Loads Which Cause Power Quality Problems

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INTRODUCTION

STATE OF ART OF NONLINEAR LOADS

CLASSIFICATION OF NONLINEAR LOADS

POWER QUALITY PROBLEMS CAUSED BY NONLINEAR LOADS

INTRODUCTION

- Electrical loads have nonlinear behavior at ac mains

- Draw harmonic currents of various harmonics such as characteristic harmonics, non-characteristic harmonics, inter-harmonics, sub-harmonics, reactive power component of current, fluctuating current, unbalanced currents from ac mains and thus these loads are known as nonlinear loads

- Majority of rotating electric machines, magnetic devices such as transformers, reactors, chokes, magnetic ballasts, etc. behave as nonlinear loads due to saturation in their magnetic circuits, geometry such as presence of teeth and slots, winding distribution, air gap asymmetry etc

- Many fluctuating loads such as furnaces, electric hammers and frequently switching devices exhibit very highly nonlinear behavior as an electrical load

STATE OF ART OF NONLINEAR LOADS

- Since inception of ac power, majority of electrical equipments are developed

✓ based on the principle of energy storage, which is used in the process of energy conversion and especially using the magnetic energy storage.

- They behave as inductive loads and they burden ac mains with the reactive power causing the power quality problem of poor power factor in ac network resulting in increased losses, poor utilization of components of distribution system such as transformers, feeders, switchgear due to increased current for a given active power

NONLINEAR LOADS

Some of nonlinear loads are

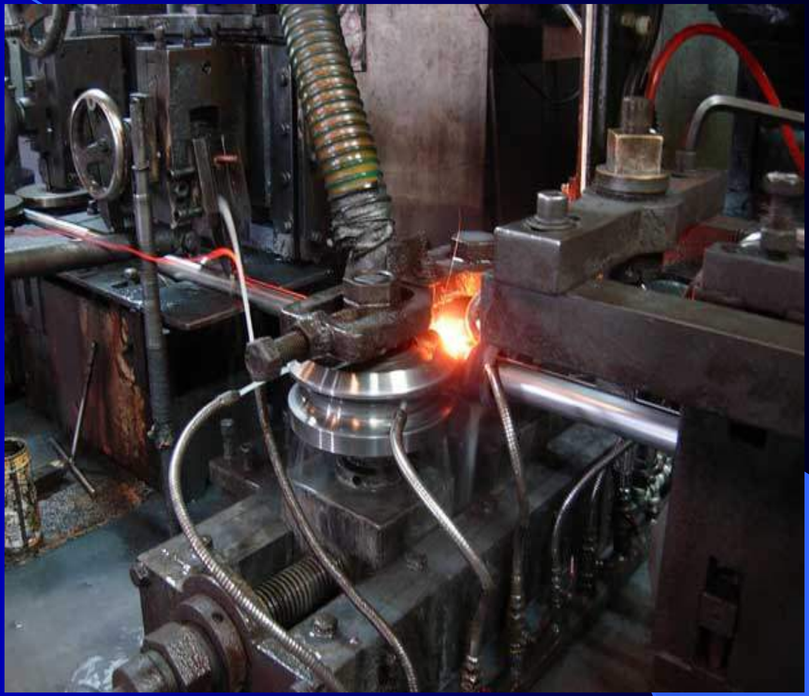
- Fluorescent lighting and other vapor lamps with electronic ballasts

- Switched mode power supplies

- Computers, copiers, and television sets

- Printer, scanners, fax machines

➢High frequency welding machines



- Fans with electronic regulators

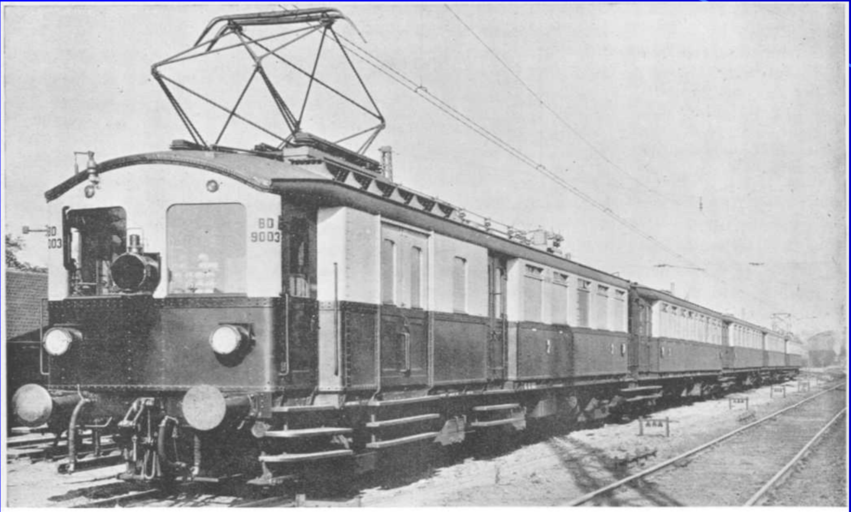
- Microwave ovens and induction heating devices

- Xerox machines, medical equipments

➢Variable frequency based HVAC systems
(Heating ventilation and air conditioning systems)

➢Battery chargers and fuel cells

➢Electric traction



ELECTRIC TRAIN, STATE RAILWAYS OF HOLLAND.

The electrification of the Dutch railways is proceeding steadily, and the throughout main line between Amsterdam and Rotterdam has recently been converted from steam to electric traction.

Arc furnaces

➢Cycloconverters

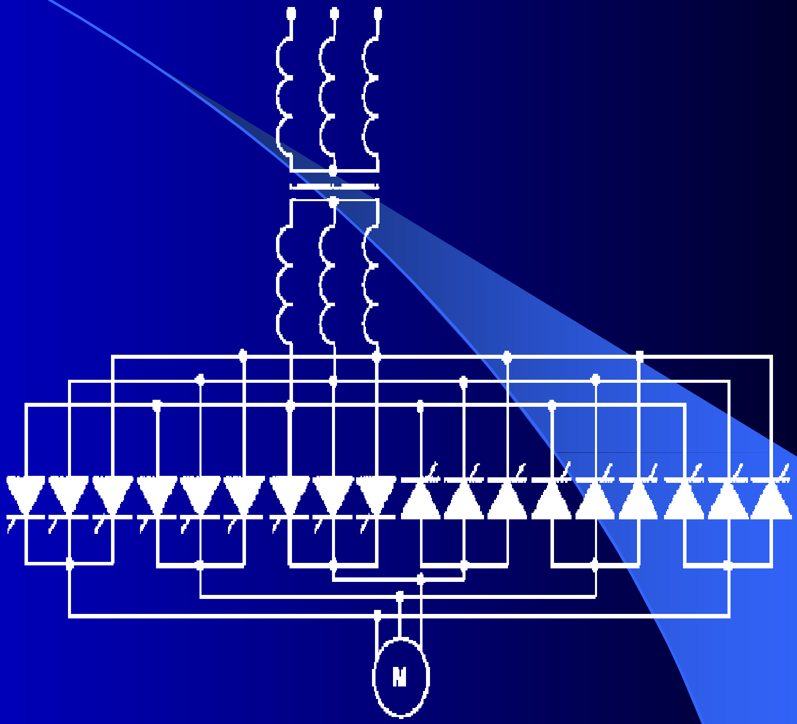
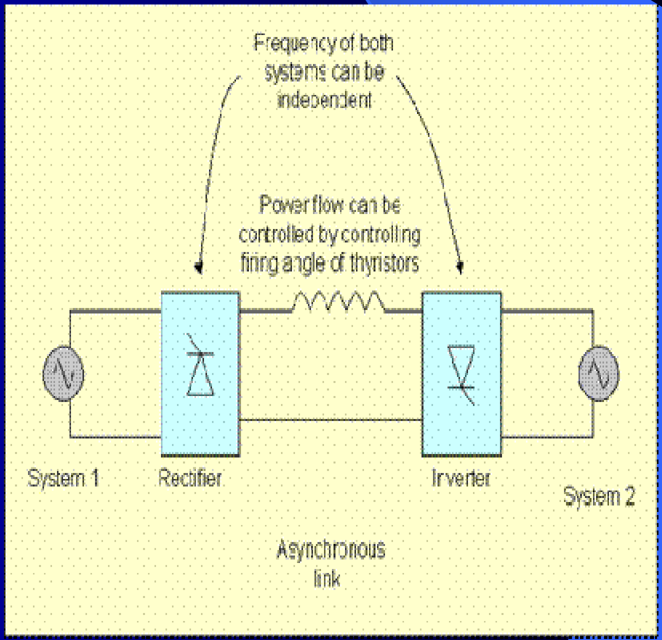


Fig. 4

➢Plasma power supplies

- Wind and solar power generation

➢HVDC transmission systems



Other loads are

- Adjustable speed drives
- Static slip energy recovery schemes of wound rotor induction motors
- Static VAR compensators
- Magnet power supplies
- Static field excitation systems

CLASSIFICATION OF NONLINEAR LOADS

These nonlinear loads can be classified based on

i) Non solid state devices type and with solid state devices.

ii) Converter types such as ac-dc converter type, ac voltage controller type and cycloconverter type.

iii) Their nature based as stiff current fed type or stiff voltage fed type of mix of them.

iv) Consisting the number of phases

Non Solid-State Devices Type and Solid-State Devices Type of Nonlinear Loads

- These nonlinear loads may be classified based whether they consist of solid state devices or they do not have solid state devices or any power converters.

- There are number of electrical loads which behave nonlinear in nature but they do not involve any power converters

Non Solid-State Devices Type Nonlinear Loads

- Most of the electrical machines fall in this category of nonlinear loads.

- A number of physical phenomena in these electrical machines cause their behavior as nonlinear loads.

- Typically the saturation in magnetic material of these machines and electromagnetic devices, skin and proximity effects in conductors, non-uniform air-gap in rotating machines, effect of teeth and slotting etc

- Result in harmonic currents under steady state and transient conditions in the ac mains when they are connected to ac supply system.

Solid-State Devices Type Nonlinear Loads

- They draw nonsinusoidal current from ac mains and they behave as nonlinear loads.
- This nonsinusoidal current consists of harmonic currents, reactive power component of current along with fundamental active power current.

- They use various ac-dc converters, ac voltage controllers, cycloconverters or combination of them in their front end converter.

- Practical examples of single-phase nonlinear loads are most of the domestic and home appliances such as
  - ✓Microwave oven, induction heaters, television sets, electronic ballasts based lighting systems, domestic inverter, and adjustable speed based air conditioners, ac voltage regulator based fans. Commercial, offices and industrial equipments are computers, copiers, fax machines, xerox machines, scanner, printers, small welding sets etc.

- In three-phase three wire supply system, in addition to harmonics currents and reactive power, they may also draw unbalanced three-phase currents.
- Some practical loads are three-phase adjustable speed drives, consisting of converter fed dc motor drives, synchronous motor drives, induction motor drives and other electric motors used in HVAC systems, waste water treatment plants, large industrial fans, pumps, compressors, cranes, elevators, electrochemical process such as electroplating, electromining, etc

- In three-phase four wire supply system, there are many single-phase nonlinear loads connected to ac mains and also cause excessive neutral current.

- Distributed single-phase loads on all three-phases such electronic ballasts based lighting systems, computer loads in high storied buildings and all other single-phase loads, burden ac mains from harmonics currents, reactive power component of currents, unbalanced currents and excessive neutral current.

Converter Based Nonlinear Loads

- There are various types of converters used in these electrical equipments which behave as nonlinear loads.
- These nonlinear loads mainly consist of ac-dc converters, ac voltage controllers, cycloconverters or combination of them.
- These are classified on the basis of these converters but not restricted only up to these converters.

AC DC Converters Classification

Uncontrolled AC/DC converter

Controlled AC/DC converter

- AC-DC Converters
  - Single-Phase Converters
    - Uncontrolled
      - Half Wave
      - Full Wave
      - Bridge
      - Voltage Doubler
    - Semi-controlled
      - Half Wave
      - Full Wave
      - Bridge
    - Fully-Controlled
      - Half Wave
      - Full Wave
      - Bridge
      - Dual
  - Three-Phase Converters
    - Uncontrolled
      - Half Wave
      - Full Wave
      - Bridge
      - Multipulse
    - Semi-controlled
      - Half Wave
      - Full Wave
      - Bridge
    - Fully-Controlled
      - Half Wave
      - Full Wave
      - Bridge
      - Dual
      - Multipulse

AC-DC Converter Based Nonlinear Loads

- Large number of loads use ac-dc converters as front end converters from few watts to MW rating.

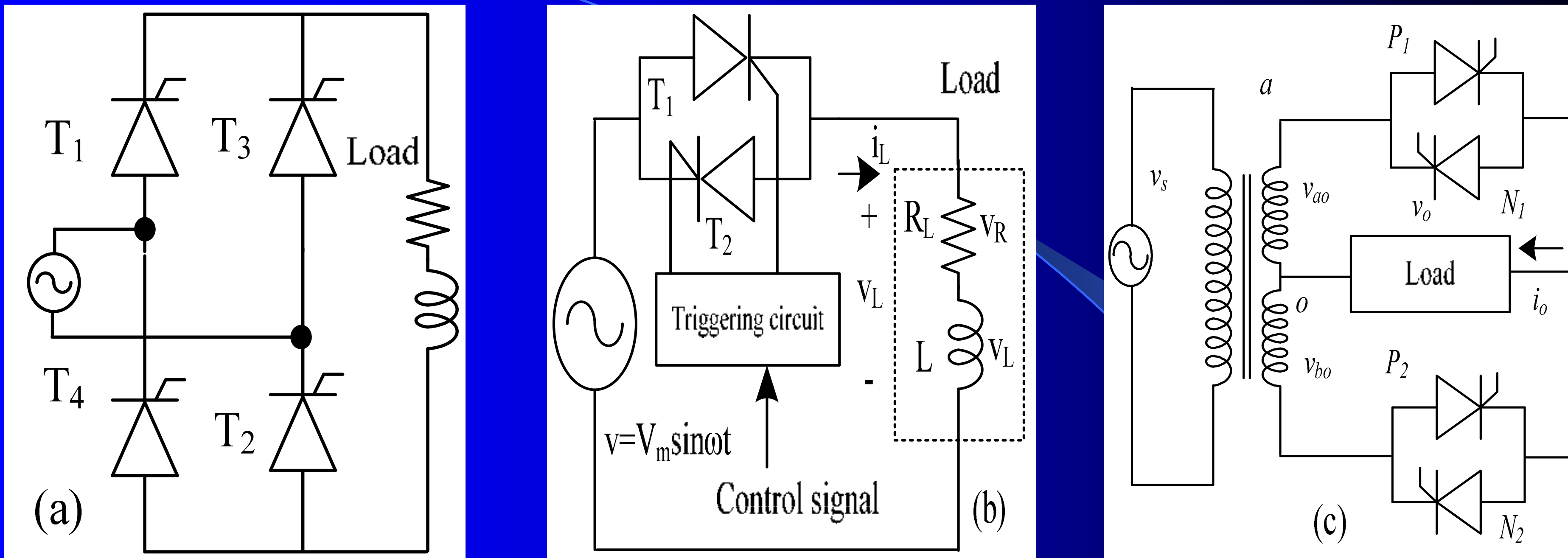
- These converters developed in many circuit configurations such as single-phase and three-phase, uncontrolled, semi controlled, and fully controlled, half wave, full wave, and bridge converter circuits to suit the requirements of specific application.

- ✓Depending upon the types of filters used for filtering the rectified dc, their behavior varies in number of ways at the ac mains.

- ✓Some of the practical examples of such nonlinear loads are microwave ovens, SMPS (switched mode power supplies), computers, fax machines, battery chargers, HVDC transmission systems, electric traction, adjustable speed drives etc.
- ✓In some case they draw current with excessive harmonics contents with high crest factor.

- Many cases they draw current with moderate harmonics and reactive power at low crest factor even less than sine wave.

- In general they exhibit poor power factor at ac mains due to harmonics only, or along with reactive power.



(a) Controlled AC/DC converter

(b) AC/AC converter

(c) AC/AC converter with Transformer

Fig. Various Types Current Fed Nonlinear Loads.

AC Controllers Based Nonlinear Loads

- ✓Some nonlinear loads use ac voltage controllers for the control the ac rms voltage across the electrical loads to control the physical process.

- ✓They draw the harmonics current along with the reactive power and cause poor power factor.

Some of the practical examples of such nonlinear loads are

ac voltage regulator for fans, lighting controllers, heating controllers, soft starters, speed controllers and energy saving controllers of the three-phase induction motors operating under light load conditions in number of applications such as hack saw, electric hammers, wood cutting machines, etc

Cycloconverter Based Nonlinear Loads

- In many applications cycloconverters are used to convert ac voltage of a fixed frequency to variable voltage at variable frequency or visa versa

- ✓ These cycloconverters based nonlinear loads draw harmonics currents at not only higher order harmonics but at sub harmonics too, reactive power and exhibit really a very poor power factor at ac mains

Some of practical examples of such nonlinear loads are

Cycloconverter fed large rating synchronous motor drives in cement mills, ore crushing plants, large rating squirrel cage induction motors, slip energy recovery scheme of wound rotor induction motor drives, VSCF systems (variable speed constant frequency generating systems) etc.

Nature Based Classification

- Most of the nonlinear loads behave either stiff current fed or stiff voltage fed, or mix of them.

- The stiff current fed loads normally consist of ac-dc converters with constant dc current load, with predetermined harmonic pattern in ac mains with reactive power burden.

- The voltage stiff loads consist of generally ac-dc converters with large dc capacitor at dc bus to provide ideal dc voltage source for the remaining process of solid state conversion and draw peaky current from ac mains with high crest factor.

- Since the analysis of the behavior and remedy for mitigation of power quality problems for these types of loads depend reasonably on this classification, therefore it becomes relevant and important to select proper compensator.

Current Fed Type of Nonlinear Loads

- The stiff current fed types of nonlinear loads generally have predetermined kind of pattern of harmonics and sometimes they have reactive power burden on the ac mains.

- They have flat current waveform drawn from ac mains and low value of its crest factor.

They typically consist ac-dc converters feeding dc motor drives, magnet power supplies, field excitation system of the alternators, controlled ac-dc converters used to derive dc current source for feeding current source inverter supplying large rating ac motor drives, HVDC transmission systems etc

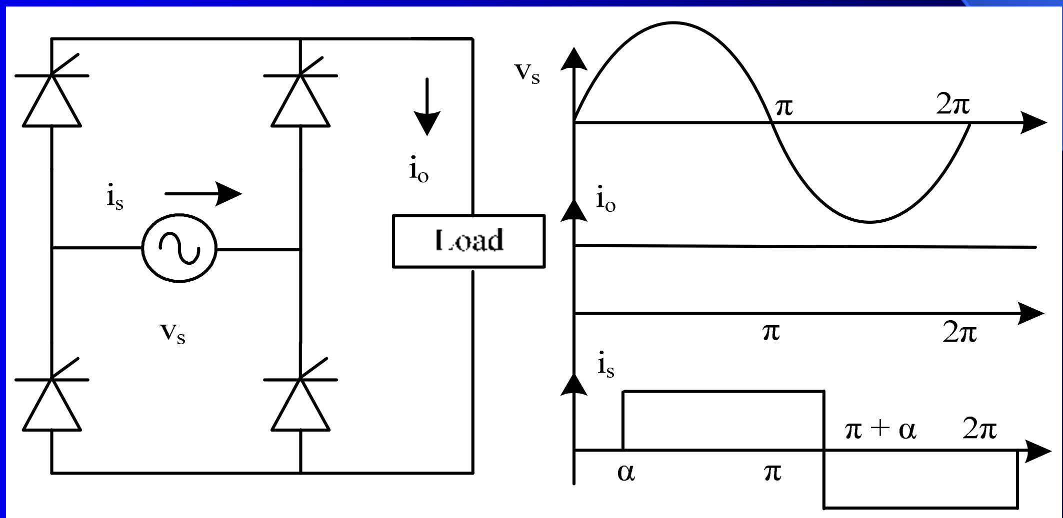


Fig. Single-phase Controlled Converter Based Current Fed Type of Nonlinear Load

Voltage Fed Type of Nonlinear Loads

- The voltage stiff types of nonlinear loads behave as sink of harmonics currents.

- Typical example of such load is an ac-dc converter with large dc capacitor at its dc bus to provide an ideal dc voltage source for the remaining process of solid state conversion and draw peaky current from ac mains with high crest factor.

They generally do not have reactive power requirement but they much greater amount of harmonics currents drawn from ac mains.

Practical examples of such loads are switched mode power supplies (SMPS), battery chargers; front end converters of voltage source inverter fed ac motor drives, electronics ballasts, most of the electronics appliances.

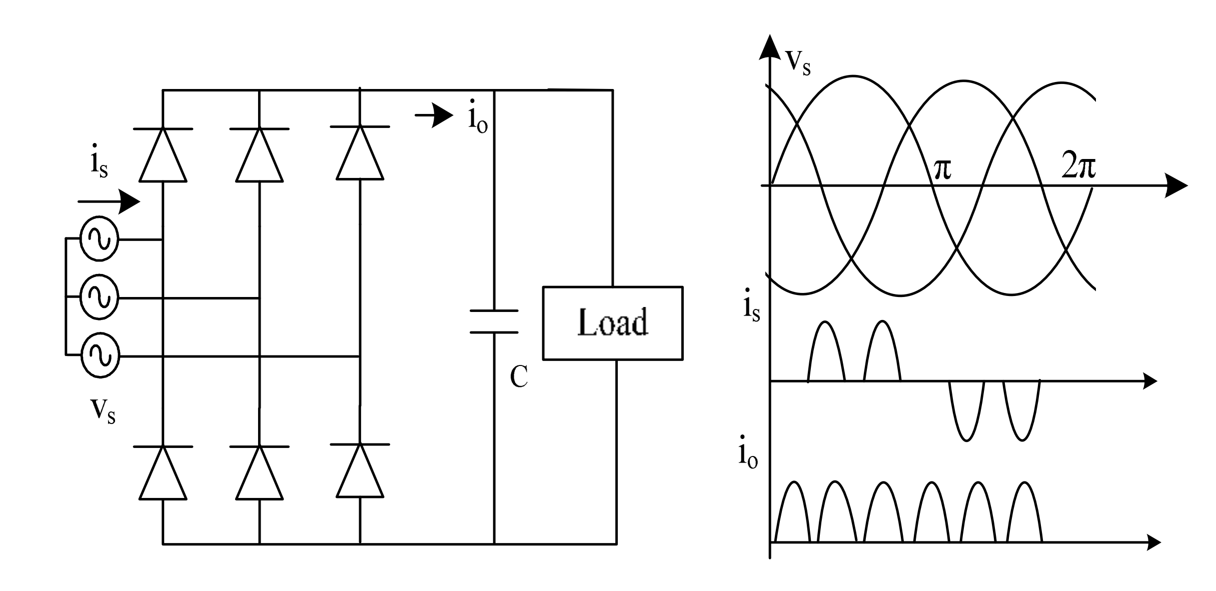


Fig. Three-Phase Converter Based Voltage Fed Type of Nonlinear Load.

Mixed of Current Fed and Voltage Fed Type of Nonlinear Loads

- The mixed nonlinear loads are combination of current fed and voltage fed types of the loads.

- A group of nonlinear loads and a combination of linear and nonlinear loads lie under this category.

- Most of the practical electrical loads consisting solid state converters behave of these types of nonlinear loads.

Supply System Based Classification

- This classification of nonlinear loads is based on the supply system having
- Single-phase (two wire) and three-phase (three wire or four wire) systems.

- There are many non-linear loads such as domestic appliances which are fed from single-phase supply systems.

- **Some three-phase non-linear loads are without neutral conductor, such as ASDs (Adjustable Speed Drives), fed from three wire supply system.**

- **There are many nonlinear single-phase loads distributed on four-wire, three-phase supply system, such as computers, commercial lighting, etc.**

Two Wire Nonlinear Loads

- There are very large numbers of single phase nonlinear loads supplied by two wire single-phase ac mains.

- All these loads consisting of single-phase diode rectifiers, semiconverters and thyristor converters behave as nonlinear loads.

➢They draw harmonics currents and sometimes they draw reactive power from ac mains.

➢Typical examples of such loads power supplies, electronic fan regulators, electronic ballasts, computers, television sets, and traction. Fig shows such type voltage fed nonlinear load.

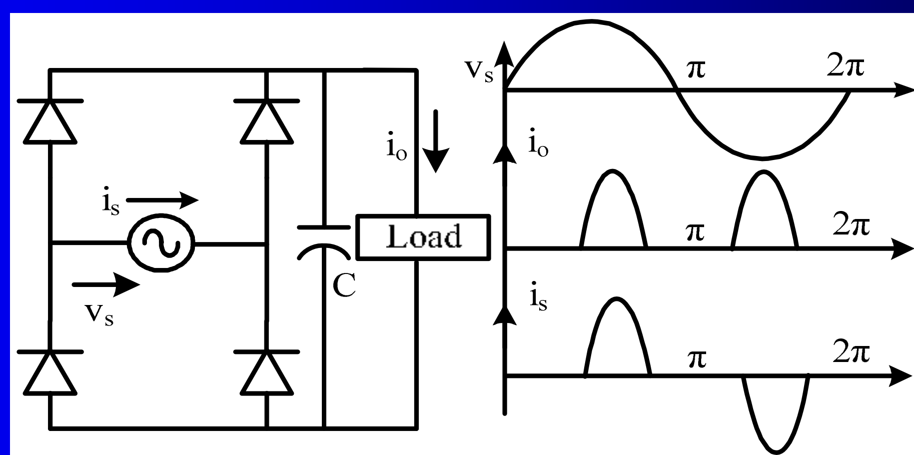


Fig. Single-phase Converter Based Voltage Fed Type of Nonlinear Load

Three Wire Nonlinear Loads

Three-phase, three wire non-linear loads inject harmonics currents, and sometimes they draw reactive power from ac mains and sometimes have also unbalancing.

These nonlinear loads are in large numbers and consume major amount of electric power. Typical examples are ASDs using dc motors and ac motors, HVDC transmission systems, wind power conversion. Fig. shows such type current fed nonlinear load.

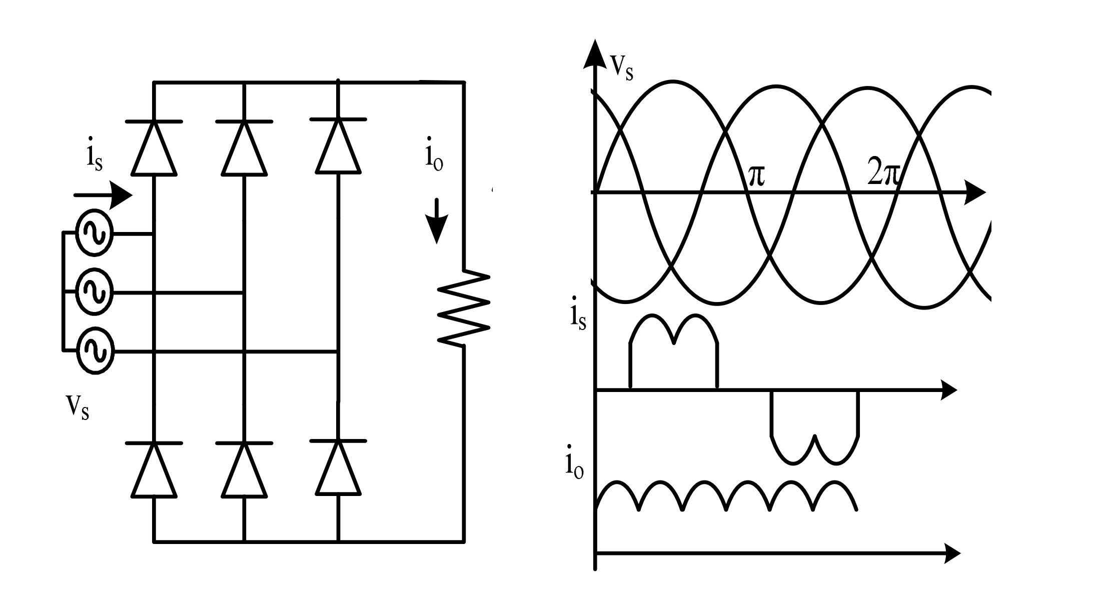


Fig. Three-phase Converter Based Current Fed Type of Nonlinear Load

Four Wire Nonlinear Loads

- A large number of single-phase nonlinear loads may be supplied from three-phase mains with neutral conductor.

- Apart from harmonics currents, reactive power and unbalanced currents, they also cause excessive neutral current due to harmonics currents and unbalancing of these loads on three-phases.

- Typical examples are computer loads and electronic ballasts based vapor lighting systems.

- Moreover, they cause voltage distortion and voltage imbalance at the point of common coupling (PCC) and some potential at the neutral conductor. Fig. shows such type current fed nonlinear load

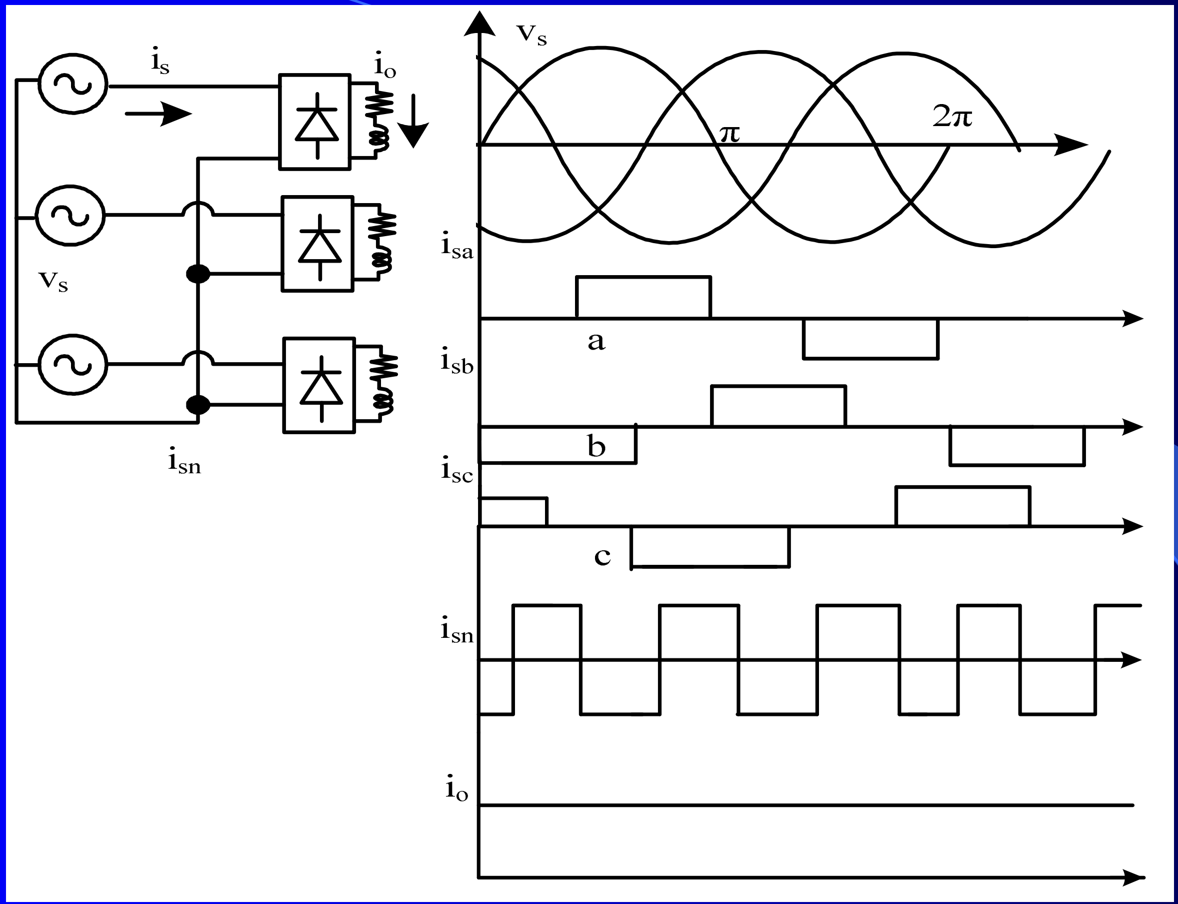


Fig. Three-Phase Four Wire Converter Based Current Fed Type of Nonlinear Loads.

POWER QUALITY PROBLEMS CAUSED BY NONLINEAR LOADS

- These nonlinear loads cause a number of power quality problems in the distribution system and also in them.
- They inject harmonics currents in to ac mains.
- These harmonics currents result in an increase in rms current of the supply and increase losses, cause poor utilization and heating of components of distribution system, and mainly the distortion and notching in voltage waveforms at the point of common coupling due to voltage drop in the source impedance.

Some of the effects are as follows

1. Increased rms supply current.
2. Increased losses.
3. Poor power factor.
4. Poor utilization of distribution system.
5. Heating of components of distribution system.
6. Derating of the distribution system.
7. Distortion in the voltage waveform at the point of common coupling, which indirectly affect many equipments.
8. Disturbance to the nearby consumers.
9. Interference to communication system.

9. Interference to controllers of many other types of equipment.

10. Capacitor bank failure due to overload, resonance, harmonic amplification and nuisance fuse operation.

11. Excessive neutral current.

12. Harmonic voltage at the neutral point.

13. Mal-operation of protection systems such as relays.

Some of these nonlinear loads, in addition to harmonics, have requirement of reactive power and create unbalancing, which increase the severity of above problems and cause the additional problems.

- Voltage regulation and voltage fluctuations.
- Imbalance in three-phase voltages.
- Dearing of cables and feeders.

The voltage imbalance creates substantial problems to electrical machines due to negative sequence currents, noise, vibration, torque pulsation, rotor heating etc. of course their derating.

ANALYSIS OF NONLINEAR LOADS

- There are varieties of nonlinear loads in the ac network which create power quality problems.

- Therefore it has become important and relevant to analyze these loads and to select right technique for power quality improvements.

- Majority of these nonlinear loads can be analyzed using the measured data at the site and then identify power quality problems to select a right technique for its mitigation.

- This technique becomes quite cumbersome, expansive and sometimes practically difficult as it requires large manpower, costly measuring equipment and analytical tools.

- The other method for analyzing these nonlinear loads is an identification of its input stage with its output requirements and set the circuit parameters for the required performance for particular application reported in the literature.

- Once the equivalent circuit of the nonlinear load is properly analyzed then it can be used to design, model and simulate the mitigation technique for power quality improvements.

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Numerical Problems

Q.1A single-phase fed bi-phase half-wave two-pulse diode converter (mid-point two-pulse converter with unity turns ratio transformer) (shown in Fig.) is supplied at 220 V line to neutral, 50 Hz and has continuous constant dc load current of 20 A. Calculate (a) the mean output voltage, (b) CF, (c) DF, (d) DPF, (e) PF, and (f) %THD of supply current.

Solution : Given that, supply voltage, V_s = 220 V, frequency of the supply f=50 Hz, dc link current, I_{dc} = 20A.

In single-phase bi-phase half-wave two-pulse diode converter (mid-point two-pulse converter with unity turns ratio transformer), the waveform of the supply current (I_s) is a square wave with the amplitude of dc link current (I_{dc}). Moreover, the rms of fundamental component of square wave is $(2\sqrt{2}/\pi) = 0.9$ times the amplitude of it.

Therefore, Supply RMS current, $I_s=I_{dc}=20A$ and Fundamental Supply RMS Current, $I_{s1}=(2\sqrt{2}/\pi)\ I_{dc}=0.9I_{dc}=18$ A

(a)Mean output dc output voltage, $V_{dc}=(2\sqrt{2}/\pi)\ V_s=0.9V_s=0.9*220=198.0$ V

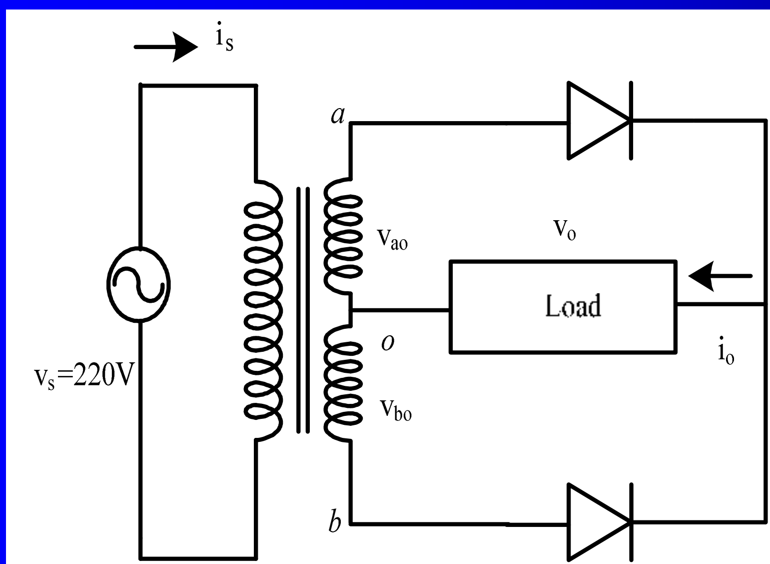
(b)Crest Factor of the supply current, CF=Supply Peak Current/ Supply RMS current=$I_{peak}/I_{rms}=I_{dc}/I_s=20/20=1$

(c)Distortion Factor, DF=Fundamental supply rms current/supply rms current=I_{s1}/I_{s}=18/20=0.9

(d)Displacement factor=$\cos\theta_1$=1 (since fundamental supply current is in phase with supply voltage)

(e)Power Factor, PF=DF*DPF=0.9*1=0.9

(f)Total Harmonic Distortion (THD) of supply current=$\sqrt{(I_s^2-I_{s1}^2)}/I_{s1}=\sqrt{(20^2-18^2)}/18=0.4843=48.43\%$



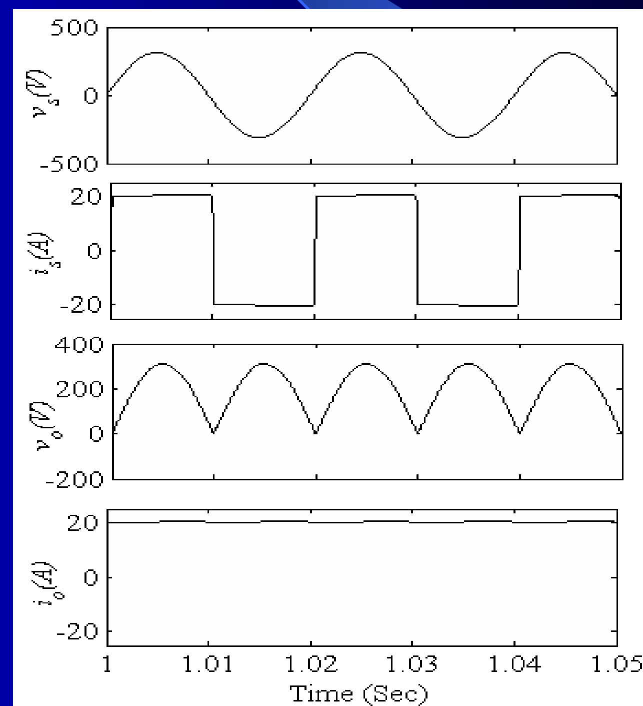


Fig. Single-Phase Bi-Phase Half-Wave Two-Pulse Converter Based Current Fed Type of Nonlinear Load.

Q.2 A single-phase uncontrolled bridge converter (shown in Fig.) has a RE load with R=5 ohms, and E=150V. The input ac voltage is V_s=230 V at 50 Hz. Calculate (a) load average current, (b) supply rms current, (c) CF, (d) DF, (e) DPF, (f) PF, and (g) %THD.

Solution :

Given that, Supply voltage, V_s=230V, V_{sm}=325.27V, Frequency of the supply f=50 Hz, Load R=5Ω, E=150V

In single-phase diode bridge converter, with RE load, the current will flow from angle (α) when ac voltage is equal to E and to the angle (β) at which ac voltage reduces to E.

$\alpha = \sin^{-1}(E/V_{sm}) = \sin^{-1}(150/325.27) = 27.46°$, $\beta = \pi - \alpha = 152.54°$, The conduction angle= $\beta - \alpha = 125.08°$

Active power drawn from ac mains, $P = I_s^2 R + E I_{dc} = 4593.22$ W

Fundamental RMS current from ac mains, $I_{s1} = P/V_s = 19.9705$A

Supply ac peak current, $I_{peak} = (V_{sm} - E)/R = 35.054$A

(a) Load Average current (I_{dc}) is as:

$I_{dc} = \{1/(\pi R)\}(2V_{sm}\cos\alpha + 2E\alpha - \pi E) = 15.886$A

(b) RMS supply current (I_s) is rms of discontinuous current in the ac mains as:

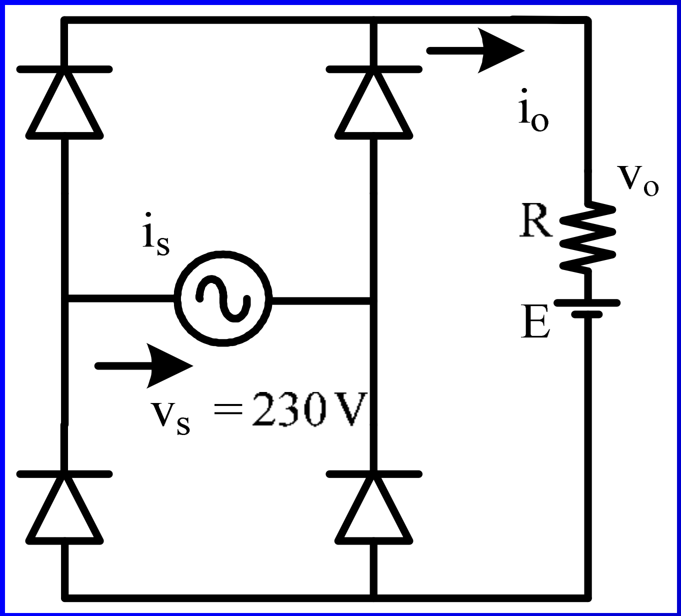
$I_s = [\{1/(\pi R^2)\}\{(0.5V_{sm}^2 + E^2)(\pi - 2\alpha) + 0.5V_{sm}^2 \sin 2\alpha - 4V_{sm}E\cos\alpha\}]^{½} = 21.025$ A (c)Crest Factor of supply current, CF=Supply Peak Current/ Supply RMS current=$I_{peak}/I_{rms}=I_{peak}/I_s$=1.66725

(d) Distortion Factor, DF=Fundamental supply rms current/supply rms current=I_{s1}/I_s=19.97/21.025=0.94982

(e)Displacement factor=$\cos\theta_1$=1 (since fundamental supply current is in phase with supply voltage, θ_1=0°)

(f)Power Factor, PF=$P/(V_s I_s)$=0.949846

(g)Total Harmonic Distortion (THD) of ac current=$\sqrt{(I_s^2-I_{s1}^2)}/I_{s1}=\sqrt{(21.03^2-19.97^2)}/19.97$= **0.3301=33.01%**



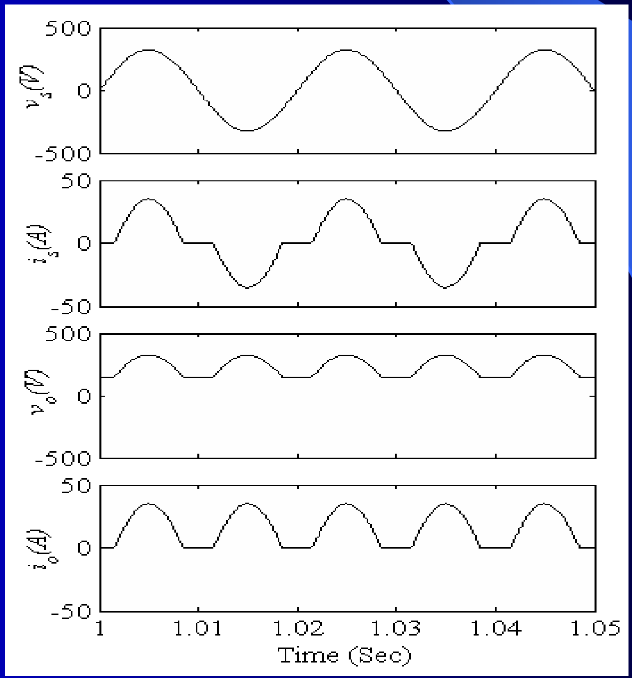


Fig. Single-Phase Converter Based Voltage Fed Type of Nonlinear Load

Q.3 Consider single-phase semi-controlled bridge converter (shown in Fig.) with sinusoidal input supply V_s of 230V, 50 Hz and constant dc load current of 25A. (a) Calculate DF, DPF, PF, %THD of the supply current for $V_o=0.5*V_{dc0}$ where V_{dc0} is the dc output at $\alpha=0°$. (b) Repeat part a for a fully controlled bridge converter.

Solution:

Given that, supply rms voltage, V_s = 230 V, Frequency of the supply f=50 Hz, I_o=25A

(a) In single-phase semi-controlled bridge converter, the waveform of the supply current (I_s) is from firing angle α to 180^0 with the amplitude of dc link current (I_o).

If $V_o=0.5*V_{dc0}$ where V_{dc0} is the dc output at $\alpha=0°$, then firing angle, $\alpha=90°$

The rms supply current, $I_s = I_o\sqrt{(\pi-\alpha)/\pi} = I_o/\sqrt{2} = 17.678A$

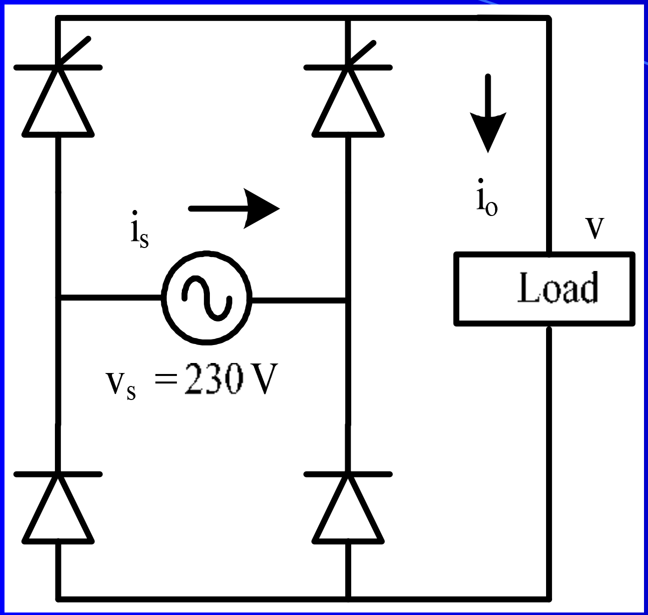
The fundamental rms supply current, $I_{s1}=0.9\ I_o \cos(\alpha/2) = 0.9\ I_o\cos(\alpha/2) = 0.9I_o/\sqrt{2} = 15.91A$

Displacement factor, DPF=$\cos\theta_1 = \cos(\alpha/2) = 1/\sqrt{2} = 0.7071$

Distortion Factor, DF=$1/\sqrt{(1+THD^2)} = 0.90$

Power-Factor, PF=DPF*DF=0.9*0.7071=0.63639

Total Harmonic Distortion (THD) of ac current=$\sqrt{(I_s^2-I_{s1}^2)}/I_{s1}$**=0.4843=48.43%**



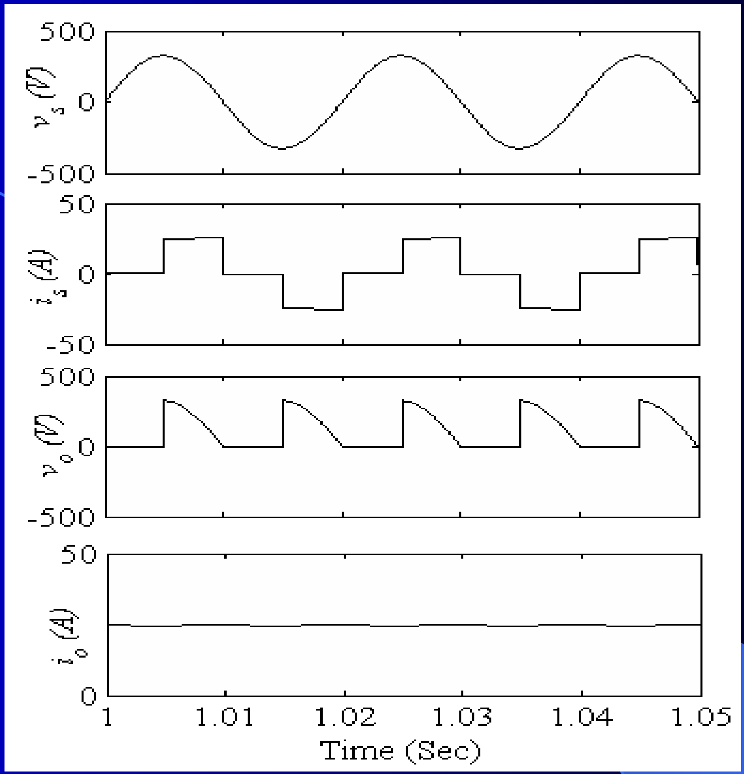


Fig. (a) Single-Phase Semi Converter Based Current Fed Type of Nonlinear Load

(b) In single-phase fully controlled bridge converter, the waveform of the supply current (I_s) is from firing angle α to (π+α) with the amplitude of dc link current (I_o).

If $V_o=0.5*V_{dc0}$ where V_{dc0} is the dc output at α=0°, then firing angle, α =60°

The rms supply current, $I_s = I_o$=25A

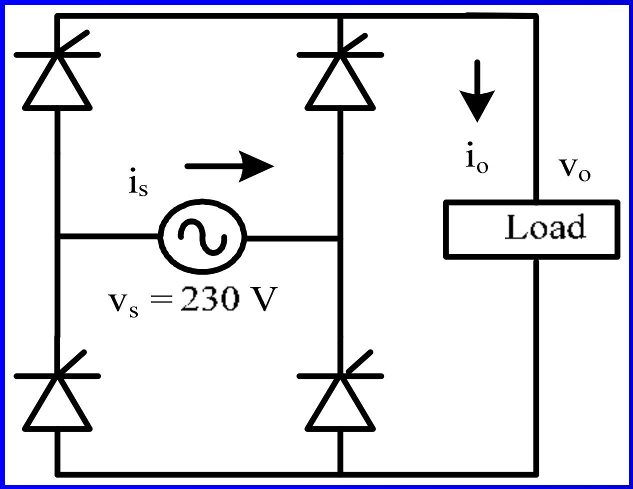
The fundamental rms supply current, I_{s1}=0.9 Io=22.5A

Displacement factor, DPF=cos θ_1= cos(α)=1/2=0.5

Distortion Factor, DF=1/√(1+THD²)=0.90

Power-Factor, PF=DPF*DF=0.9*0.5=0.45

Total Harmonic Distortion (THD) of ac current= $\sqrt{(I_s^2 - I_{s1}^2)}/I_{s1}$**=0.4843=48.43%.**



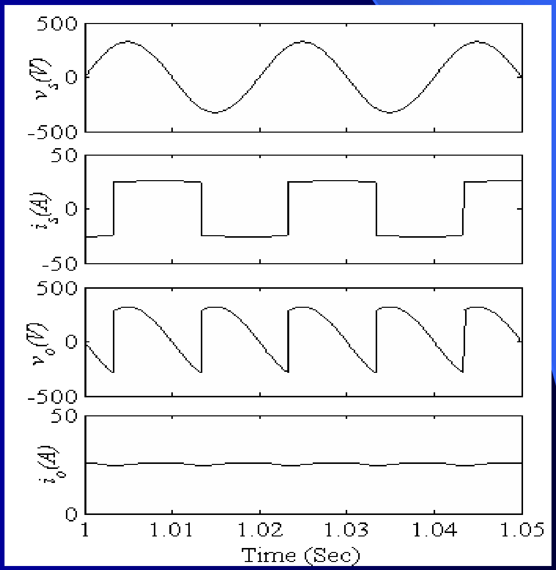


Fig.(b) Single-Phase Fully Control Bridge Converter Based Current Fed Type of Nonlinear Load.

Q.4 A single-phase fully controlled bridge converter (shown in Fig.) is used as a line commutated inverter (LCI) to feed power from a battery with 180 V and an internal resistance of 0.1 ohm. The supply rms voltage is 220V and sufficient inductance is included in the output circuit to maintain the current virtually constant at 20A. Determine the required delay angle (α), distortion factor (DF), displacement factor (DPF), total harmonic distortion of ac source current (THD_I), crest factor of ac source current (CF), the power factor (PF), ac source rms current (I_s).

Solution :

Given that, Supply rms voltage, V_s = 220 V, Frequency of the supply f=50 Hz, I_o =20 A, E=180V, R_{dc}=0.1Ω.

In single-phase thyristor bridge converter operating as a line commutated inverter (LCI), the waveform of the supply current (I_s) is a square wave with the amplitude of dc link current (I_o). Moreover, the rms of fundamental component of square wave is 0.9 times the amplitude of it.

Therefore, supply rms current, $I_s = I_o$=20 A

The rms fundamental current, I_{s1}= 0.9 I_o=18 A

The average output voltage, $V_o = (2\sqrt{2}/\pi)\, V_s \cos\alpha = 0.9 V_s \cos\alpha = -(E - I_oR_{dc}) = -(180-20*0.1) = -178$ V, $\alpha = 154.03^0$

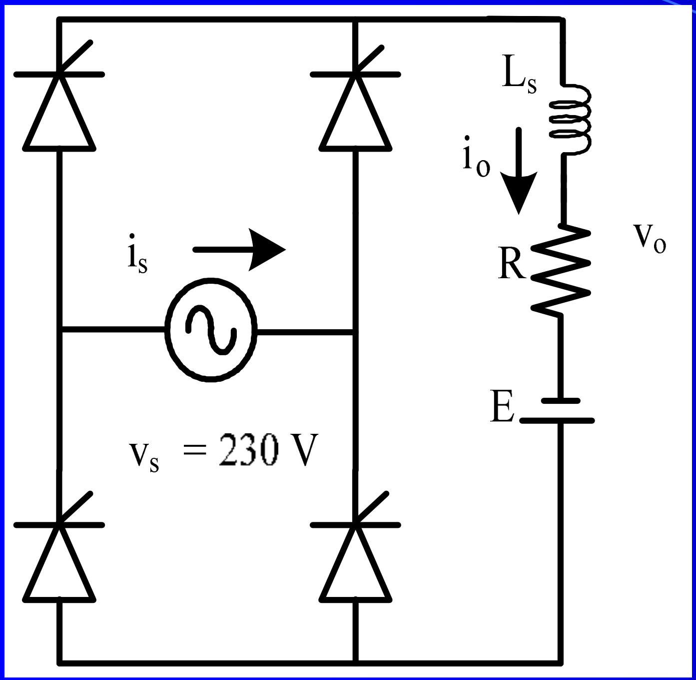
Distortion Factor, $DF = 1/\sqrt{(1+THD^2)} = 0.90$

Displacement factor, $DPF = \cos\theta_1 = \cos\alpha = \cos 154.03^0 = -0.899$

Power-Factor, PF=DPF*DF=0.9*0.899=0.8091

Total Harmonic Distortion (THD) of ac current=$\sqrt{(I_s^2 - I_{s1}^2)}/I_{s1}$=**0.4843=48.43%%**

Crest Factor of supply current, CF=Supply Peak Current/ Supply RMS current=$I_{peak}/I_{rms} = I_{peak}/I_s$=1.0



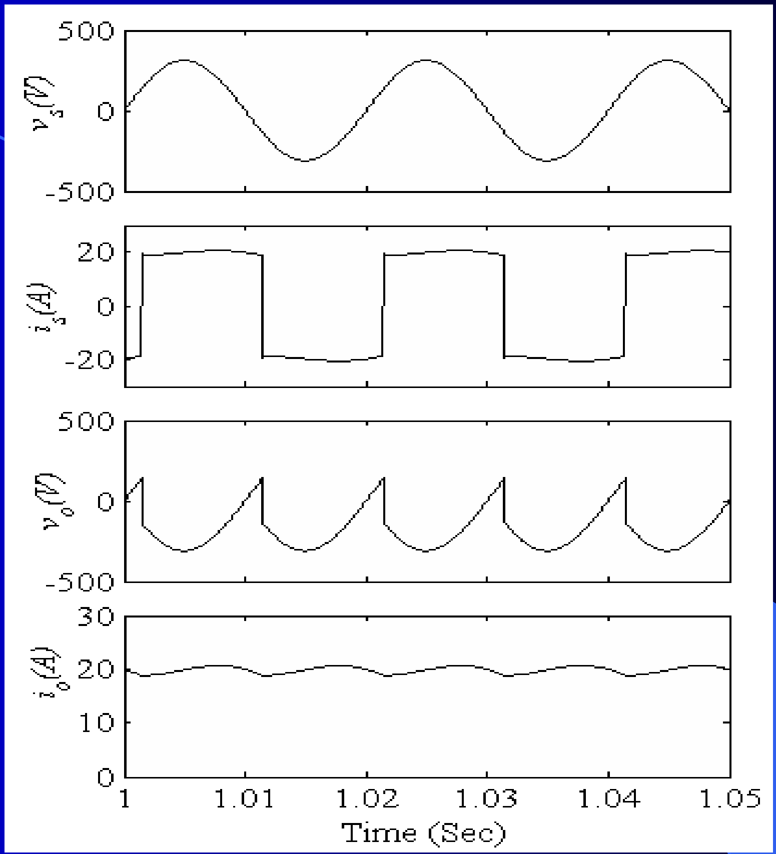


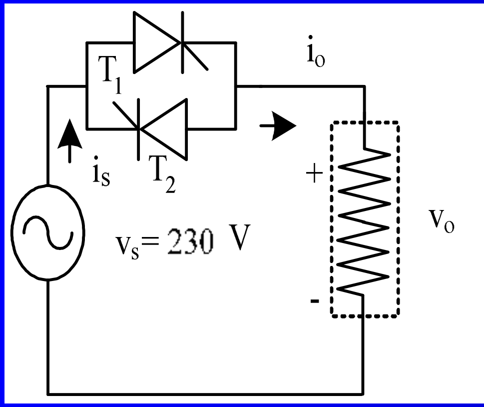
Fig. Single-Phase Converter Based Current Fed Type of Nonlinear Load

Q.5 A single-phase ac voltage controller (shown in Fig.) is used to control the heating load of a maximum power of 2 kW fed from single-phase ac mains of 230 V, 50 Hz. Its power is to be controlled to deliver 1 kW. Calculate (a) load resistance, (b) rms voltage across the load, (c) supply rms current, (d) supply power factor.

Solution:

Given that, Supply rms voltage, V_s = 230 V, Frequency of the supply f=50 Hz, P_{max}=2 kW, P=1kW.

1. The load resistance, $R=V_s^2/P_{max}=26.45\ \Omega$
2. The rms voltage across the load, $V_{ls}=I_sR=162.6346V$
3. The supply rms current, $I_s=\sqrt{(P/R)}=6.14875A$
4. The supply power factor, $PF=P/(V_sI_s)=0.70711$



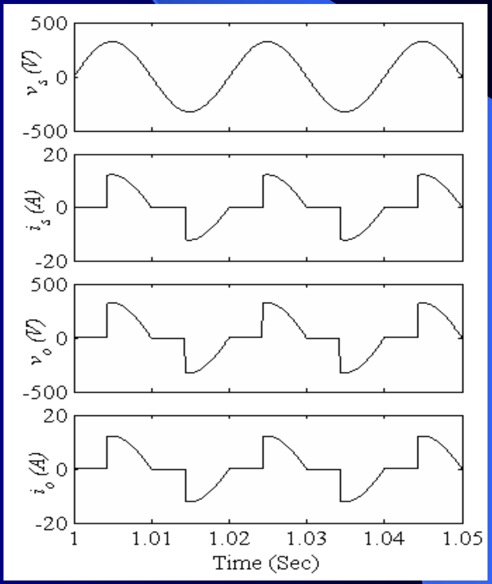


Fig. Single-Phase Converter Based Current Fed Type of Nonlinear Load

Q.6 A single-phase, 230V, 50 Hz supply system is feeding a set of nonlinear loads, which consists of a semi-controlled bridge and a diode bridge rectifier connected in parallel (shown in Fig. E3.13). The diode bridge converter is drawing 20 A constant dc current. The semi-controlled bridge AC-DC converter is drawing 10 A constant dc current at 45^{o} firing angle of its thyristors. For this composite nonlinear load, calculate (a) active power consumed, (b) reactive power drawn, (c) displacement factor (DPF), (d) distortion factor (DF), (e) total harmonic distortion of ac source current (THD_I), (f) power factor (PF), (g) crest factor of ac source current (CF), (h) ac source rms current (I_s).

Solution: Given that, supply rms voltage, $V_s = 230$ V, frequency of the supply f=50 Hz. A set of nonlinear loads consists of a semi-controlled bridge and a diode bridge rectifier connected in parallel. The diode bridge converter is drawing 20 A constant dc current. The thyristor-bridge AC-DC converter is drawing 10 A constant dc current at 45° firing angle of its thyristors.

In single-phase diode bridge converter, the waveform of the ac current (I_{LD}) is a square wave with the amplitude of dc link current (I_{Ddc}). Moreover, the rms of fundamental component of square wave is $(2\sqrt{2}/\pi) = 0.9$ times the amplitude of it.

Therefore, $I_{LD} = I_{Ddc} = 20$ A and $I_{LD1} = (2\sqrt{2}/\pi)\, I_{Ddc} = 0.9\, I_{Ddc} = 18$A.

Moreover, active component ac current of the diode converter is as, $I_{LD1a} = I_{LD1} = 18$ A.

In single-phase semi-controlled bridge converter, the waveform of the ac current (I_{TD}) is from firing angle α to 180^0 with the amplitude of dc link current (I_{TDdc}).

Moreover, the rms of ac current, $I_{TD} = I_{TDdc}\sqrt{\{(\pi-\alpha)/\pi\}} = 8.66$ A

RMS of fundamental of supply current, $I_{TD1}=0.9\ I_{TDdc}\cos(\alpha/2)=8.3149A$

Active power component of ac current in semi-controlled converter, $I_{TD1a}= I_{TD1}\cos\theta_1= I_{TD1}\cos(\alpha/2)=7.682A$

Reactive power component of ac current in semi-controlled converter, $I_{LT1r}= I_{LT1}\sin\theta_1= I_{TD1}\sin\alpha/2=3.1819A$

Therefore total rms active power component of ac current of the load is as. $I_{s1a}= I_{LD1a}+ I_{TD1a}=25.682A$.

Therefore total rms reactive power component of ac current of the load is as. $I_{s1r}= I_{LD1r}+ I_{TD1r}=3.1819A$.

- Active power consumed, $P=V_s\, I_{s1a}=5906.86W$.
- Reactive power drawn, $Q=V_s\, I_{s1r}=731.837VAR$.
- The displacement factor (DPF), $\cos\theta_1=P/S=P/\sqrt{(P^2+Q^2)}=5906.86/5952.02=0.9924$.
- The distortion factor (DF) is computed by computing rms current (I_s) and fundamental rms current (I_{s1}) of the composite load as.

The ac current of diode rectifier is square wave with unity displacement factor. However, ac current of the thyristor bridge converter is also square wave but phase shifted by firing angle, $\alpha = 60^0$. The rms value of supply current will be rms value of combined load current consisting diode and thyristor bridge converters.

Therefore, rms current of the composite load is computed with the half cycle integration as.

$$I_s=\sqrt{[1/\pi\{\int_0^{\alpha}(20)^2 d\theta+\int_{\alpha}^{\pi}(20+10)^2 d\theta]}=27.8388A.$$

The rms fundamental current of the composite load is computed with the half cycle integration as.

$I_{s1}=S/V=\{\sqrt{(P^2+Q^2)}\}/V_s=5952.02/230=25.878A.$

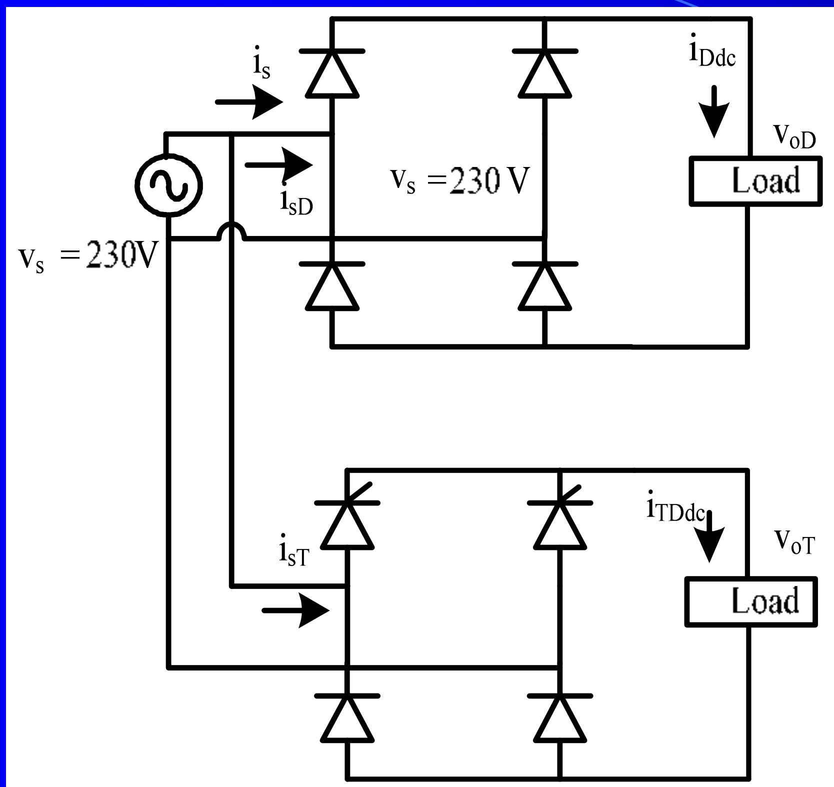
The distortion factor (DF)=$I_{s1}/I_s=0.92958.$

(e) The total harmonic distortion of ac source current (THD_I)=$\{\sqrt{(I_s^2-I_{s1}^2)}\}/I_{s1}=0.3966*100=39.66\%.$

(f) The power factor (PF)=DPF*DF=0.9225.

(g) The crest factor of ac source current (CF)=$I_{speak}/I_s=(20+10)/27.8388=1.0776.$

(h) The ac source rms current (I_s)= $\sqrt{[1/\pi\{\int_0^{\alpha}(20)^2 d\theta+\int_{\alpha}^{\pi}(20+10)^2\}d\theta]}=27.8388A.$



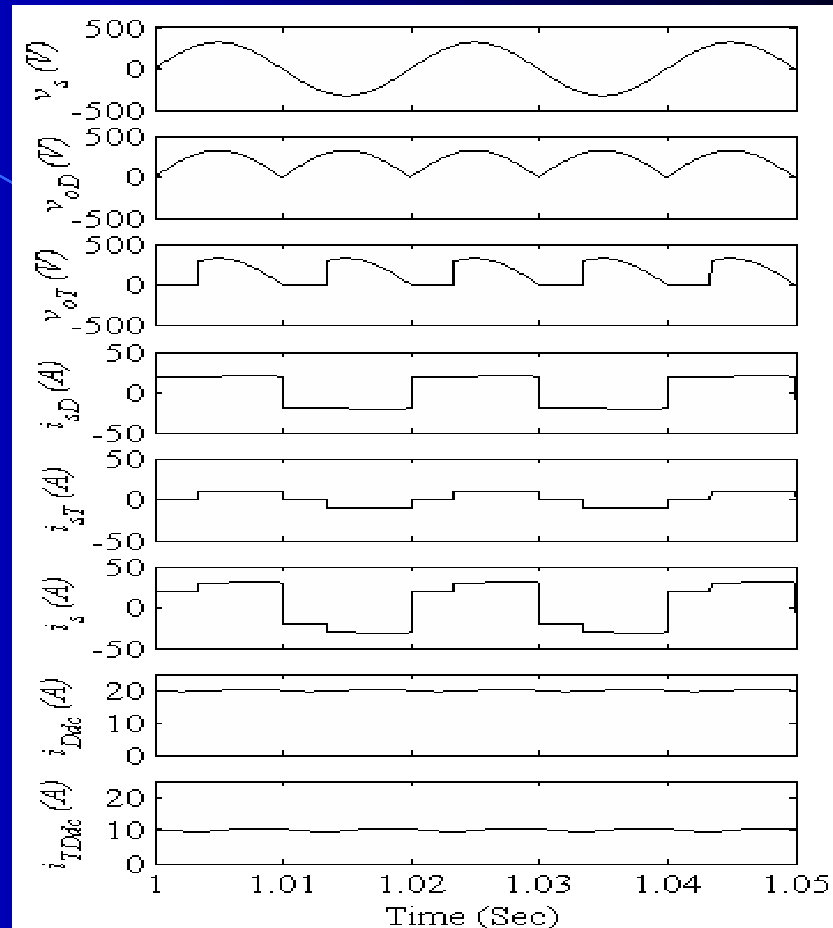


Fig. Single-Phase Converter Based Current Fed Type of Nonlinear Load.

Q.7 An uncontrolled three-phase bridge rectifier (shown in Fig.) is fed by a line voltage of 415 V, 50 Hz. If a continuous constant load current is of 40A in RL load, calculate (a) the mean dc load voltage, (b) load resistance, (c) load power, (d) rms ac mains current, (e) DF, (f) DPF, (g) PF, and (h) THD of the supply current.

Solution:

Given that, Supply rms phase voltage, $V_s=415/\sqrt{3}=239.6$ V, Frequency of the supply f=50 Hz, $I_o=40$A.

In three-phase diode bridge converter, the waveform of the supply current (I_s) is a quasi-square wave with the amplitude of dc link current (I_o).

Therefore, the rms of quasi-square wave load current, $I_s=I_o\sqrt{(2/3)}=32.659$ A

Moreover, the rms of fundamental component of quasi-square wave, $I_{s1}=\{(\sqrt{6})/\pi\}I_o$**=31.188 A**

The active power drawn by the load, $P= 3V_sI_{s1}\cos\theta_1=22.4178$ kW

(a) Average output dc voltage, $V_o=3\sqrt{3}\sqrt{2}V_s/\pi=56.446$ V

(b) $R=V_o/I_o=560.446/40=14.011\Omega$

(c) Load power$=3V_sI_{s1}\cos\theta_1 = V_o I_o =22.41$ kW

(d) The rms of quasi-square wave load current, $I_s=I_o\sqrt{(2/3)}=32.659$ A

(e) Distortion Factor, $DF=I_{s1}/I_s=3/\pi=0.9549$

(f) Displacement factor, $DPF=\cos\theta_1=\cos\alpha=\cos 0^0=1.0$

(g) Power-Factor, PF=DPF*DF=0.9549*1=0.9549

(h) Total Harmonic Distortion (THD) of ac current$=\sqrt{(I_s^2-I_{s1}^2)}/I_{s1}=0.3108=31.08\%$

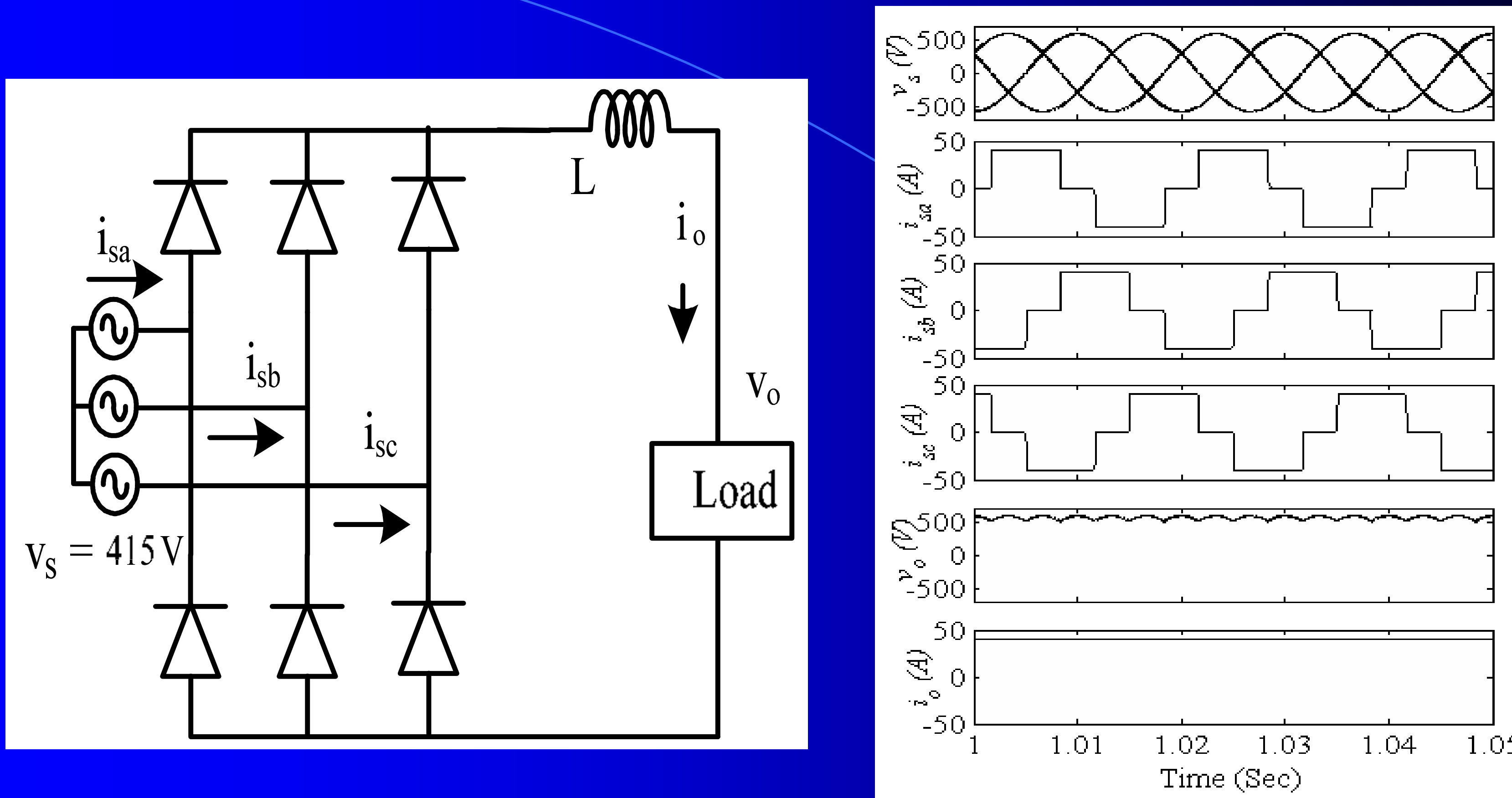


Fig. Three-Phase Converter Based Current Fed Type of Nonlinear Load

Q.8 Consider three-phase semi-controlled bridge converter (shown in Fig.) with sinusoidal input line supply voltage of 415V, 50 Hz, and constant dc load current of 50A. (a) Calculate DF, DPF, PF, %THD for V_o=0.75*V_{d0} where V_{d0} is the dc output at α=0°.(b) Repeat part a for a fully controlled bridge converter.

Solution:

Given that, Supply rms voltage, $V_s=415/\sqrt{3}=239.6V$, supply Frequency f=50Hz,, $I_o=50A$

(a) In three-phase semi-controlled bridge converter, the waveform of the supply current (I_s) is from firing angle α to 180^0 with the amplitude of dc link current (I_o).

If $V_o=0.75*V_{dc0}$ where V_{dc0} is the dc output at α=0°, then firing angle, α =60°

The rms supply current, $I_s = I_o\sqrt{\{(\pi - \alpha)/\pi\}} = I_o\sqrt{(2/3)}=40.825A$

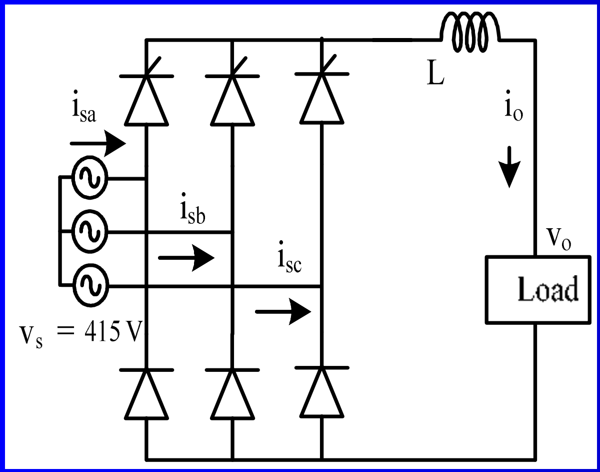
The fundamental rms supply current, $I_{s1}=I_o\sqrt{6}/\pi * \cos(\alpha/2)=33.73A$

Displacement factor, $DPF=\cos\theta_1= \cos(\alpha/2)=0.866$

Distortion Factor, $DF=1/\sqrt{(1+THD^2)}=0.9549 \cos(\alpha/2)=0.826968$

Power-Factor, PF=DPF*DF=0.71615

Total Harmonic Distortion (THD) of ac current, $THD=\{(1/DF^2)-1\}^{1/2}=68.006\%$



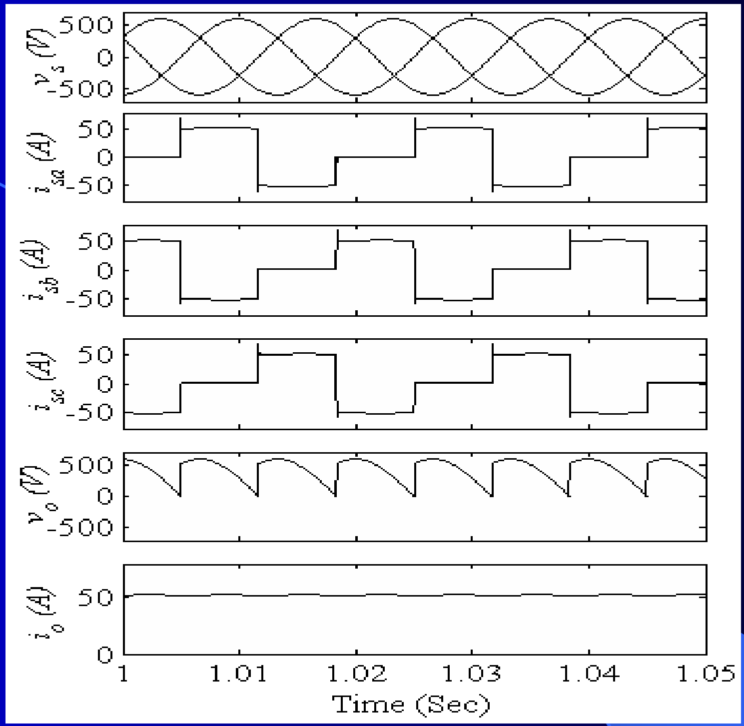


Fig. (a) Three-Phase Semi-Controlled Bridge Converter Based Current Fed Type of Nonlinear Load

(b) In thee-phase fully controlled bridge converter, the waveform of the supply current (I_s) is from firing angle α to (2π/3+α) with the amplitude of dc link current (I_o).

If $V_o=0.75*V_{dc0}$ where V_{dc0} is the dc output at α=0°, then firing angle, α =31.057°

The rms supply current, $I_s = I_o\sqrt{(2/3)}=40.825A$

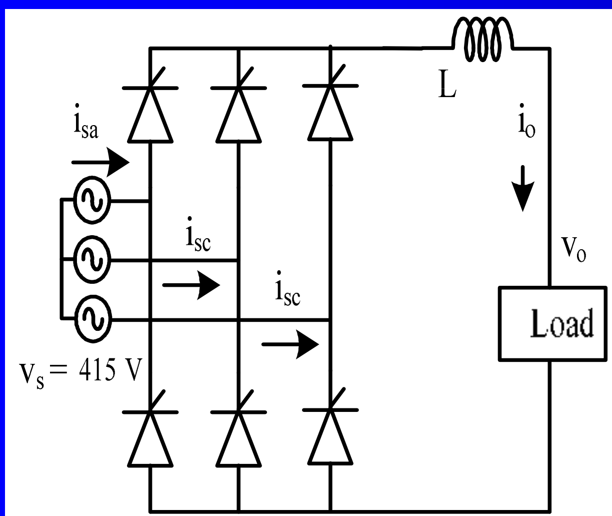
The fundamental rms supply current, $I_{s1}=I_o\sqrt{6}/\pi =38.985A$

Displacement factor, $DPF=\cos \theta_1= \cos(\alpha)=0.85665$

Distortion Factor, $DF=1/\sqrt{(1+THD^2)}=0.9549$

Power-Factor, $PF=DPF*DF=0.818$

Total Harmonic Distortion (THD) of ac current$=\sqrt{(I_s^2-I_{s1}^2)}/I_{s1}$**=0.3108=31.08%**



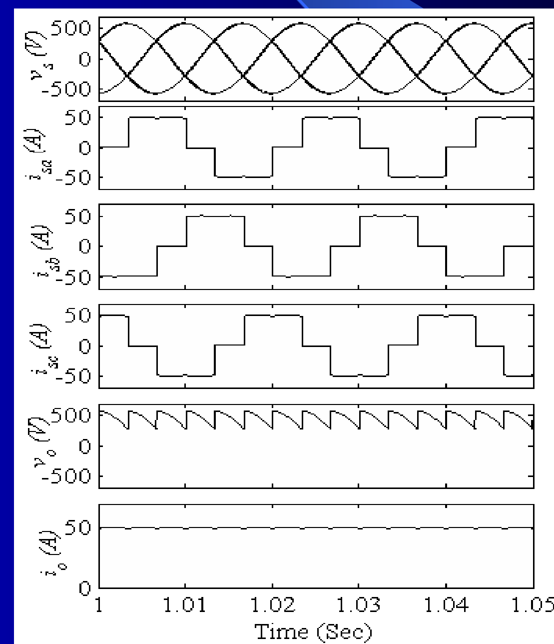


Fig. (b) Three-Phase Fully Controlled Bridge Converter Based Current Fed Type of Nonlinear Load.

Q.9 A three-phase nonlinear load (shown in Fig.) is supplied from a three-phase 415V, 50 Hz, having a 12-pulse diode bridge converter with 100A constant dc current. It consists of an ideal transformer with single primary star connected winding and two secondary windings connected in star and delta with same line voltages and unity turns ratios to provide 30° phase shift between two sets of three-phase output voltages. Two 6-pulse diode bridges are connected in series to provide 12-pulse ac-dc converter. Calculate (a) the fundamental active power drawn by the load, (b) power-factor, (c) rms supply current, (d) distortion factor, (e) fundamental rms supply current, (f) peak current of ac mains, and (g) total harmonic distortion of ac source current (THD_I).

Solution:

Given that, Supply rms phase voltage, $V_s = 415/\sqrt{3} = 239.6$ V, Frequency of the supply f=50 Hz, The amplitude of dc link current $I_o = 100$A.

In three-phase 12-pulse diode bridge converter, the waveform of the input ac current (I_s) is a stepped waveforms as (i) first step of $\pi/6$ angle (from 0° to $\pi/6$) and input current magnitude of ($I_o/\sqrt{3}$), (ii) second step of $\pi/6$ angle (from $\pi/6$ to $\pi/3$) and input current magnitude of $\{I_o(1+1/\sqrt{3})\}$, (iii) third step of $\pi/6$ angle (from $\pi/3$ to $\pi/2$) and input current magnitude of $\{I_o(1+2/\sqrt{3})\}$ and it has all four symmetric segments of such steps.

Therefore, RMS of 12-pulse converter input current, $I_s = I_o[(1/3)+(1+1/\sqrt{3})^2+(1+2/\sqrt{3})^2]^{1/2} = 1.57735 I_o = 157.735$ A

RMS of fundamental component of 12-pulse converter input current, $I_{s1} = \{(2\sqrt{6})/\pi\} I_o$ **= 1.559393I_o = 155.939 A**

(a) The active power drawn by the load, P= 3$V_s I_{s1}$ cosθ_1=112.08895 kW

(b) The Power factor, PF=P/(3$V_s I_s$)=0.9886138

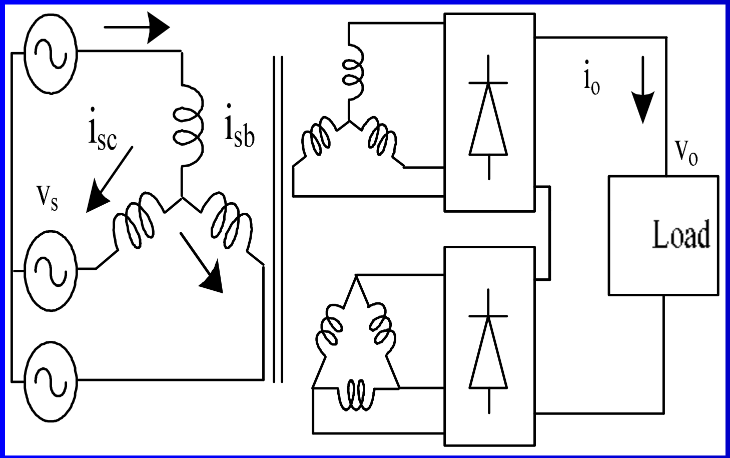
(c) RMS of 12-pulse converter input current, $I_s = I_o[(1/3)+(1+1/\sqrt{3})^2+(1+2/\sqrt{3})^2]^{1/2} = 1.57735 I_o = 157.735$ A

(d) The distortion factor, $DF = I_{s1}/I_s = 0.9886138$

(e) RMS of fundamental component of input ac mains current, $I_{s1} = \{(2\sqrt{6})/\pi\} I_o = 1.559393 I_o = 155.939$ A

(f) The peak current of ac mains, $I_{peak} = \{I_o(1+2/\sqrt{3})\} = 2.1547 I_o = 215.45$ A

(g) The total harmonic distortion of ac source current (THDI) $= \sqrt{\{(1/DF^2)-1\}} = 15.22\%$



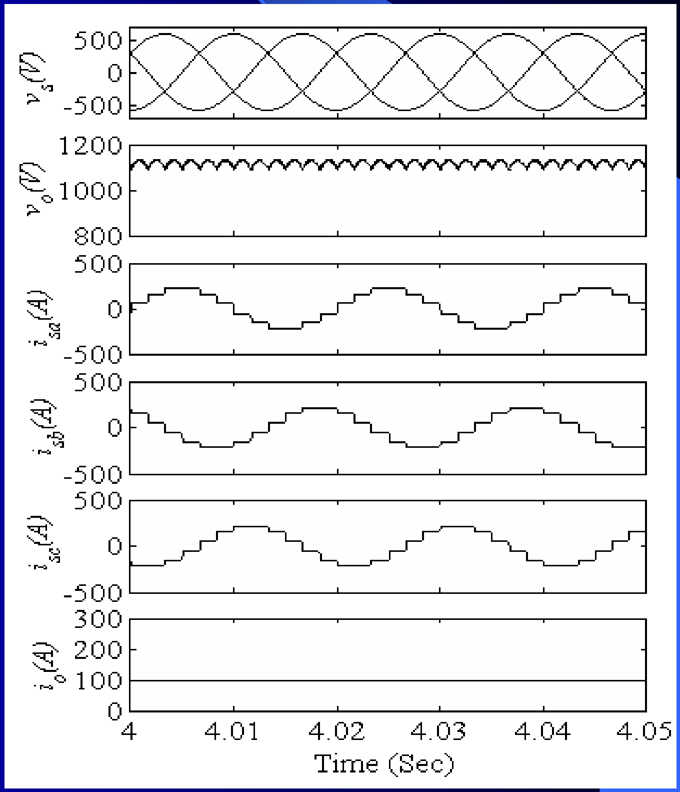


Fig. Three-Phase Converter Based Current Fed Type of Nonlinear Load

Q. 10 In a three-phase, line voltage of 415 V, 50 Hz, 4-wire distribution system, three single-phase loads (connected between phases and neutral) having a single-phase thyristor bridge converter drawing equal 20 A constant dc current at 60º firing angle of its thyristors (shown in Fig.). Calculate (a) active power consumed, (b) reactive power drawn, (c) displacement factor (DPF), (d) distortion factor (DF), (e) total harmonic distortion of ac source current (THD_I), (f) power factor (PF), (g) crest factor of ac source current (CF), (h) ac source rms current (I_s), and (i) neutral current (I_{sn}).

Solution:

Given that, Supply voltage, V_s = 239.6 V, Frequency of the supply f=50 Hz, DC link current, I_o = 20A, Firing angle, α= 60º.

In single-phase thyristor bridge converter, the waveform of the supply current (I_s) is a square wave with the amplitude of dc link current (I_o). Moreover, the rms of fundamental component of square wave is $(2\sqrt{2}/\pi)$ =0.9 times the amplitude of it.

Therefore, $I_s = I_o = 20$ A and $I_{s1} = (2\sqrt{2}/\pi)\, I_o = 0.9\, I_o = 18$ A

RMS Fundamental active power component of load current, $I_{s1a} = I_{s1} \cos\alpha = 9.0$A

The neutral current I_{sn}=20 A (since it will also be a square wave as 3 times the fundamental frequency)

(a) The active power consumed, $P_1 = 3V_s\, I_{s1a} = 6469.21$W

(b) The reactive power consumed, $Q_1 = 3V_s\, I_{s1} \sin\alpha = 11205.00$ VAR

(c) The displacement factor (DPF)= cosα=0.5

(d) The distortion factor (DF)= $I_{s1}/I_s=(2\sqrt{2}/\pi)=0.9$

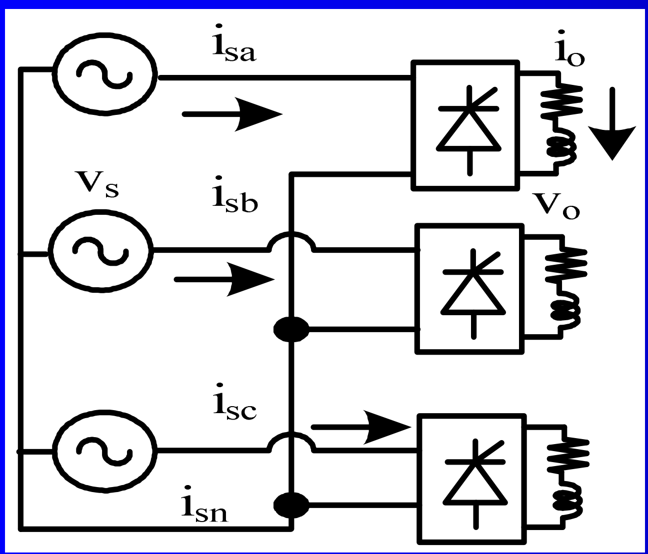
(e) The total harmonic distortion of ac source current (THD_I)= $\sqrt{(1/DF^2)-1}=48.43\%$

(f) The power factor (PF) = $(2\sqrt{2}/\pi)\cos\alpha=0.45$

(g) The crest factor of ac source current (CF)= $I_{peak}/I_{rms}=I_o/I_s=1$

(h) The ac source rms current (I_s) = I_o =20 A

(i) The neutral current (I_{sn}) =20 A (since it will also be a square wave as 3 times the fundamental frequency).



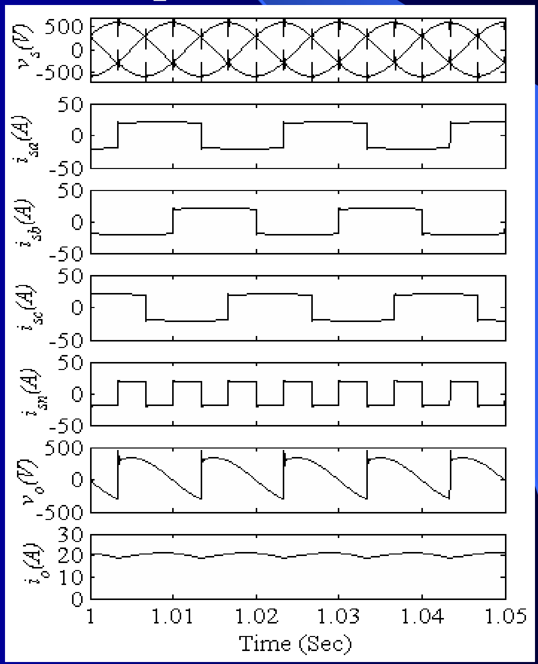


Fig. Three-Phase Converter Based Current Fed Type of Nonlinear Load.

Thank You