THREE PHASE SOLID STATE INVERTERS

by

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A MASTER'S REPORT

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Electrical Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1970

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TABLE OF CONTENTS

THIS BOOK CONTAINS NUMEROUS PAGES WITH ILLEGIBLE PAGE NUMBERS THAT ARE CUT OFF, MISSING OR OF POOR QUALITY TEXT.

THIS IS AS RECEIVED FROM THE CUSTOMER.

THIS BOOK CONTAINS NUMEROUS PAGES WITH DIAGRAMS THAT ARE CROOKED COMPARED TO THE REST OF THE INFORMATION ON THE PAGE.

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LIST OF FIGURES

ACKNOWLEDGEMENTS

The author is deeply indebted to Dr. W. W. Koepsel for his invaluable help and guidance in this work. The author is also thankful to Mrs. Jeanne Carpenter for typing and Mr. Prasad Pathare for the figures and sketches.

CHAPTER 1

INTRODUCTION

1. General Consideration.

An inverter is a device which converts d-c power to a-c power. A three-phase inverter is a device which converts d-c power to three-phase a-c power. In this report three-phase solid-state inverters are discussed. A solid-state inverter is one which uses solid-state devices such as SCR's, transistors, tunnel-diodes, etc., for switching purposes. Class A amplifiers converting d-c plate voltage into sinusoidal output voltage upon application of grid signal can also be considered as inverters. This type of inverter can have up to 25% maximum theoretical efficiency. A class C operated amplifier can also be considered as an inverter. In this case, maximum theoretical efficiency is about 80%. But due to the cost, the power handling capacity and the volume, these circuits are no longer used as inverter circuits. For higher power, voltages and good efficiencies, only SCR's and transistors offer good inverter circuits. When cost factor is considered, transistors also are eliminated and only SCR's offer good inverter circuits. Transistors and tunnel-diode circuits are of particular importance when the power source has very small output voltage as from solar cells or chemical cells.

Any static inverter operating from a d-c source naturally produces square-wave output. There are some applications where square-wave output can be effectively used (as in induction motors). But in many applications, elimination of selected harmonics or all the harmonics is essential. Hence, a filter becomes an essential part for many inverter circuits.

A basic block diagram for an inverter is shown in Fig. 1. Some blocks can be eliminated in some applications. The input is assumed to be single-phase a-c which is rectified and filtered to give d-c voltage. Normally, a capacitor with large capacity is connected at the output terminal to give a stiff d-c source. Sometimes, a center tapped d-c supply is required. In this case, two such capacitors of same capacity are connected in series across the output. This d-c voltage is converted to three-phase a-c voltage by switching elements with the help of logic circuits and commutating circuits. This a-c voltage is a square-wave and can be filtered if necessary. A voltage control block is shown before the filter unit. Voltage control in an inverter can be achieved at three stages. (1) Input d-c level. (2) As an integral part of an inverter. (3) Output a-c level. In this chapter some blocks of an inverter are discussed. They may or may not be necessary, depending on the type of load.

2. Filters.

An inverter is basically a polarity reversing switch. To

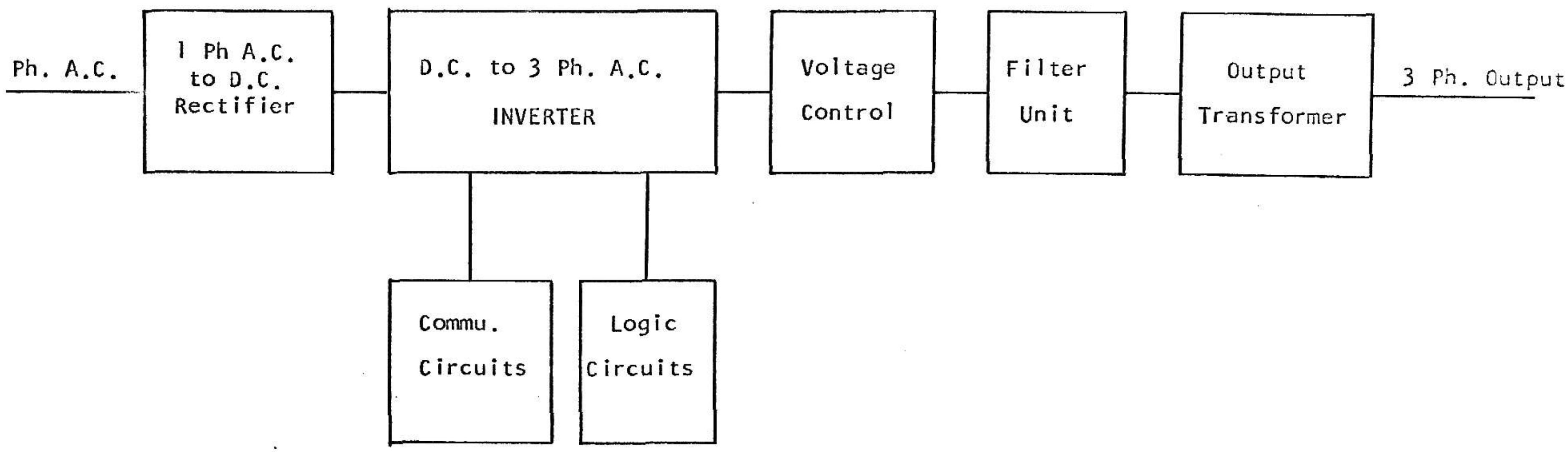


Fig. 1 Block Diagram for Inverter

provide sinusoidal voltages necessary to replace commercial power sources (alternators), a filter is essential in some applications. The type of filter chosen greatly affects the design of the inverter. It also has an effect on logic circuits, the number of power switching modules, the means of synchronization, and the voltage control system. Hence choosing a filter is a very important part of any inverter design. Three important types of filters are discussed below.

A ferro-resonant filter is most suitable for small sizes. It offers harmonic reduction of about 5%.[1] It offers good short circuit protection, input-output isolation and stabilized output voltage. It has the inherent disadvantage of voltage phase shift from input to output which varies with load. It also has large input current requirements on start up and large load changes. The capacity of the inverter driving the type of filter is roughly four times larger (with respect to commutating capacity) than that required by the load. The losses in this type of filter are very high due to the very high flux levels in core material. The loss contributes for higher cabinet temperature and lower unit efficiency. A balancing transformer is essential to a phantom neutral for three-phase three-wire loads. This prevents the unwanted output voltage oscillations. It can be concluded that ferro-resonant filters offer many advantages in smaller single-phase and three-phase inverter circuits, but in larger unit size, it is inefficient, expensive and creates voltage oscillations. The cost per kva of ferro-resonant filter is about $100/kva.

The stored energy filter is another type of filter that can be used with three-phase inverters. As implied by the name, the stored energy filter employs inductors and capacitors for filtering purposes. It is very effective at high frequencies because of the type of elements that are utilized for filtering purpose. The principal use of stored energy filter is to provide final filtering of the higher harmonics, which are not sufficiently reduced by a switching filter. (The switching type filter is discussed in the next paragraph.) The cost of static energy filter is also about $100/kva. (This can be expected because stored energy filter also employs similar elements as in a ferro-resonant filter.)

The third type of filter is the switching filter. It has many advantages over the ferro-resonant type and the stored energy type. The switching filter is again subdivided into multiple frequency type and phase shifted type. Multiple frequency type is again subdivided into multiple pulse and cascaded frequency types. The multiple pulse method is described by Bedford and Hoft[2] and by Turnbull.[3] It involves a very complicated logic circuit. It eliminates the selected harmonics, but the remaining harmonics generally have an increased amplitude.

Additional switching losses occur because of multiple pulses. Voltage symmetry is also a problem in multiple pulse method of filtering. The cascaded frequency method consists of subtraction of harmonics. Three or four (depending upon requirement on harmonic content) inverter stages are connected in series. The second inverter stage operates at three times the fundamental frequency. The third stage has five times the fundamental frequency and so on. When these inverter stages are connected in series, and when 2nd, 3rd, ... inverter stages are 180 defrees out of phase with main inverter, the output does not contain 3rd, 7th, ... harmonics (depending on the number of stages). A detailed analysis is given by Stuart P. Jackson.[1] The cascaded frequency method does not add to the capacity of the main inverter. Secondly, the amplitude of the harmonics, which is not eliminated by filtering, is not altered. With four inverters operating at different frequencies, the lowest harmonic present in the output is the 11th.

Phase shifting to reduce harmonic content of the output of the inverter is discussed by Bedford and Hoft,[2] Kernick, Roof and Heinrich,[4] and Kernick and Heinrich.[5] The basic technique involves producing a number of square waves displaced by a multiple of $2\pi/N$, where N is the number of inverter or output stages. The amplitude of each of the stages must be fixed relative to the others to obtain maximum harmonic reduction. Five inverter stages are required to produce a single phase 12-step output having a total harmonic content of 15%. The lowest harmonics are the 11th and 13th. To obtain the same waveform with three-phase output, six inverter stages are required. In the case of the phase shifting scheme, the output of the stages are added. This increases the output capacity of the inverter. Phase shifting method of filtering appears to be most suitable for large three-phase inverters. Whether to use six-power stages and a larger stored energy filter to reduce harmonic content from 15% to 5%, or to use 12-power stages and a smaller stored energy filter is dictated by cost and output capacity. In most cases number of stages is determined by output capacity rather than by filtering requirements, with a minimum of six inverter stages.

3. Voltage Control.

Voltage control is an important factor in inverter design. Many types of controls are possible. Again the type of filter and type of inverter also affect the voltage control. A mechanically operated tap on the output transformer can give satisfactory performance in some cases. Secondly, if the input to the inverter is single phase a.c., the d-c voltage can be controlled by changing tap on input transformer before rectifiers, by incorporating a saturable core reactor, by induction regulators, by magnetic amplifiers or by phase-controlled rectifiers.

In the case where the input is a d-c power source, the voltage supplied to the inverter can be controlled by transistor series or shunt regulators or semiconductor switching-type d-c voltage controls. The principal advantages of voltage-control schemes where the d-c inverter supply voltage is controlled are, (1) The inverter output voltage waveshapes and its harmonic contents are not significantly changed; (2) In certain applications, the principal reason for voltage-control is to compensate for source voltage fluctuations. The inverter can be designed for a very limited voltage range and hence can be more efficient and economical. The principal disadvantages of controlling the d-c voltage to an inverter are, (1) The commutation voltage in some inverters is proportional to d-c supply voltage. This makes the inverter current capability decrease as the d-c voltage is reduced. This creates difficulty in design of commutating circuits and generally involves higher circuit losses for satisfactory commutation. (2) The total power is handled twice. This involves more equipment than is required if the voltage control is made an integral part of the inverter itself. (3) Most d-c voltage control schemes require filtering in d-c circuit. This may cause slower response time.

Voltage control in inverters can be achieved internally by phase shifting. Phase shifting within the inverter involves two full capacity units whose relative phase is varied to change output voltage. This method offers poor utilization for the material unless the size of the inverter required the use of additional power switching devices.

Another method of voltage-control within inverter is multiple pulse width. Multiple pulse width has the same advantages as mentioned under filters. This method is very suitable if the number of power switching devices must be minimized. Pulse width modulation method of voltage-control is best suited for high capacity three-phase systems. It offers voltage control without increasing the number of power switching devices. Low-frequency harmonics are not re-introduced because of this method of voltage-control. The multiple pulse width method is uneconomical for general usage because of high switching losses and logic complexity.

In the case of parallel inverter, the commutating angle is approximately equal to the power factor of the a-c load. (This includes commutating capacitance output transformer and load.) With fixed d-c supply voltage the output voltage varies with commutating angle. Hence controlling the load power factor offers an excellent method of voltage control in this case. The load power factor can be changed by phase-controlling electric valves, using feedback rectifier circuits and using saturable reactors in shunt with the load. Normally, this method is suitable for applications requiring only small amount of voltage control.

When a large control range is required, the rating of the components used to provide the necessary control range may become excessive.

Inverter frequency may be varied to obtain voltage control. Normally, the frequency controlling element is the unijunction transistor oscillator (UJT) providing pulses for logic circuit. The frequency of UJT oscillator can be varied very easily by changing either resistor or capacitor value. This type of voltage control is only of use when the inverter output frequency need not be constant.

4. Commutation.

Commutation is the most important factor in any inverter circuit. The improvement of any inverter circuit is mainly improvement in its commutation method. While the transfer of current from one valve to another occurs naturally and automatically in a rectifier circuit, the accomplishment of current transfer from one valve to another is one of the basic problems of inversion process. The commutation involves following three important events. (1) The reduction of forward current to zero in the conducting valve. (2) The delay in application of forward voltage to this valve until it has regained its forward blocking capability. (3) The buildup of forward current in the second valve. A direct short circuit across the power source results if the commutation fails.

In earlier solid-state inverters, SCR was directly replaced for mercury arc rectifiers. This did not use the smaller turnoff time and lower forward voltage drop of SCR's effectively. The circuits utilizing this important and advantageous characteristics of SCR's were first described by McMurray and Shattuck.[6] A small value capacitor and a center tapped inductance is utilized in this circuit for commutation. This was in 1961.

During later years, most of the circuits described in literature use auxiliary SCR for commutation purposes. The auxiliary SCR is fired and it offers a better path for current. This charges a capacitor such that reverse voltage is impressed across the conducting SCR. As the cost of the SCR's is going down, and as it does not contribute greatly to the cost of an inverter, this method of commutation is becoming very attractive. This method greatly reduces the size of the capacitors and the inductors. Also, the voltage across the capacitor is greatly reduced in this method, making it more economical.

A. J. Humphrey's[7] paper describes various methods of commutation and tabulates advantages and drawbacks of each of them. In the bibliography references 61 through 65 give an extensive list of literature on inverter commutation.

5. Logic Circuits.

The logic circuits required to provide three-phase output can be very simple. It can be built with an UJT oscillator providing correct number of pulses (depends upon frequency), and a count by six ring counter. But the basic logic becomes very complex and involved when filtering and voltage-control functions are associated.

Whatever may be the complexity, the whole logic circuit package can be very much reduced in size and can be considerably economized by using modern techniques of medium scale integration. By means of medium scale integrated circuits (generally called MSI), circuits requiring extreme complexity and large number of components can be built very easily and economically.

A detailed discussion about logic circuits and description of various alternatives available is given by R. L. V. de Lima Mendes.[8]

CHAPTER 2

DEVELOPMENT OF INVERTER CIRCUITS

1. Introduction.

When the SCR was introduced, it was a direct replacement for mercury arc rectifiers and other thyristors, in inverter circuits. Since then the inverter circuits are constantly modified and improved. The commutation, voltage control, and filtering techniques have considerably improved over the years. Circuits are developed without use of any switching components. In this chapter all these circuits are presented. An effort is made to give a short description, the major advantages and drawbacks and important applications. In some cases experimental results as obtained by persons who have presented these circuits are also included. References are given where the detailed analysis and description of the circuits can be found.

2. SCR Inverter with Good Regulation.

This circuit is described by M. Lilienstein.[9] The block diagram is as shown in Fig. 2. The inverter described uses SCR's in conjunction with magnetic amplifiers, static devices having many advantages over the rotating machines.

The inverter operates from a 26 to 30 V d-c supply. It uses a Hartly oscillator producing 1200 pulses per second. The

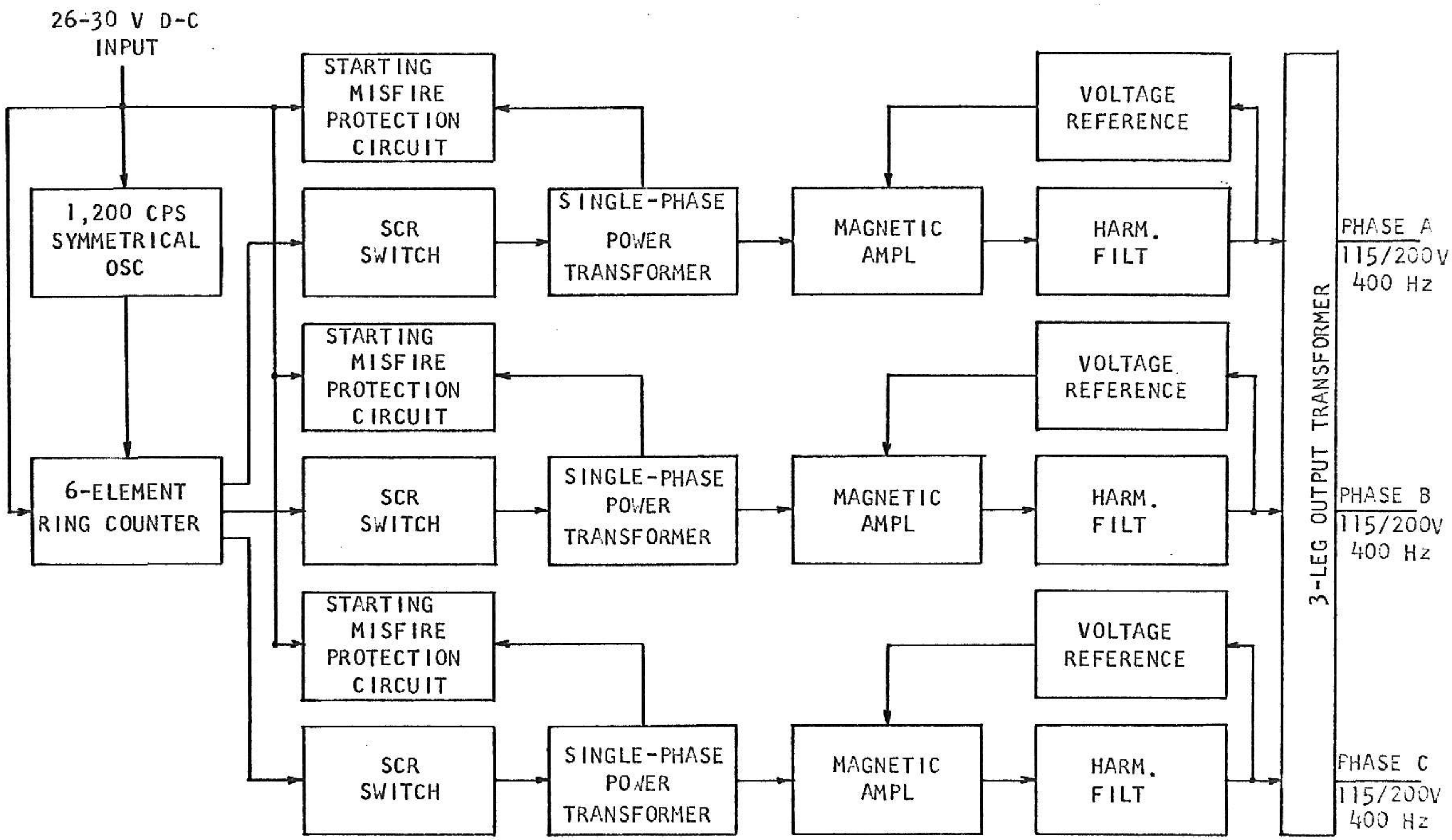


Fig. 2[9] (a) Three-Phase Silicon Controlled Rectifier Inverter.

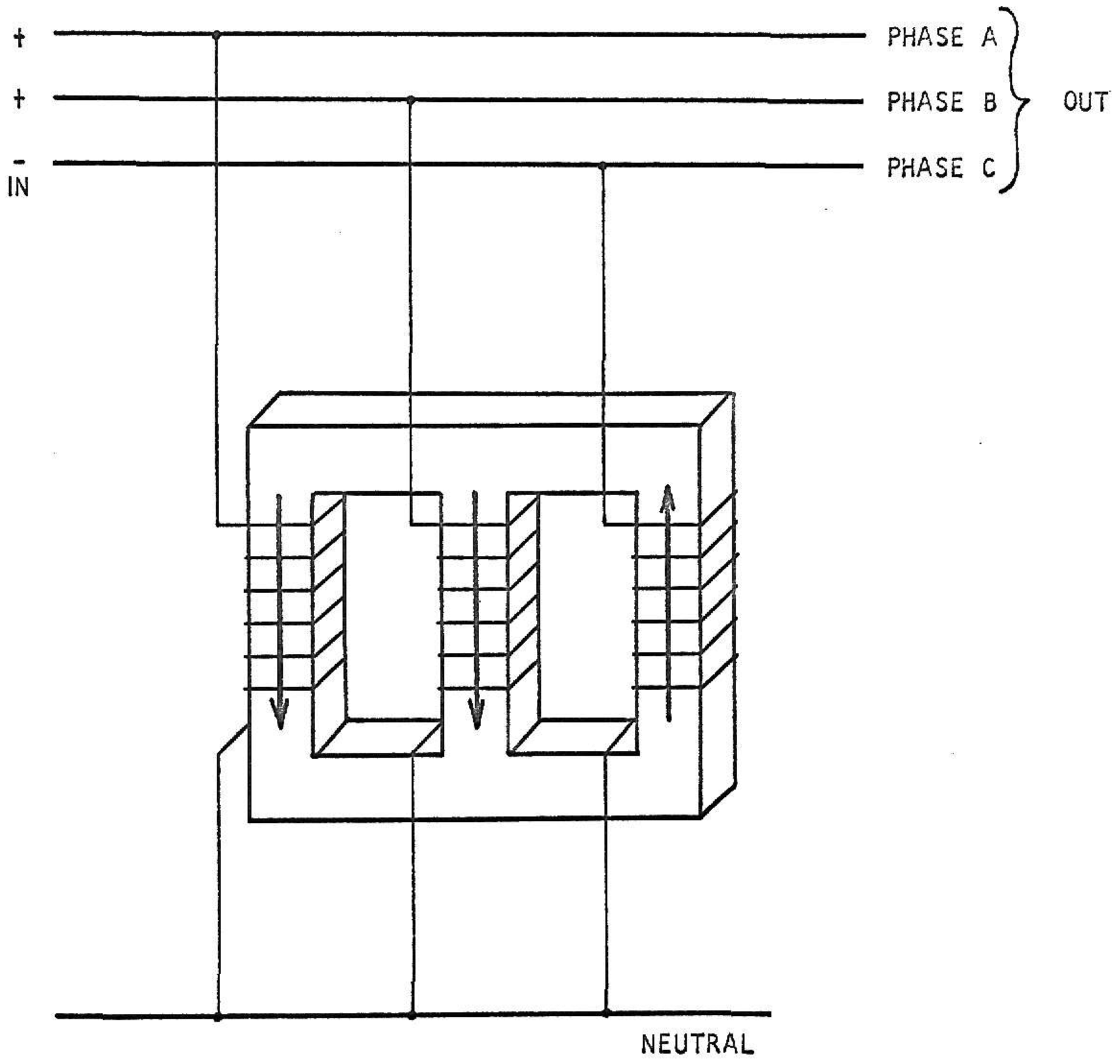


Fig. 2[9] (b) Three-Legged Autotransformer output of the inverter is 400 Hz 115/200 V three-phase a-c supply. The output parameters can be easily altered by changing frequency of oscillator and changing the single phase power transformer.

The d-c voltage is converted into square wave a-c voltages by SCR's. The square wave output of the SCR's is fed to the power transformer. The power transformer changes the voltage to the desired level. The circuit mainly consists of three single-phase switching units fired at proper time to produce three-phase output. The output of the power transformer is fed to the magnetic amplifier, which is used as a voltage control device. The output of the magnetic amplifier is fed to the harmonic filter, which eliminates the undesired harmonics. The output of harmonic filter is fed to the three-legged autotransformer. The three-legged autotransformer balances the phase difference to exactly 120 degrees. The load is connected to the output of the three-legged autotransformer.

The inverter is capable of handling reactive power. A tertiary winding is provided on the power transformer. In case of reactive load the power is fed back to the d-c supply through tertiary winding and full wave rectifier. The tertiary winding also gives a good short circuit protection. In case any SCR continues to conduct, the tertiary winding does not have any voltage. A relay is held through the tertiary winding and when the tertiary does not have any current, this relay drops, opening a contactor, which breaks the circuit and prevents any damage to the equipment.

By having three individually regulated phases, regulation is good over the entire load range and even on unbalanced loads. Magnetic amplifier acts as a reactive element, as a regulatory medium and therefore yields very high efficiency. The regulated output does not vary any more than between 115½ to 114 volts, except at 1½ times rated capacity. At this point the output voltage is 110 volts. The harmonic content can be kept as low as 2% from line to neutral, by combination of series and parallel tuned filters. The efficiency range is between 70% to 75% depending on the load, the input voltage and the power factor.

Though this inverter offers very good regulation and good waveform, the efficiency figure is very low, which makes the unit unpracticable. As the amount of power handled by the inverter increases, the total equipment and cost of the inverter becomes very high. This circuit is the first circuit described in literature for three-phase a-c power from a d-c source using SCR's, and hence has only academic importance as of today.

3. Inverter Using Saturable Core Transformer.

A circuit using transistors and saturable core transformers is described by Allan G. Lloyd.[10] The complete circuit for d.c. to three-phase a.c. inversion is as shown in Fig. 3. The

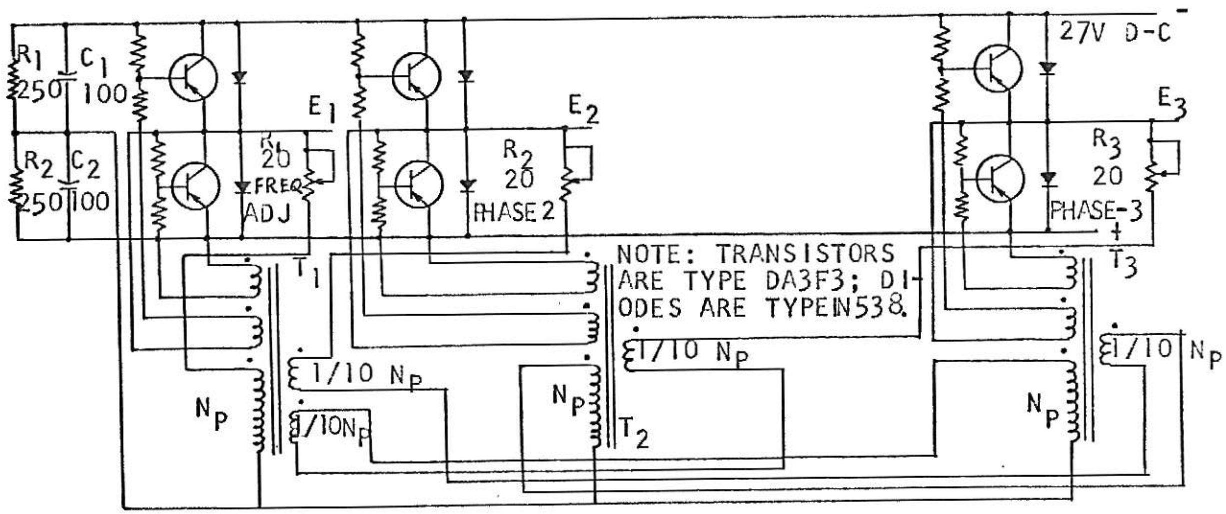
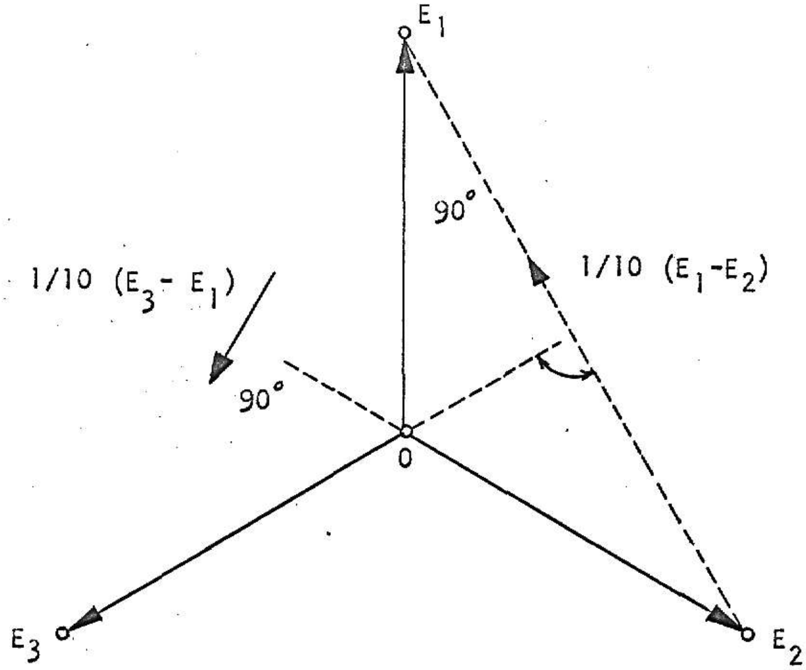


Fig. 3[10] (a) Self Excited Three-Phase Bridge Inverter.



(B)

Fig. 3[10] (b) Phase Diagram.

circuit operates in self-excited half-bridge inverter configuration. The circuit employs two transistors and a transformer per phase.

The phase diagram is as shown in Fig. 3b. It shows that 90-degree signal required to synchronize E_3 is derived from (E_1-E_2), while E_2 in turn is synchronized by (E_3-E_1). Two capacitors, (very high and equal in value), are connected in series across the d-c power supply. These capacitors are large in value and can be of electrolytic type for reasons of economy. This gives a center tapped stiff d-c power source. Each capacitor waveform is square and equals one half the primary current in any one of the switching transformers at three times the inverter frequency.

The variable resistor R_1 controls the frequency of the inverter. The variable resistors R_2 and R_3 are adjusted to obtain correct phase difference for E_2 and E_3.

Each base drive winding on transformer is wound for 2.5 to 3 V peak and the resistors in series with them are selected for proper drive current at the required collector current level in the two transistors. Switching of the current from on transistor to the other is caused by magnetic saturation of the transformer core material. The maximum voltage transistor is the d-c supply voltage.

The transformer can be connected in delta-delta. This eliminates all multiples of three harmonics. This greatly reduces the filtering requirement of the inverter as the lowest frequency to be handled by the filter is five times the supply frequency.

The circuit described above does not need any logic circuits and firing circuits. The circuit does not need any commutating circuits as well as starting circuits. These are the major advantages of this circuit over the others. This can be expected as transistors are used as switching elements. But it should be noted that transistors of equivalent voltage and current rating as SCR are very expensive compared to SCR's. Secondly, transistors are not available in very high ratings as SCR's. The input voltage is also restricted because the maximum voltage rating of transistors is low. All this means that the inverters using this circuit will have limited voltage and power handling capacity. Moreover, two large capacitors are required across the input to insure stiff source, which yields good waveform and proper circuit operation. As the power level increases, these capacitors will have to be of very high value and can be very expensive. This inverter circuit utilizes a saturable core transformer. This is a special type of transformer and has to be specially wound and hence can be expensive. All these factors make the circuit unpracticable today.

4. Inverter Using Saturable Core Reactors.

A single-phase to polyphase inverter using saturable core reactors and capacitors is described by F. Butler.[11] The device does not use any switching elements. This eliminates the need for logic circuits, commutating circuits, firing circuits and filtering requirements on the inverter.

The circuit operates on simple principle of circuit shown in Fig. 4. E_S is the single-phase supply voltage which is to be converted to three-phase voltage. A mesh connected, balanced, resistive load is assumed. The voltage across each phase is E_L, E_C and E_S. It can be shown very easily that E_L, E_C and E_S are exactly 120 degrees out of phase if and only if $LC = 1/\omega 2$ and $\omega L = R/\sqrt{3}$, where ω is angular frequency in radians per second, R is load resistance per phase in ohms, L is inductance in henrys and C is capacitance in Farads.

The inverter circuit is as shown in Fig. 5. The input is 400 V, 50 Hz single-phase supply while the output is 400 V, 50 Hz three-phase balanced supply.

The reactor frame in this inverter carries separate d-c and a-c coils. The construction is such that the two sets of windings are decoupled electromagnetically in such a way as to minimize the mutual inductance. The d-c windings are supplied through a bridge rectifier in series with a variable resistance.

The inverter can be employed to run a three-phase motor. The inverter is not capable of providing high starting current.

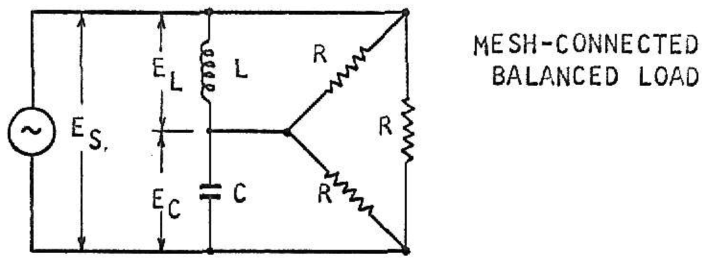


Fig. 4[11]
A Circuit Illustrating Principle of Inverter

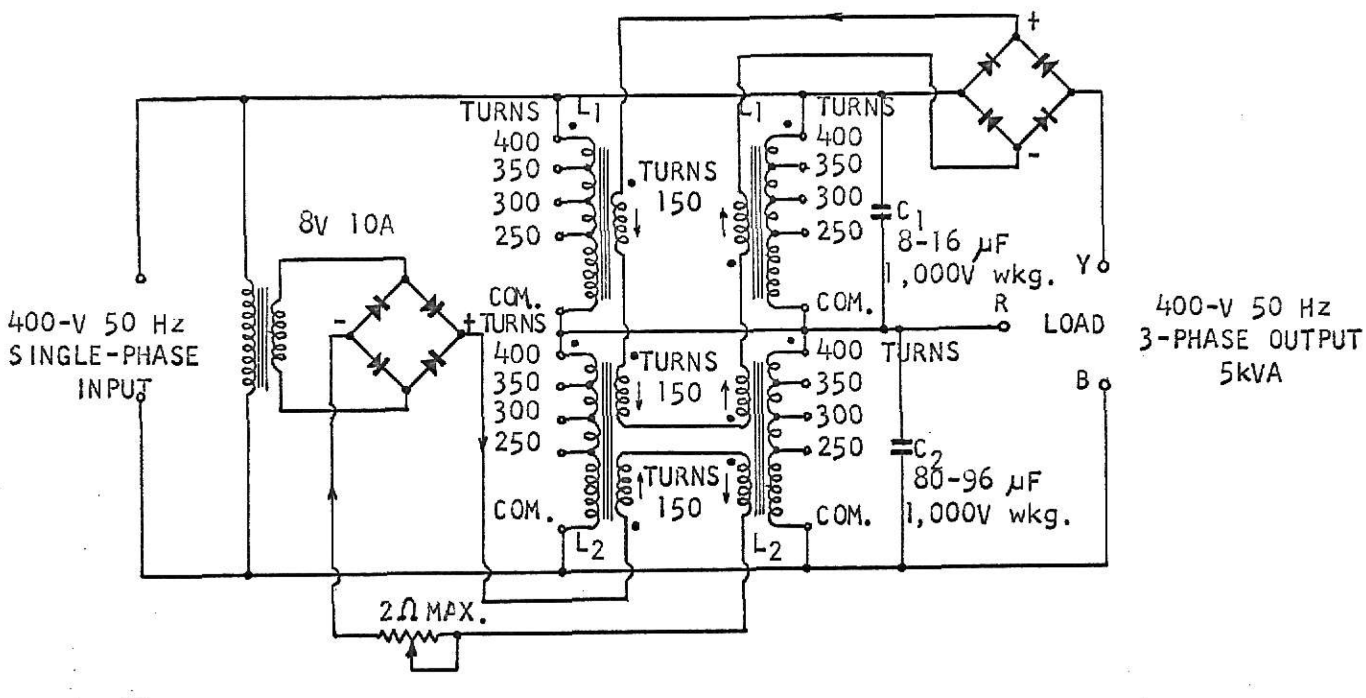


Fig. 5[11] Complete Diagram for the Inverter.

The open circuit voltage is about 5% higher than the full load voltage. The converter losses are attributed to iron and copper loss in reactors, rectifier loss and the energy dissipation in the d-c magnetization winding. The overall efficiency is of the order of 90%.

The major advantage of this inverter is that it is reversible. It can convert three-phase power to single phase. (This is required to supply heavy single-phase loads such as welding equipment.) The use of this inverter in reversed phase eliminates unbalancing of the three-phase mains supply.

This inverter utilizes specially built saturable core reactors. These can be very expensive. The inverter output frequency is exactly equal to the single-phase a-c supply frequency and hence does not offer any advantage in driving three-phase induction motors or synchronous motors for accurate speed control. The cost of this inverter becomes very high when the capacity is increased over 5 kva, but the efficiency and regulation does not improve beyond a certain point. This inverter is not capable of handling any unbalanced loads. Any unbalance in the load can cause the supply to be unbalanced. It is not possible to control each phase separately in this inverter.

All these factors make this inverter impracticable for inversion purposes. But this inverter circuit can be very useful if the requirement on the inverter is to operate from single-phase to three-phase as well as from three-phase to single-phase.

5. SCR Inverter with Improved Commutation

A SCR inverter with improved commutation is described by W. McMurray and D. P. Shattuck.[6] Several circuits are possible as suggested in the article and are shown in Fig. 6. The design is based on work by C. F. Wagner.[12,13] The symbol E is used for d-c supply voltage and the symbol I_{00} is for maximum value of the load current in Fig. 6. Also symbol C is the value of commutating capacitance and L is the commutating inductance. The required values of C and L are related to the values of C and L in circuit A. In circuits (C) and (D), the two halves of the primary winding of the output transformer are assumed to be tightly coupled. This may require special techniques, such as interleaving or bifilar winding. In circuits (A), (B), (E) and (F), coupling between the two halves of the center-tapped inductance is necessary.

Circuits (A) and (B) require center-tapped d-c supply. This can be easily achieved by connecting two large capacitors in series across the supply. (These capacitors can be of electrolytic type.) In case rectified single-phase a.c. is used, these capacitors can act as filters. Arrangement (C) is equivalent to parallel inverter with improved method of commutation. The parallel inverter can also exist in circuits shown in other

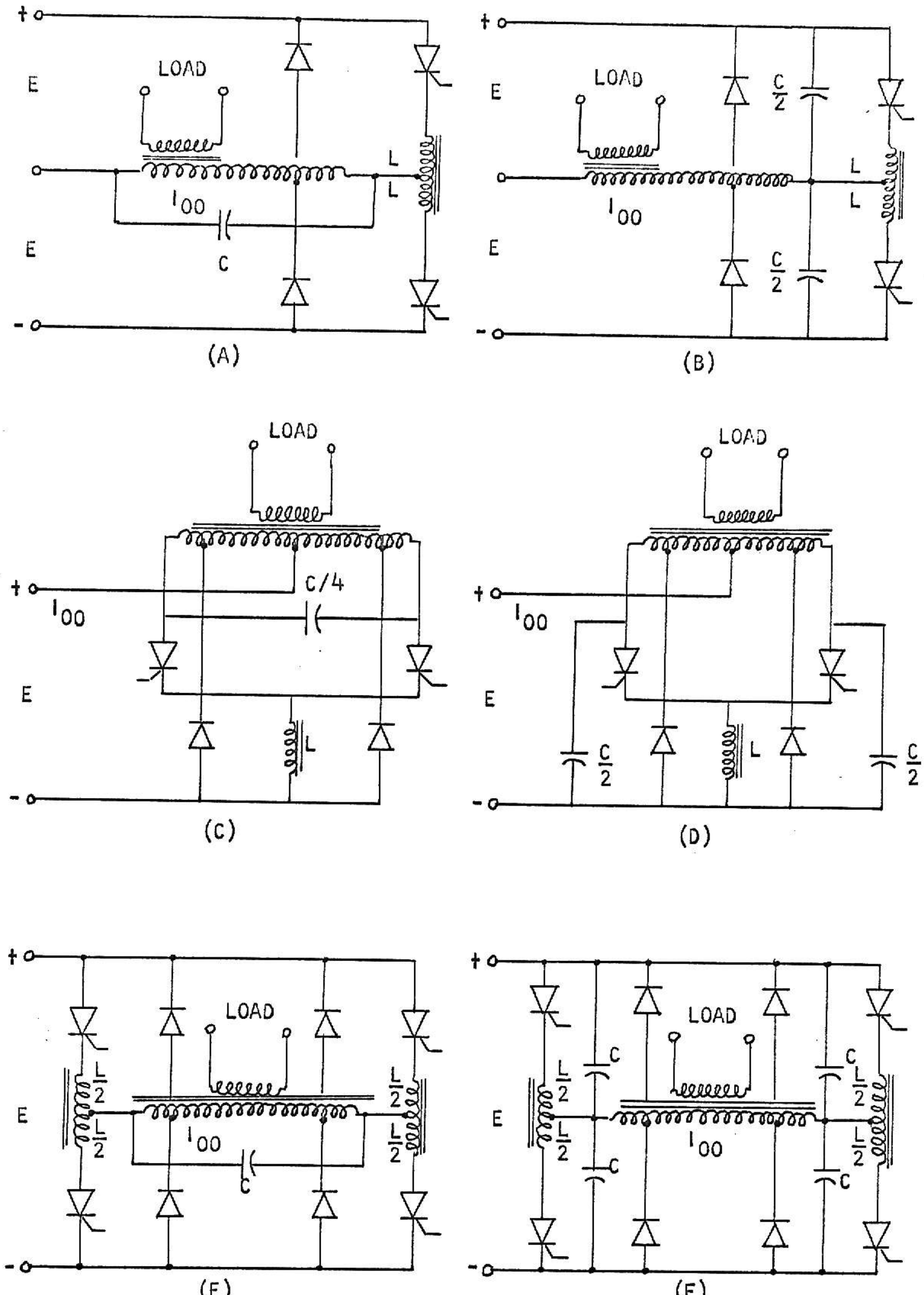


Fig. 6[6] Inverter Circuits with
Improved Mode of Commutation.

configurations. Circuits (E) and (F) are biphase versions of circuits (A) and (B) respectively, and do not require a center-tapped d-c supply. The inductance in each half of the bridge may or may not be coupled. In circuit (F), when the inductances are not coupled, the two halves of the bridge may be operated out of phase, enabling the load voltage to be controlled by pulse width modulation. All the circuits can be used as basic building blocks for polyphase inverter circuits.

The common feature of the improved mode of operation in these inverter circuits is the use of feedback rectifiers to return the reactive power associated with inductive or capacitive load to the d-c supply. When the load is capacitive, some of the energy drawn from the d-c supply during the first part of the half cycle of load voltage is temporarily stored in the load capacitance, and then fed back to the d-c supply through a feedback rectifier later in the same half cycle. When the load is inductive, energy stored in the load inductance during the latter part of the half cycle is returned to the d-c supply during the first part of the next half cycle. The feedback rectifiers are connected to tap rather than the end of the primary winding of the transformer. This enables the return of energy stored in inductance L just after commutation. This causes variation in output voltage with load power factor but the regulation is still better compared to the conventional parallel inverter and offers higher efficiency because of lower losses.

Provision of feedback rectifiers eliminates the need for large commutating capacitance and a large d-c choke. This is achieved because these elements are no longer required to store large energy for successful commutation. The commutation parameters are selected such that the energy W trapped in inductance L after commutation is minimum. This energy determines rating of the inductance and circuit losses because of imperfection in feeding back energy to the d-c supply.

A square-wave signal, which is positive when SCR is to conduct and negative when SCR is to hold off, is applied to the gate rather than short pulses. The presence of negative voltage on gate of SCR when it is to hold off avoids false firing due to transient or spurious pulses coupled in gating circuit. High current pulses flow through commutating capacitors. This requires care in selection of capacitors. Extended foil construction proves useful. A dynamically stiff source is essential in order to insure proper commutation and good waveform. This can be achieved by providing a large capacitor across d-c supply, which also works as a filter in case of single-phase a-c input voltages. This capacitor can be of electrolytic type and hence cheaper.

This circuit operates from no load to full load and with wide variation in power factor with good results. The commutating circuit performs satisfactorily on all power factors. The inverter efficiency is very high, of the order of 95% and more, at full load. The efficiency drops down to about 90% if the inverter is operated at higher frequency then desired. The efficiency and operation at lower frequency are better if commutation parameters are selected sufficiently large. This inverter has considerably reduced cost and size compared to inverters of same capacity described before.

The major drawback of this inverter is its regulation. The regulation becomes very bad if power factor goes down to about 0.7. This can create problems during starting of induction motors. Secondly, three separate single-phase supplies are combined in order to obtain a three-phase supply. This makes the unit more expensive and heavy compared to a single three-phase unit. But this also reduces cost for stand by supply. Moreover, inverters are designed lately with better regulation, commutation and efficiency which are more economical. But this circuit is a basic inverter circuit and a major breakthrough in design of inverters.

6. Three-phase Inverter with Feedback Loops.

A three-phase inverter with feedback loops has been described by Temple J. Gilliam.[14] This inverter has high efficiency, good regulation and is capable of giving balanced three-phase output even under heavily unbalanced load conditions. The circuit operates from a 30 V d-c supply as input and produces 400 Hz, three-phase balanced a-c output. The circuit utilizes solid-state logic circuits, which generate an exact three-phase square-wave signal. Each signal is amplified by a switching amplifier and then applied to the gate of SCR. At the output of SCR's, band-pass filters are connected. These filters eliminate the undesired harmonics. The output is balanced three phase and does not contain any undesired harmonics. There are two servo loops associated with each phase. One loop regulates the voltage variations for load and line. The voltage variations can be due to change in power factor, change in load, unbalance of the load or variation in supply voltage. The other loop helps to maintain exact phase difference between three phases in spite of heavy unbalance of the load.

The inverter has applications where good regulation and good balanced supply is essential. The inverter is capable of providing balanced supply in spite of heavy unbalance in the load. The price paid to achieve this is increased cost, weight and circuit complexity along with lowered efficiency. These are the major drawbacks of this inverter.

7. Inverter with Sinusoidal Output.

A true solid-state static inverter has been described by Robert H. Murphy.[15] The device can generate polyphase sinusoidal output without filtering and can be successfully used to generate three-phase power. This device uses SCR's in ring-counting circuits for polyphase sinewave synthesis. In this inverter, the current-inducing magnetic field is sequentially switched. Fig. 7 is the circuit diagram for this alternator.

The inverter circuit uses SCR's in ring-counting circuits for polyphase sinewave synthesis. The system is based on electronic analog of the conventional rotary alternator in which the current-inducing magnetic field is sequentially switched rather than mechanically rotated. Any electronic or mechanical rotary sequential switch can produce polyphase repetitive waveforms that closely approximate the sinusoidal across the diametrically opposite contacts. The circuit requires a special network geometry. The circuit can be viewed as a ring of RC differentiating networks on which the point of step function excitation is moved progressively around at a constant switching speed. There is only one optimum value of RC, depending on the triggering frequency, for a desired waveform.

The major advantage of this static alternator over the conventional inverter circuits is that it needs only one set of trigger pulses. The output transformer can be replaced by a three-phase induction motor, with center-tapped winding, thus saving in cost of the transformer and making the alternator more attractive. Secondly, the reverse voltage appearing across

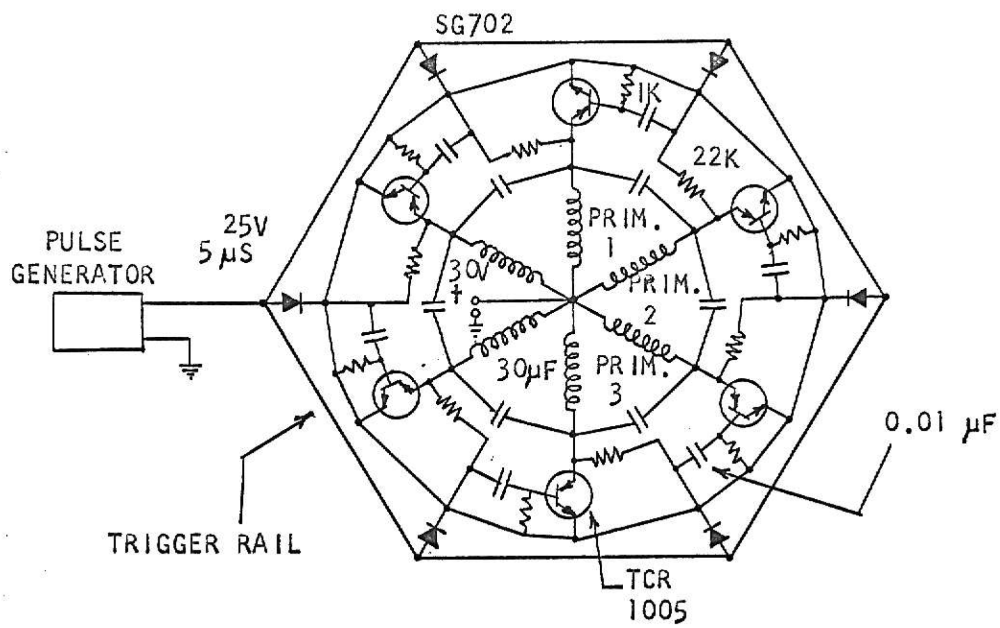


Fig. 7 [15] Solid-State Static Alternator.

SCR when they are not conducting is only about 0.5 times the supply voltage. This helps to lower the rating on reverse voltage on SCR resulting in some economy. In conventional inverters, the reverse voltage is about twice the supply voltage.

The major drawback of this inverter (alternator) is that it is unable to accept wide variation and unbalance of loads. The circuit given here is not capable of returning reactive power to the supply. The component values and the whole design changes with change of frequency and hence this alternator is useless for motor speed control.

8. Inverter Based on 'Voltano' Principle.

A single-phase to three-phase inverter is presented by K. Hisano, H. Kobayashi and T. Kobayashi.[16] This inverter design is based on previous device 'Voltano'[17] which is a voltage regulator. The voltano can also be used to produce three-phase power from single-phase source. But in applying voltano as an inverter circuit, the output capacity reduces to about 66%, the phase sequence of the output is indeterminate and efficiency is lower than 80%. The single-phase to three-phase inverter described by K. Hisano, H. Kobayashi and T. Kobayashi[16] overcomes these difficulties. It can produce more output power than voltano, but the price is paid in terms of variation in output voltage.

Fig. 8 shows the practical circuit for single-phase to

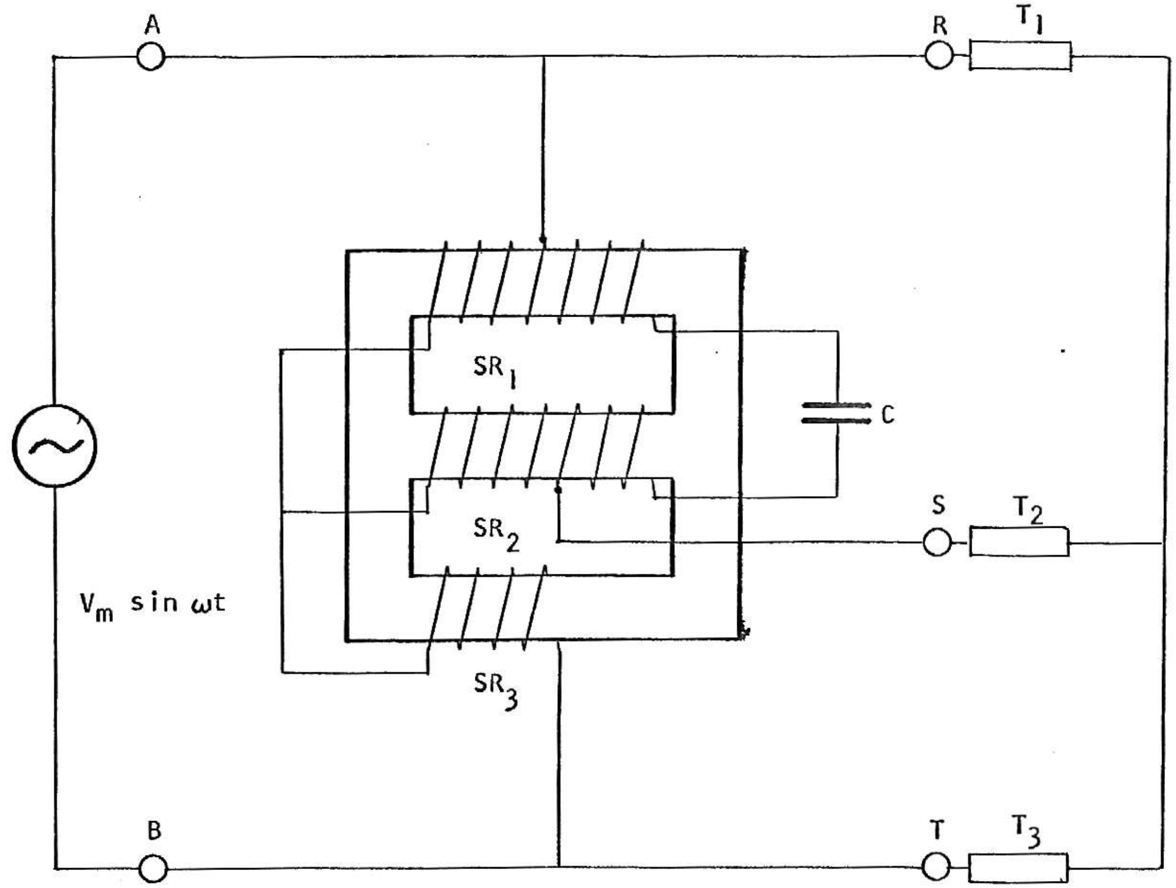


Fig. 8[16] Practical Circuit for Single-Phase to Three-Phase Inverter.

three-phase inverter. The SR is a three-phase saturable reactor whose windings are wound on a three-legged core. C is a capacitor which acts as a ferro-resonant capacitor. The linear reactors, which are part of voltano are absent in this circuit. The authors[16] present a graphical vector method by which circuit parameters can be obtained relatively easily. The mathematical analysis is very complex and gets involved.

The major advantage of the inverter is its simplicity of design. The inverter is capable of delivering balanced three-phase output with good regulation. The efficiency is of the order of 90% and higher. The device is considerably cheaper than other inverter circuits but its voltage regulation is its major drawback.

9. SCR Inverter with Auxiliary Commutation.

A SCR inverter with auxiliary commutation for a-c motor drive has been described by S. Miyairi and U. Tsunehiro.[18] The work is based on previous work of W. McMurray and D. P. Shattuck.[6] Any inverter for motor drive must be high in efficiency and have excellent stability. Secondly, the inverter should be able to handle wide variation of load changes and changes in power factor. For driving a-c motors (particularly of induction motor type), a square waveform with third harmonic eliminated from it is satisfactory.

Two separate commutation circuits, one for low frequency and one for high frequency, are described in complete detail by S. Miyairi and U. Tsunehiro.[18] The advantage of the circuit for low frequency is that the signal of the main circuit and the SCR require no modification. The major disadvantage is reduced efficiency due to voltage drop in series diodes. Some of the energy stored in reactors immediately after commutation will be dissipated partially in the SCR and the series diode. Additionally, if the commutation fails in the main circuit, the charging circuit also fails. These disadvantages make this circuit unsuitable for high capacity motors and operation at high frequencies.

The circuit for inverter with high frequency is shown in Fig. 9. The portion surrounded by solid line is the main inverter circuit. The gate signal of the SCR is same as the conventional one. The circuit for commutation of the main circuit is surrounded by dotted line.

The major advantages of this circuit are as follows. (1) In a three-phase inverter, when a fault occurs on one of the SCR, it can be easily separated from the circuit by means of a fuse. The rest of the circuit can be run as a single-phase inverter and can operate a motor on light loads. (2) The design is flexible and economical. (3) The inverter can be started or stopped by the gate signal of SCR without using switch in the main circuit.

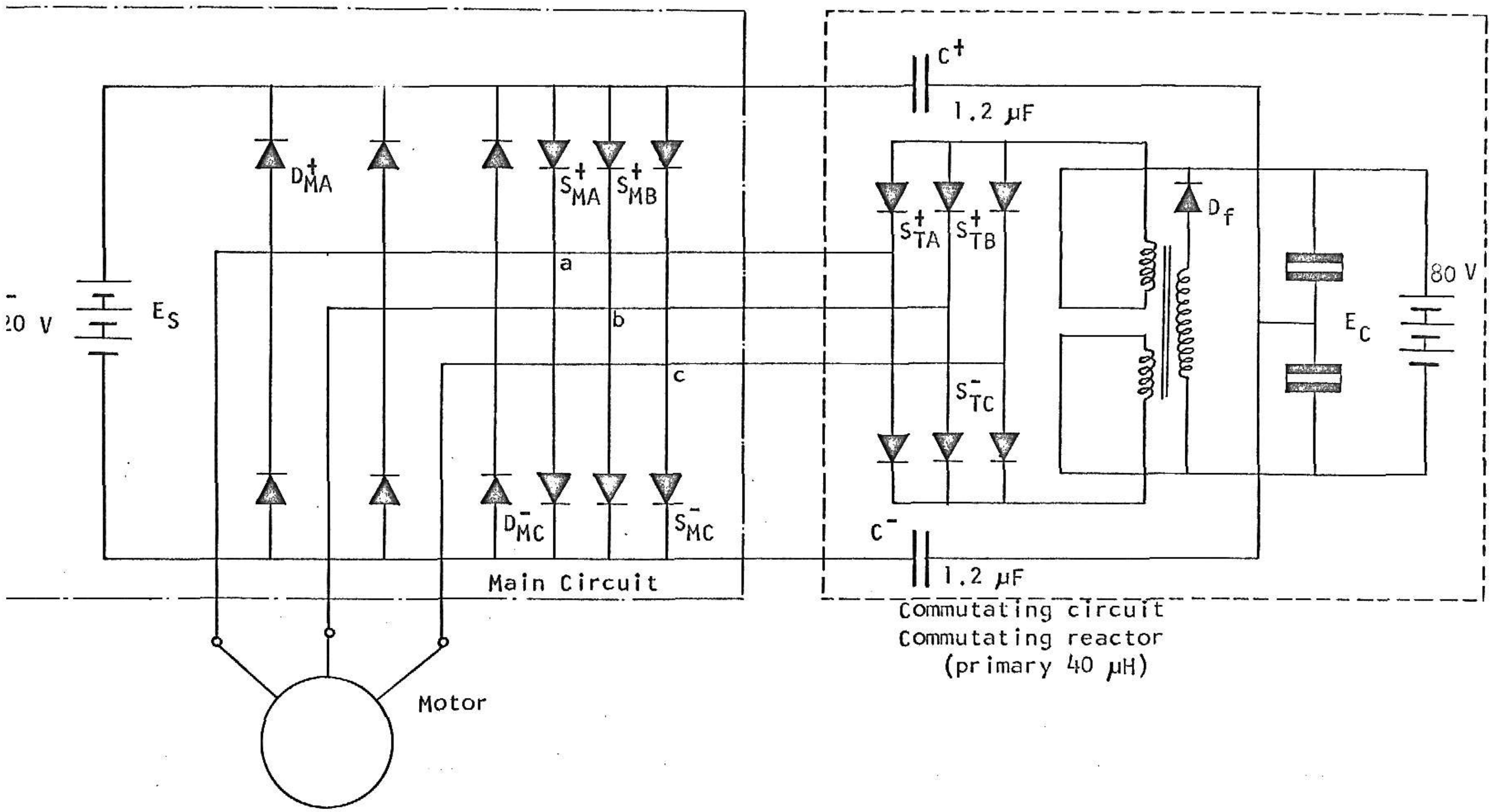


Fig. 9[18] Three-Phase Inverter with Auxiliary Commutation.

The drawbacks of this circuit are as follows. (1) The total number of elements in the circuit is considerably more than an inverter performing the same function. (2) The gate signal and logic is very complicated.

10. Inverter for A-C Motor Drive.

Another single-phase to three-phase inverter for a-c motor drive using a new commutation method is described by S. Nonaka and H. Okada. A circuit is presented with new commutation method and its modification which makes it capable of controlling the conduction angle of SCR. The circuit is designed to control the charging of each of the commutating capacitors in the bridge-type three-phase SCR inverter, and discharge during commutation, using a silicon rectifier and a SCR in parallel with reverse polarity. The inverter waveforms are controlled by controlling the gate signal to the commutation SCR.

The modified circuit is as shown in Fig. 10. The gating signals are as shown in Fig. 11. The losses in this inverter consist of loss in SCR,charging and discharging losses of commutating capacitors, iron and copper loss of commutation circuit elements, gate circuit losses and others. The loss in SCR and diodes increases considerably with load current. The switching loss is proportional to frequency, and loss in commutation circuit elements is proportional to load current. The gate circuit loss is constant and negligible. The losses may go high if the

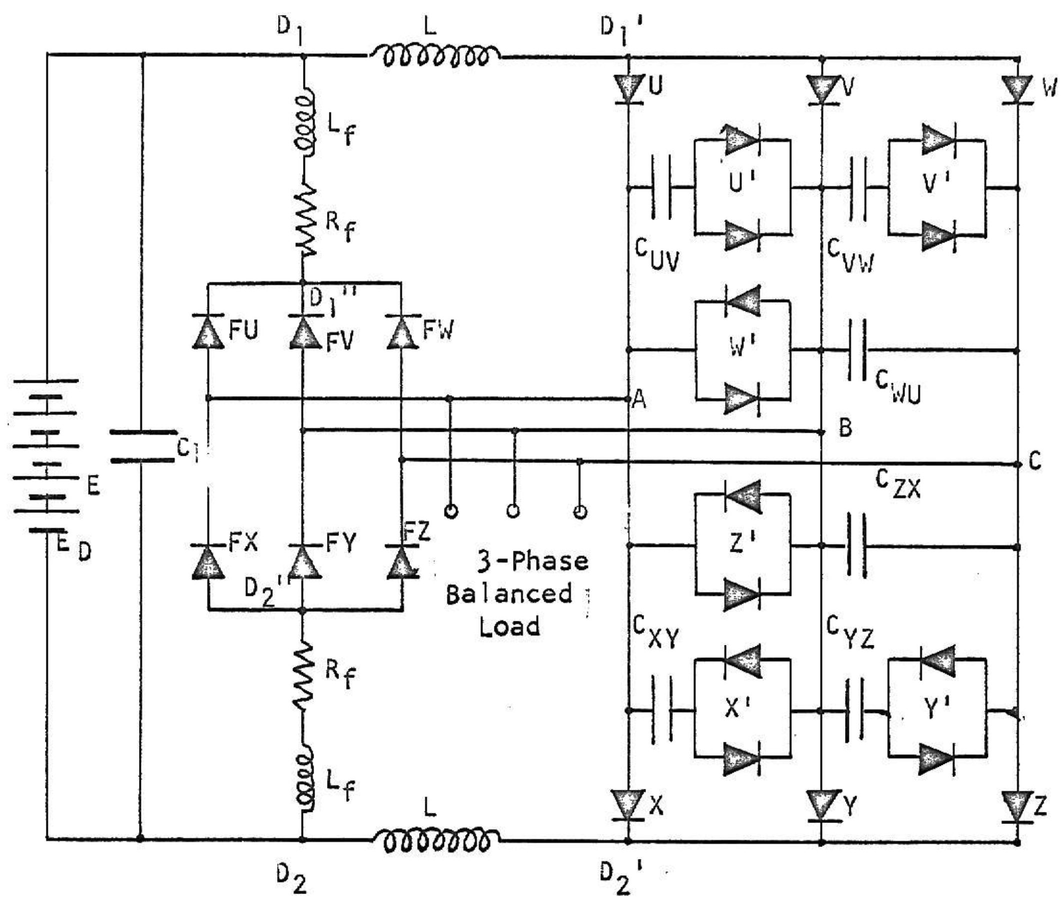


Fig. 10[20] Complete Inverter Circuit.

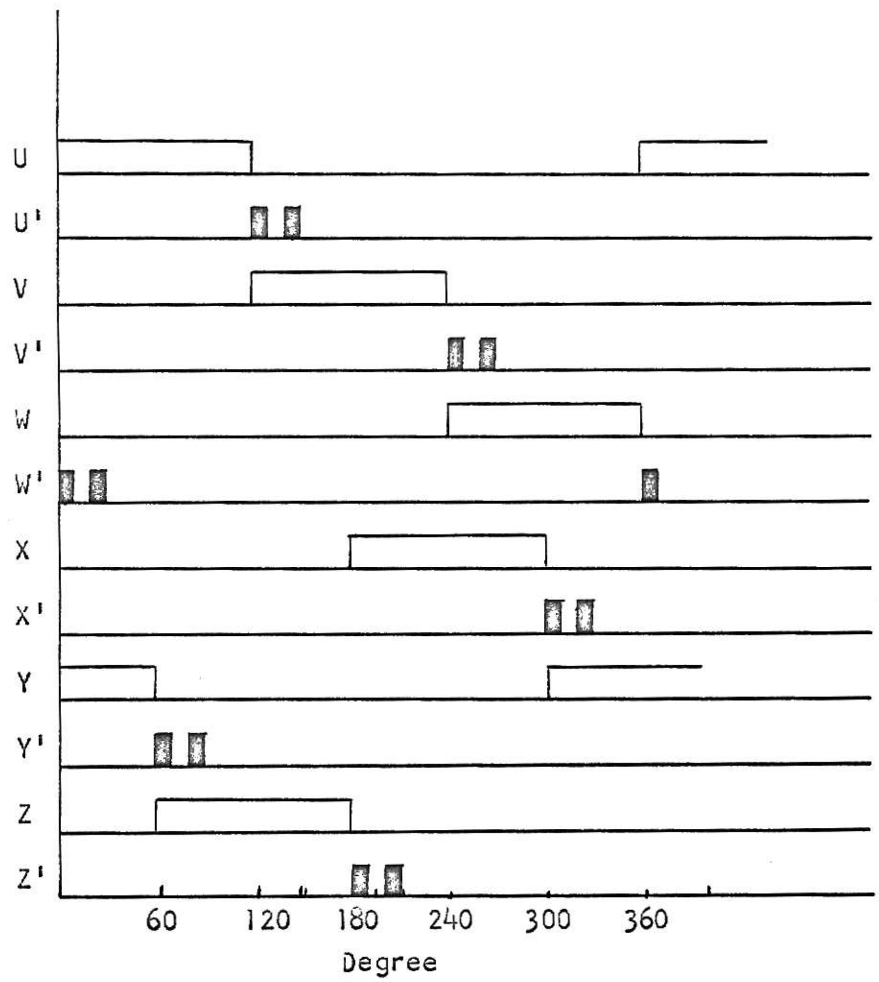


Fig. 11[20] Gating Signals.

harmonic contents are high. In spite of all these losses, the efficiency of the inverter is about 90% and more. The efficiency is very high from about 10% of the rated capacity, and remains high for a large variation of the load. The inverter is capable of supplying reactive power, is stable over a wide range of load variations and load power factor variations.

This inverter circuit can be employed with great advantage to drive medium size induction machines. This inverter circuit is not suitable for driving a synchronous machine, because synchronous machine exhibits hunting tendency on starting with this inverter supply. This is due to the discontinuity of phase rotation.[23] This appears to be the drawback of this circuit. Also there is no way of controlling voltage of this type of inverter. No filtering method is suggested.

11. A Variable Frequency Inverter.

A three-phase variable frequency inverter is described by K. Y. G. Li.[21] The inverter is capable of controlling output voltage by an on-off method. The commutation circuit is simple, and is so arranged that the inverter output voltages are independent of load condition. The triggering circuit and protection circuits are also devised. The inverter operates at about 90% efficiency.

Fig. 12 shows the complete inverter circuit and Fig. 13 shows the SCR conduction sequence. Fig. 13 also shows the line

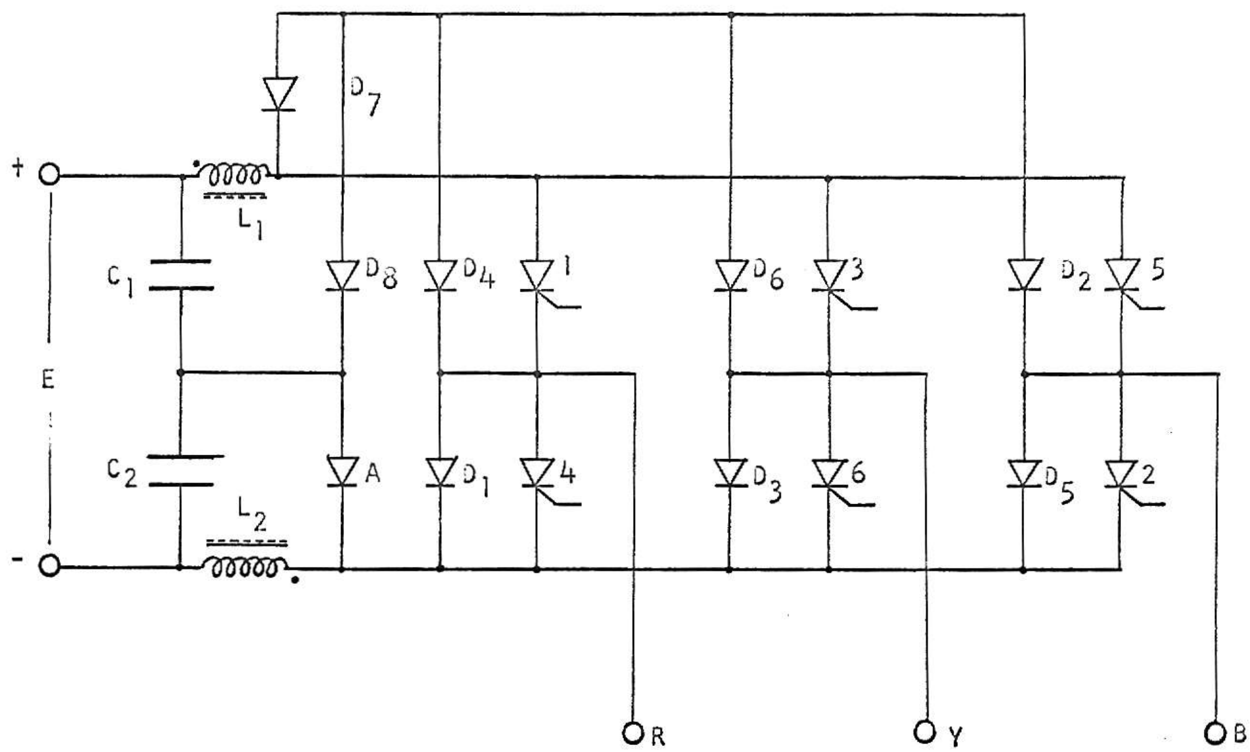


Fig. 12 [21] Complete Inverter Circuit.

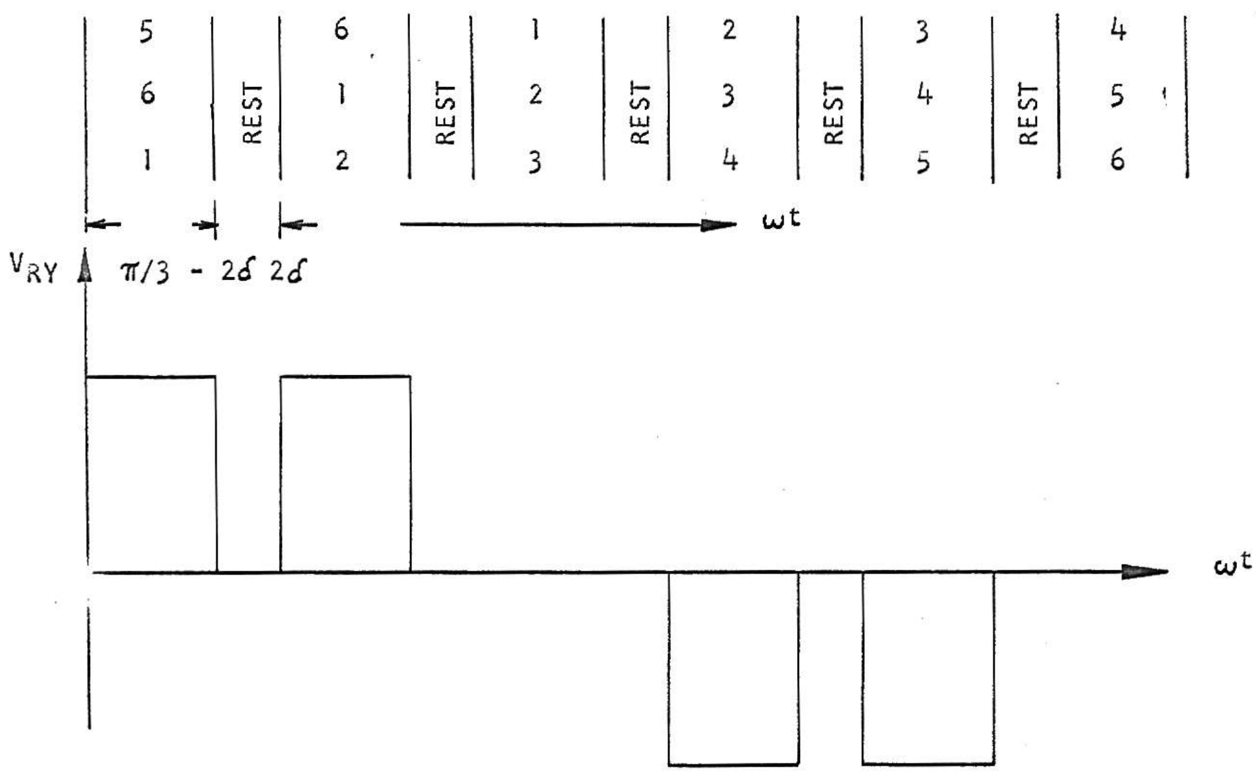


Fig. 13 [21] SCR Conducting Sequence.

voltage output waveform. The angle 'δ' as indicated in Fig. 13 controls the output voltage of the inverter. It can also be shown that all even harmonics and multiples of third harmonic are totally eliminated from output waveform by this configuration. But the remaining harmonics have increased amplitude.

The inversion is accomplished by SCR's in their natural firing order. The SCR's are arranged in conventional bridge circuit. It can be easily seen from Fig. 12 that three SCR's are fired at a time. Six steps (one step means firing a set of three SCR's), are required to complete a cycle. When changing from one state to another, there is a gap equivalent to angular period 2δ, where δ is the control angle. During this angular period 2δ, all the inversion SCR's are in nonconducting state. During this interval, only one commutating SCR, SCR A, is fired and is conducting. This SCR completes a free-wheeling path with diode D through D_6. This insures zero output voltage during rest period.

The logic circuit for this inverter is complicated. It uses a UJT oscillator producing a correct number of pulses per second. This is fed to an adjustable delay circuit and through an output unit to the commutating thyristor A. All the inversion SCR's are connected through an adjustable output unit, the ring counter and adder circuit.

The advantage of this inverter is its voltage control. The commutation circuit is simple and involves only one additional SCR. The output voltage is independent of load. All the six SCR's use the same commutating circuit.

The disadvantage of this inverter circuit is the increase in amplitude of the harmonics that are not eliminated (5th, 7th, 11th, and so on) and an additional SCR for commutation. Also, the logic is very complicated.

CHAPTER 3

APPLICATIONS AND FUTURE SCOPE

1. Advantages of Inverter Circuits.

Basically, the inverter circuits have many advantages. The inverters can be designed to operate from a d-c source or single-phase a-c source. The frequency range of operation of inverters is very wide and the units are designed to operate from a few cycles per seconds to hundreds of kilocycles per seconds. The inverter frequency can be adjusted very accurately because of improved logic circuits. An excellent voltage control scheme can be devised for inverters, relatively easily. The voltage can be maintained nearly constant over a wide load range, sudden variation in load and load power factor, and change of frequency. The voltage control also overcomes the problem of d-c source voltage variations or a-c supply voltage variations. The inverter units have a very wide range in terms of frequency, voltage and kva ratings. The reliability of inverter systems has been good and will keep on improving as more and more units are built and more experience is gained. The inverter systems exhibited stability problem when self-excited synchronous motor load was connected to them.[22] The motors that worked satisfactorily when supplied by motor generator set exhibited hunting of their rotors about their mean angular velocity. For this purpose inverter output impedence must be properly matched to the load.

During a power supply voltage dip, a motor-generator set will slow down; and output frequency will fall below the rated frequency. An inverter usually has a large input capacitance and will perform better in such instances. The inverter installations are very flexible. Voltage or frequency can often be changed without or with little additional cost. Changes in kva ratings and other modifications in inverter systems are relatively simple and less expensive compared to rotating machine systems. The inverter systems are relatively easy to install and can be installed much faster and are cheaper than rotary machines. They do not need much consideration for foundation beds or vibrations. The cooling requirements are also lower than rotary machines because of higher efficiency. The inverters do not have any moving parts and hence need very little maintenance.

All the above mentioned advantages make the inverter systems very attractive for many applications. All the possibilities of inverter applications are listed in the next part of this chapter.

2. Applications.

In an aircraft, need exists for an efficient method of d.c.

to a.c. power inversion. In this case a sinusoidal waveform is necessary. The inverters make a very strong case for them because of their reliability, ruggedness and need for only very little maintenance.

An a-c motor can operate for a very long time without any maintenance. A d-c motor has the advantage of variable speed, directional control and good torque. An induction motor operated by a variable frequency inverter system meets both these requirements. It combines the maintenance-free feature of a-c machines with the excellent speed control of d-c machines.

A variable frequency inverter supplying a synchronous motor gives a system where very accurate speed control is possible.

An inverter is particularly advantageous in applications where the inherent square-wave output of inverter is required or can be tolerated.

The inverter systems are very useful to small laboratories and small workshops. Normally, due to low load level, such installations get a single-phase supply. Many electrical appliances need three-phase a.c. In such cases, inverters are ideally suited. The inverters can also improve the power-factor of the installations because they operate almost at unity power factor.

The static inverter systems are replacing most of the rotary converters because of the advantages listed. It is successfully used in motor vehicles, boats, submarines and other mobile equipment.

3. Future Scope.

The range of three-phase inverter units is going higher and higher. It is also possible to operate several units in parallel provided their waveforms, output voltage and phase sequence are matched. Many units are utilized in industry of over 100 kva range and are commercially available. Efficiency and other performance of inverters are constantly improving, and most of the problems associated with them are either solved or are no longer out of reach. Hence, at present it looks like inverters will replace all d-c motor-alternator sets in the industry and completely dominate the field.

As the voltage and current ratings on SCR keep on rising and they become quite cheap, it will be possible to have high voltage d-c transmission. The d-c transmission has many inherent advantages over a-c transmission such as better efficiency, regulation, cost and no interference with communications lines. Terminal equipment consisting of inverter sets will be utilized to produce a three-phase supply wherever necessary. Secondly, distribution need not be three-phase. Any unit not requiring large amounts of power can be supplied with single-phase power, which is more economical, and an inverter set. When an inverter is used, it supplies all the reactive power of the load. In this way, the supply power factor can be kept very close to unity.

Another important application for inverters is converting energy of small fuel cells, solar cells and other sources, which generate small d-c voltages and can either give considerable power or are available in large numbers. A tunnel-diode of transistor d-c to d-c inverter can convert this power to 26 to 30 V d-c level. Then an inverter can be successfully employed to obtain a three-phase power.

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THREE PHASE SOLID STATE INVERTERS

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AN ABSTRACT OF A MASTER'S REPORT

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Electrical Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1970

Approved by:

W. W. Koepsel
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ABSTRACT

The single-phase to three-phase inverters are finding themselves increasingly used in industry. A study of the different parts of the inverters and inverter units was made.

First, the different units of an inverter circuit are discussed in detail, with the help of the inverter circuit block diagram. The second chapter presents a study and comparison of ten different types of inverters in use; some of them use switching elements and others use reactors. The switching elements used are semi-conductor rectifiers (SCR's) or transistors. The order in which the circuits are discussed is chronologically arranged, the most recent one to be developed appearing last. In the third chapter, the advantages of the inverter circuits, their important applications and their future scope are considered.

It is observed that the three-phase inverters are constantly being improved and their short-comings are progressively being eliminated. Their inherent advantages find them increasing applications. It can be said with reasonable certainty that in the future all single-phase to three-phase conversion and d-c to a-c three-phase conversion will be taken over by Three-phase Solid-state Inverters.