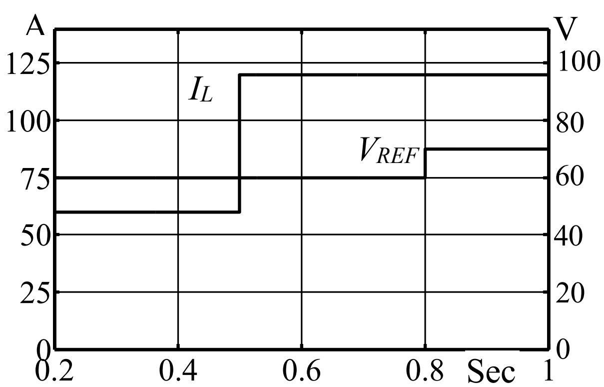


Fig.4c Supply Current and Voltage Waveforms of The CSC

Fig.4d Harmonic Spectrum of CSC Supply Current



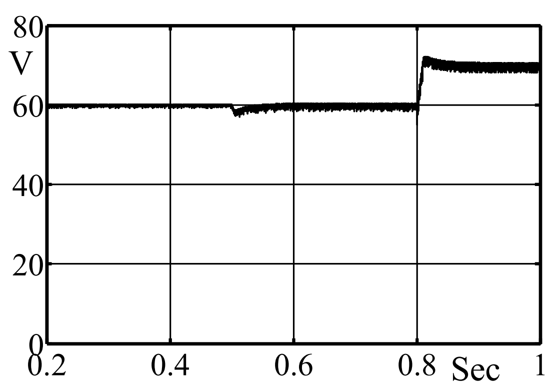


Fig.5a Step in Voltage Reference and Current disturbance for VSC

Fig.5b DC-Link Voltage For Step input and disturbance of Fig.5a

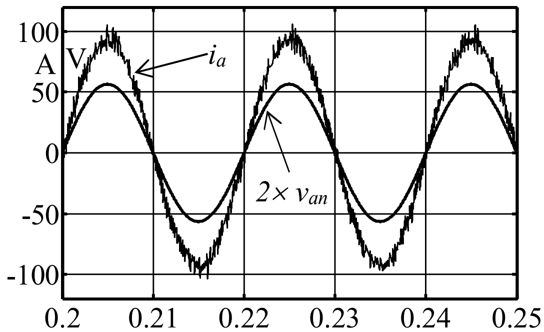


Fig.5c Supply Current and Voltage Waveforms Under light loading

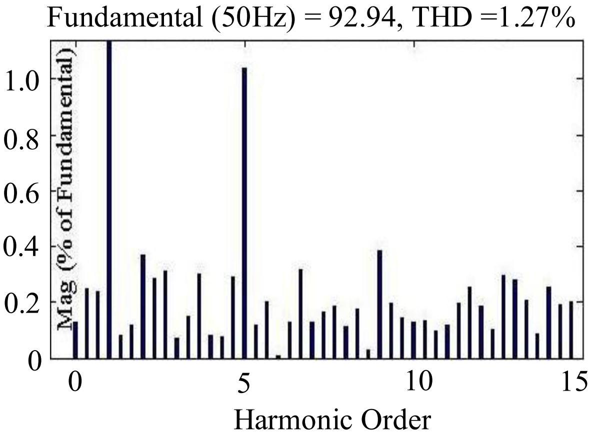


Fig.5d Harmonic Spectrum of Supply Current shown in Fig.5c

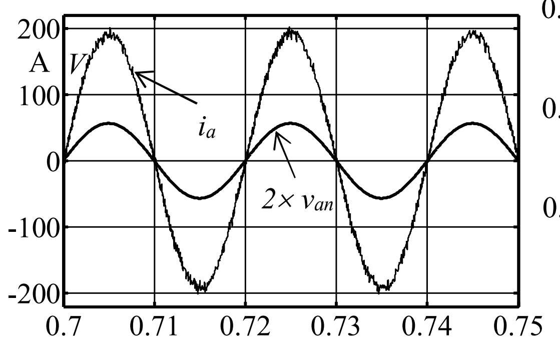


Fig.5e Supply Current and Voltage Waveforms Under heavy loading

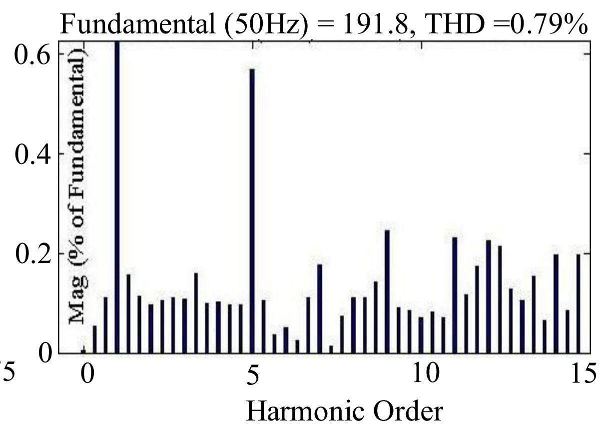


Fig.5f Harmonic Spectrum of Supply Current shown in Fig.5f

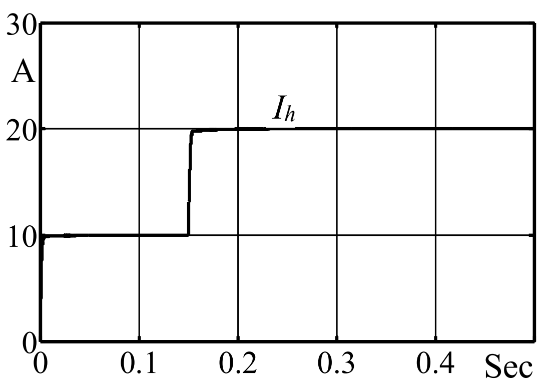


Fig.6a Response of Chopper Current Controller Feeding the Harmonic Coil

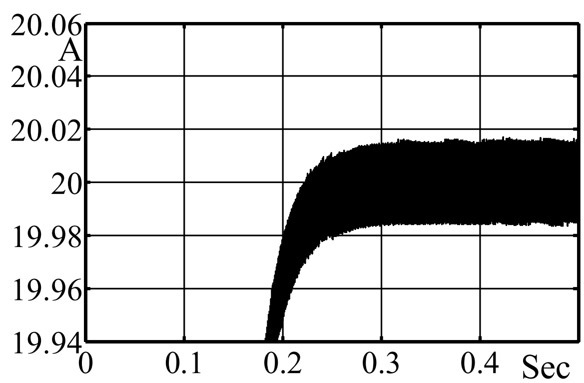


Fig.6b Expanded View of Fig.7a to show the Ripple Content in Current