

Energy Efficient 600 Hz Power Systems for Industrial and Commercial Zones to Reduce the Weight and Size of the Equipments

¹K. Rajan, ²P. Sujatha and ²K.S.R. Anjaneyulu

¹Department of Electrical and Electronics Engineering,
 VEL Sri Rangarajan Sakunthala College of Multimedia Engineering College,
 60 Avadi-Alamadhi Road, Chennai-600062, India

²Department of Electrical and Electronics Engineering, J.N.T.U. College
 of Engineering, Anantapur-515002, Andrapradash, India

Abstract: This study presents energy efficient 3 phase 600Hz-power system, suitable for industrial and commercial zones that require high efficiency, less weight and space for the equipments. This system has many advantages like higher efficiency, less space and less weight of the equipments. An experiment has been conducted on 40 Watt, 220V fluorescent tube light with 600Hz and 50Hz supply. The results show that the 600Hz system is efficient than 50Hz power system. A three phase parallel resonant inverter circuit has been modeled and simulated using Matlab/simulink. Further for compensating line voltage drop and unbalance voltage, Thyristored Switched Capacitors are adopted. XLPE Power cables are used for transmission to reduce the inductance drop. An application of high frequency drive systems used in synthetic yarn textile industrial drives is explained.

Key words: Amorphous metal core, hysteresis component, magnetic losses, reactive power, energy efficiency, parallel resonant inverter

INTRODUCTION

Demand for electrical energy is increasing at a very rapid pace and unable to cope with this increasing demand. This paper describes an energy efficient 600Hz power system. Aircraft and space vehicle industries use 400 Hz frequency for hydraulic pumps, fuel boost pumps, fuel jettison pumps, override fuel pumps, flaps and slats electric motors because of lesser weight and smaller size of the electric equipments (Jie, 2005; Takahashi, 1989). The needs for high frequency power supply for industries, commercial and domestic utilities are also increasing (Jie and Anhua, 2004). With the development of modern power semiconductor devices like GTO, BJT, IGBT, IGCT and MOSFET (Steffen, 2000) many different frequency power supplies have been increasingly employed in most of the industries, offices and domestic applications. MOSFET and IGBT have replaced bipolar junction transistor almost completely. The high power semiconductors such as 3.3, 4.5 and 6.5kV Insulated Gate Bipolar Transistors (IGBTs) and 4.5, 5.5kV Insulated Gate Commutated Thyristors (IGCTs) are used in converter design ranging from 0.5 MVA-10 MVA which are

becoming price competitive in the market (Jie and Anhua, 2004). The 600Hz centralized power system found major attention as an alternate to the conventional 50/60 Hz supply for industrial and commercial zones. Using amorphous core, the reasonable operating frequency ranging from 400Hz-1 kHz is obtained.

APPLICATION OF 600HZ POWER SYSTEMS

Figure 1 shows the application of 600Hz Power Systems. The system will be useful in the following areas (Takahashi, 1989):

- Induction heating.
- HDL lamps
- Synthetic yarn spinning mills.
- DC power supply.
- High-speed induction motors in process industry
- Cycloconverter fed motors Drives.

Induction heating: In steel industry, induction heating furnace use 400Hz-1 kHz supply for melting cast iron, heating of steel bar and heat treatment of steel pipes. Induction heating furnace offers high efficiency and clean

environment. The conventional frequency power systems use high value capacitors to improve the power factor. The use of 600Hz power supply is economical as it uses smaller value capacitors.

HDL lamps: The use of 600Hz power supply for high discharge lamps, fluorescent lamps in factories, sports centers, offices and high ways will result in drastic reduction in the size and weight of the chokes. The efficiency and stability of the system is also improved. In this study, an experiment has been conducted on 40 Watt, 220V fluorescent tube light with 600Hz and with 50Hz. The results indicated that amorphous metal choke reduces copper loss and iron loss.

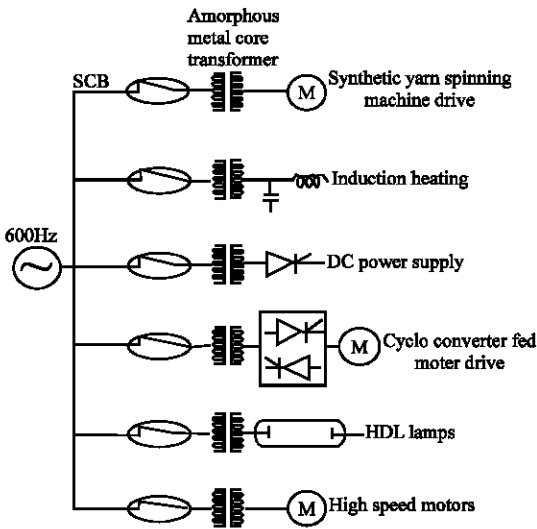


Fig. 1: Application of 600Hz power systems

DC-DC power supply: Quick response DC power supply is available by using 600Hz power supply, for high power application. The development of quick response power supply is easier by applying modern control theory with combination of thyristors and embedded controllers.

High speed induction motors: The large power range conventional machines have been driven by steam turbines or gas turbines to obtain high speed, which recently have being replaced by inverter, drive systems. It can be seen that motors with capacity range from 0.5-30MW and speed of 5000rpm have been widely used to drive turbine compressors for the condensation of ammonia, ethylene gas, menthol and blowers for gas pipeline in which high speed is often required.

Cycloconverter fed motors drive: A naturally commutated cycloconverter has high efficiency and reliable operation because it performs direct AC to AC conversion with natural commutation. The Cycloconverter has been successfully employed in very high power applications. By using 600Hz power supply, the maximum output frequency of the cycloconverter is 200Hz, which satisfies most of the industrial drive applications. The 600Hz power supply with naturally commutated cycloconverters will find wide applications by replacing PWM inverters, which are very popularly employed in medium power applications.

Synthetic yarn textile drives: In synthetic yarn spinning machine's take-up winders has a number of small high speed synchronous ac motors below 1-2 hp, which are controlled precisely at the same rotating speed by a single

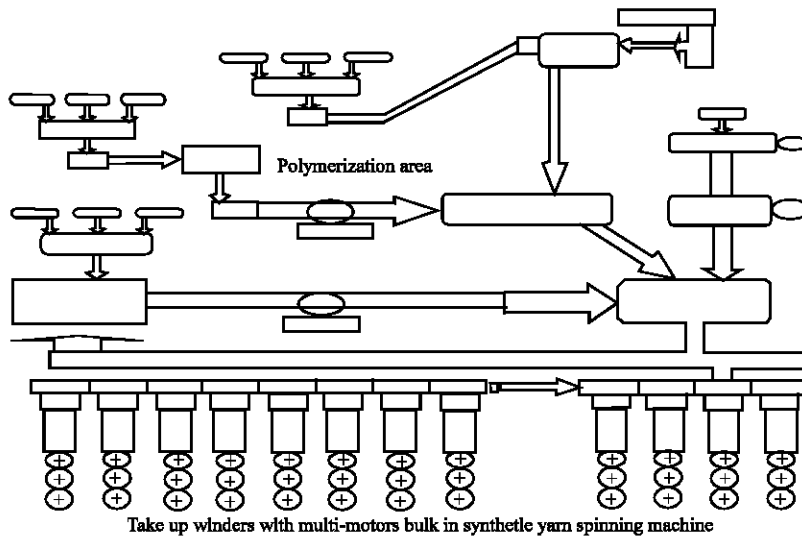


Fig. 2: Precision and high frequency take up winders in synthetic yarn spinning machine

high frequency voltage source inverter. The specifications for the inverter control are very stringent to control multiple axes at a precision and high speed. The bulk textile fiber spinning system consists of multiple motors as shown in Fig. 2. There are 16 spinning axes that must be controlled precisely at the same rotating speed, as if they are interconnected by a virtual axis for synchronization. The synthetic yarn processing is very fine, fragile and the take up winder speed is also high, any slight period variations from one fundamental current cycle to another would possibly generate disturbances in the winding process, affecting the product quality. The proposed 600Hz power system will replace the existing PWM based high frequency inverter.

AMORPHOUS METAL CORE AND ITS MAGNETIC PROPERTIES

The discovery of amorphous metal is generally credited to P.Duwez, who in 1960 produced amorphous samples by rapidly quenching an $Au_{75}Si_{25}$ alloy from the liquid state. Duwez used a pressurized gas gun to propel small droplets of molten alloy onto a polished copper plate. On the impact, each droplet deformed into a thin film. Intimate contact with the highly conductive copper plate allowed the molten film to cool rapidly and solidify into flake or splat form. Figure 3 shows the B-H loop of amorphous $Fe_{80}B_{11}Si_9$ and grain-oriented silicon steel (Nicholas, 1998). The narrowness of the B-H loop for an amorphous metal has high permeability and low hysteresis loss. The components of magnetic losses are measured by the area within the B-H loop, which indicates the relative ease of magnetization. The atomic disorder and high solute content of amorphous metals limit the mean-free path of electrons, which results in electrical resistivity of two to three times of the grain oriented silicon steels. The thin gauge of amorphous metals,

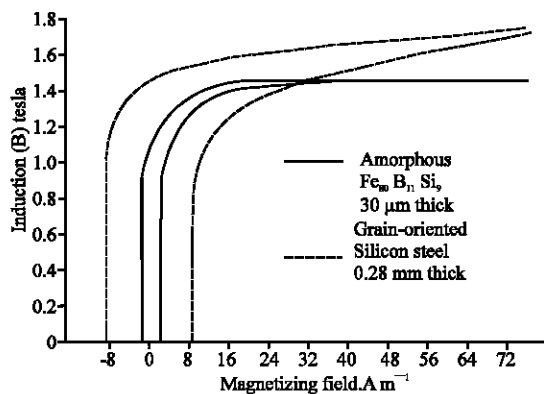


Fig. 3: B-H loop of amorphous $Fe_{80}B_{11}Si_9$ and grain oriented silicon steel

typically 30 μm compared to 0.28 mm for grain-oriented silicon further increase the total electrical resistance.

Infrared analysis indicates that the grain-oriented silicon-steel unit reaches an average temperature of 59 $^{\circ}$ C. Comparable operation of the most efficient amorphous-metal core results in a smaller temperature rise of about 31 $^{\circ}$ C (Nicholas, 1998). The amorphous metal cores are used in transformers (Moses, 2002) and inductors in 600Hz power systems.

EXPERIMENT ON A FLUORESCENT LAMP

Figure 4 shows a single-phase parallel resonant inverter, designed to produce 220V, 600Hz to glow a 40-watt fluorescent tube light. The inductor L1 acts as a current source and the capacitor C1 is the resonating element. L_m is the mutual inductance of the transformer T1 which acts as the resonating inductor. A constant current is switched alternatively into the resonant circuit by MOSFETs Q1 and Q2. The output 220V of the transformer T1 is given to the 40Watt tube light and 10V transformer tap is connected to oscilloscope to measure the resonant waveform. The tube light choke L2 is designed with Amorphous Metal Core-Metglas 2605SA1. The control unit generate square wave to trigger the MOSFETs. An experiment has been conducted on 40 Watt, 220V fluorescent tube light with 600 and 50Hz supply. Table 1 shows the comparison parameters of the chokes used for 50 and 600Hz supply. From the Table 1, it has been seen that amorphous metal choke reduces 76% of copper loss and 72% of iron loss, in addition the weight and size of the choke is also reduced to 83 and 72% respectively when compared to the 50Hz-silicon choke.

The inductance required for the conventional choke at 50Hz is 820mH but at 600Hz, the inductance requirement is only 72 mH. At 600Hz, the tube striking voltage is 125V, which is much lesser than 165V at 50Hz. Figure 5 shows

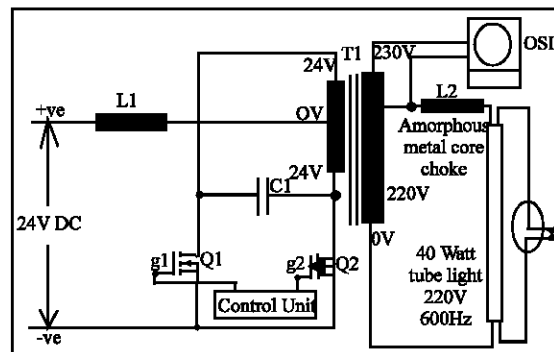


Fig. 4: Experiment setup of single phase parallel resonant inverter with 40W tube light

Table 1: Result comparison of 50Hz and 600Hz Chokes in 220V, 40Watt fluorescent lamp

Core used	Metglas		Experiments results
	Silicon steel	Amorphous alloy 2605SA 1	
Supply frequency at 220V	50Hz	600Hz	---
Thickness of core (mm)	0.35	0.022	Core thickness is reduced by 94%
Rated current (A)	0.40	0.40	----
Number of Tums (T)	2094	455	Number of turns is reduced by 78.3%
Inductance (mH)	820	72	Inductance of the choke is reduced by 91.21%
Copper loss (W)	6.2	1.47	Copper loss is reduced by 76%,
Iron loss (W)	12	3.4	Iron loss is reduced by 72%
Weight of the core (g)	408	72	Weight of the core is reduced by 83%
Weight of the copper (g)	122	32	Weight of the copper is reduced by 74%
Volume (cm ³)	169.2	47.1	Volume of the choke is reduced by 72%

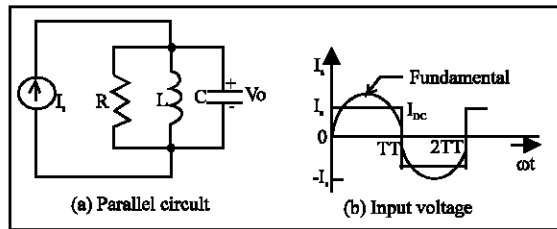


Fig. 5: Parallel resonance circuit

the parallel resonant circuit (Jih *et al.*, 1990; Rashid, 2004). It is supplied from a current source so that the circuit offers high impedance to the switching current. The damped-resonant frequency 600Hz is given by:

$$\omega_r = \left[\frac{1}{LC} - \frac{1}{4R^2C^2} \right]^{1/2}$$

REACTIVE CURRENT REQUIRED FOR POWER FACTOR IMPROVEMENT

A circuit is considered with the current I supplied to the load. The current I is lagging the voltage by an angle φ. The current supplied to this circuit can be resolved into two components, one along the voltage vector and another in quadrature to the voltage vector. The component along with the voltage vector I_a is known as active component and the other is known as reactive components of the current. Active and reactive components of currents are shown in vector diagram (Fig. 6). In order to improve the power factor, angle φ should be increased and for unity power factor, angle φ component of the current, I sin (I_r) is to be decreased. This is achieved by introducing leading current I_c of magnitude equal to the reactive component, in the circuit as shown by OA in the Fig.6. This leading current I_c will lead the voltage by 90° and will be in phase opposition to I_r, the reactive component of the current. The current I_{ain} phase with the voltage thereby giving the unity P.F. Therefore the leading current required to neutralize the

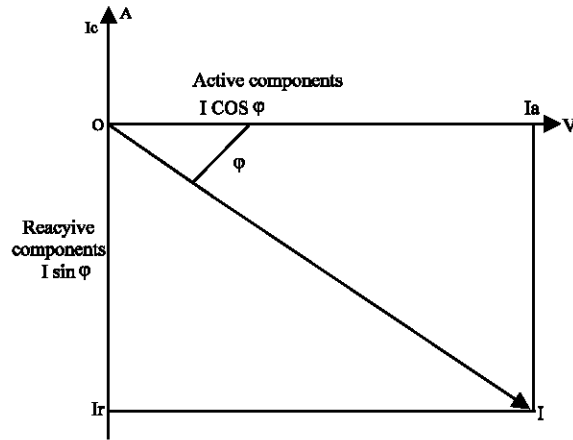


Fig. 6: Vector diagram of the load

lagging reactive component of the current to obtain unity power factor is given as:

$$I_c = I_r = I \sin \phi; = I \times \sqrt{1 - \cos 2\phi}; \tag{1}$$

$$I_c = I \times \sqrt{1 - (P.F.)^2}$$

POWER FACTOR IMPROVEMENT BY USE OF STATIC CAPACITORS

This method of introducing a leading component of current is mostly employed. It is achieved by connecting a number of capacitors in parallel across the mains at the load end. The value of the total capacitance required for improving the power factor to unity for the given power P in the circuits at frequency ‘ f ’ and volts ‘ V ’ is determined as follows:

$$I_c = \omega C V = 2 \pi f C V \tag{2}$$

Equating equations $2\pi f C V = I \times \sqrt{1 - (p.f)^2}$

$$C = \frac{I \times \sqrt{1 - (p.f)^2}}{2\pi f V} \text{ Farads} \tag{3}$$

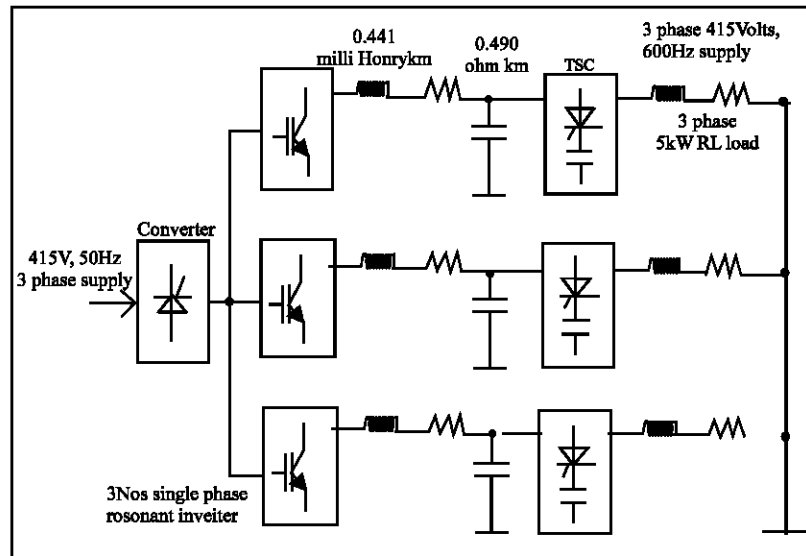


Fig. 7: Single line diagram of 3 phase resonant inverter circuit with TSC

$$\text{Also, } P = IV\cos\phi = IV \times (\text{p.f.}) \quad (4)$$

$$I = \frac{P}{V \times (\text{p.f.})} \quad (5)$$

Substituting the value of I from Eq. (5) into (3)

$$C = \frac{P}{V^2 \times (\text{p.f.}) \times 2\pi f} \times \sqrt{1 - (\text{p.f.})^2} \text{ Farads}$$

$$C = \frac{P}{V^2 \times 2\pi f} \times \sqrt{\frac{1}{(\text{p.f.})^2} - 1} \text{ Farads}$$

$$C = \frac{P \times 10^6}{2\pi f V^2} \times \sqrt{\frac{1}{(\cos)^2} - 1} \text{ MicroFarads} \quad (6)$$

It is seen from Eq. 6 that the capacitance required for improving the P.F. is inversely proportional to ‘F’ frequency. This indicates that the static capacitors are best suited for high frequencies. Further it is observed that the capacitance required is inversely proportional to the square of the operating voltage thus the total value of the capacitance required per phase in a three phase system depends upon the nature of the connections whether star or delta.

MATLAB/SIMULINK SIMULATION

Matlab/simulation have become a very powerful tool in industry application as well as in academics, nowadays. A 3 phase 415V, 600Hz parallel resonant inverter is

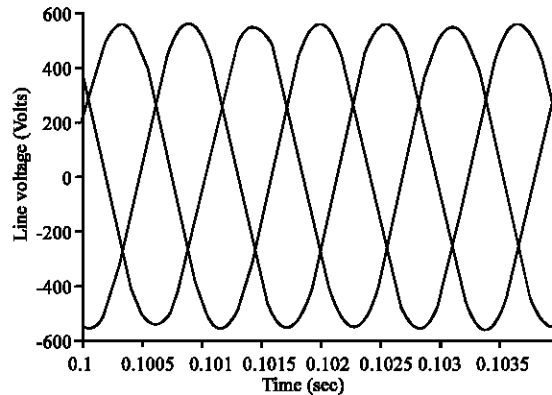


Fig. 8: Three phase output-600Hz wave form from Matlab Simulink simulation

simulated using MATLAB/SIMULINK to supply a load of 5kW. Figure 7 shows the single line diagram of three phase simulation circuit. The circuit consists of three phase converter, three numbers of identical single phase parallel inverter circuits with 120° phase shift, transmission line resistance, inductance and capacitance, TSC and 5kW RL load. To maintain voltage regulation, thyristored switched capacitor-TSC is added to the circuit. Figure 8 shows the waveform of simulated three phase resonant inverter. In the simulation circuit, cable inductance, resistance and capacitance are added.

PROPOSED HIGH FREQUENCY POWER SYSTEM CONFIGURATIONS

Figure 9 shows the proposal of 600Hz-power system. The system consists of three phase full wave rectifier,

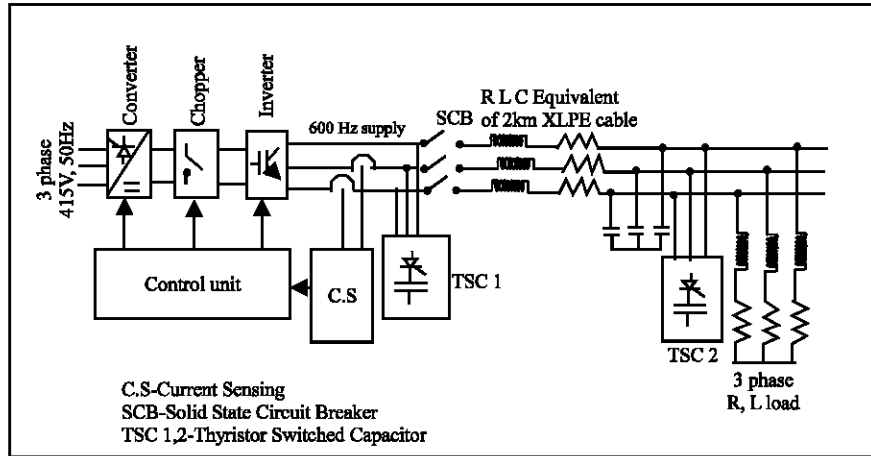


Fig. 9: Proposed 600 Hz power system

chopper, 3 phase resonant inverter, XLPE power cable, solid state circuit breaker and thyristor switched capacitor-TSC. Microcontroller PIC16F877 is used to control the DC Link voltage. Trigger pulses for inverter and TSC 1 and 2 are produced by the microcontroller. TSC2 will suppress the very fast fluctuating line voltage. This is achieved by injecting leading reactive power to the line by the TSC2 (Narain, 2004). The three phase resonant inverter produce the three phase A.C. output. The solid-state circuit breaker, resonant inverter, amorphous metal core transformer can be used effectively in commercial power system. Capacitors can be made much smaller as about 1/12 times with low cost. Distributed natural energy generation and co-generation systems can be directly used for the energy source of the 600Hz-power system. Higher frequency power supply will be used in steel plants, chemical plants and induction heating. The system will be effectively used in commercial areas and in intelligent buildings. Large reduction in size of the transformer and reactor by 1/3-1/4 times is also possible.

CONCLUSION

This study presents a 600Hz power system for supplying particular areas such as industrial zones, commercial complex, intelligent buildings and offices, where high efficiency, less weight and less space for the equipments are desired. An experiment has been conducted on 40W fluorescent lamp with 220V, 600Hz with amorphous choke and 220V, 50Hz with silicon steel choke. In the experiment, using 600Hz power supply system, the weight of the amorphous metal core is reduced by 83%, iron loss is reduced by 72%, copper loss

is reduced by 76%, weight of the copper is reduced by 74%, volume of the choke is reduced by 72% and inductance of the choke is reduced by 91.21%. The 600Hz power system will be useful for HDL lamps, high-speed induction motors, induction heating, DC power supply, cycloconverter fed motors drives for steel, chemical plants and synthetic yarn textile industry. The 600Hz power system is suitable for a 20 km by 20 km industrial zone or 1 km by 1 km commercial areas is proposed.

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