

CHAPTER THREE

DESIGN OF DYNAMIC REACTIVE POWER COMPENSATOR

3.1 INTRODUCTION

This attempts to raise the capabilities of Voltage Source Converters (VSCs), which have been presented in the previous chapter gives directions to improve the converter performance with the help of configurations, converter input voltage waveforms, by carefully evaluating and using the harmonic elimination and current control techniques with optimal utilization of new generation power devices and control electronics. Further combination of power devices getting switched at the frequency much higher than the supply voltage frequency, with the controller operating at logic voltage levels of few volts (typically 5V/3.3V) in MHz or higher clocks, forces the designer with additional challenges. The chapter describes the fundamentals of Reactive Power Compensation (RPC) in the initial part and then gives details of different traditional RPC methods. This is then followed by the detailed design of single-phase and three-phase dynamic reactive power compensator (STATCON) for Low Voltage (LV) applications using selected VSC topologies. Subsequent sections then highlight key innovations implemented for achieving the necessary dynamic reactive power compensation. At the end field performance results of designed compensator in actual applications are presented.

3.2 REACTIVE POWER COMPENSATION

Most of the linear and non-linear loads tend to draw reactive power apart from active power required by these loads. The reactive power drawn can substantially change the load supplied voltage due to presence of network short circuit impedance. In weak network, hence the load applied voltage varies due to reactive power drawn. The voltage fluctuates severely if the load dynamically varies. Few popular analogies for explaining reactive power are described in ref. [217].

Typically, when the load current is inductive (lagging power factor), capacitive compensation is needed. Similarly, when load current is capacitive (leading power factor), inductive compensation is needed. The basic vector diagram for capacitive and inductive compensation is shown in the fig. 3.1 below.

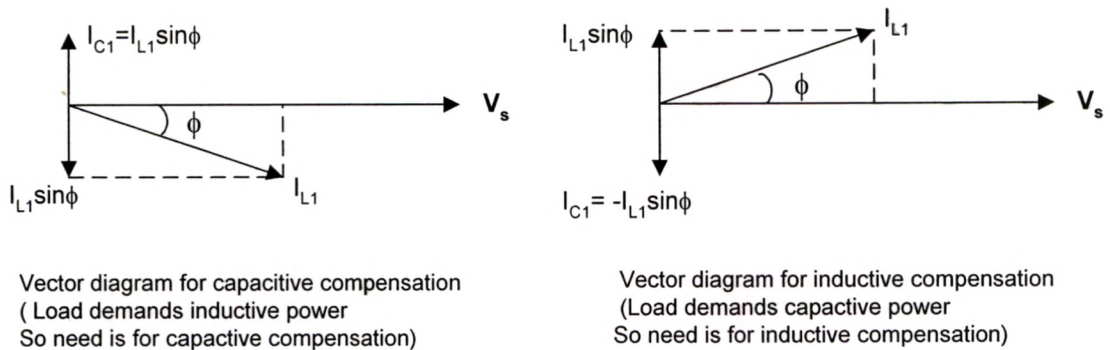
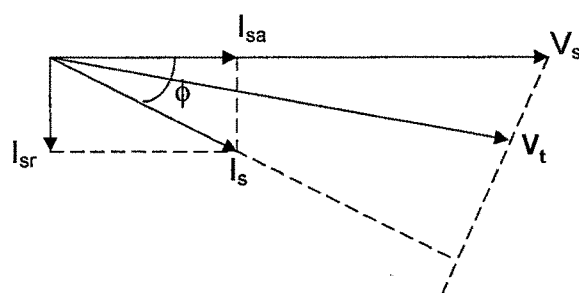
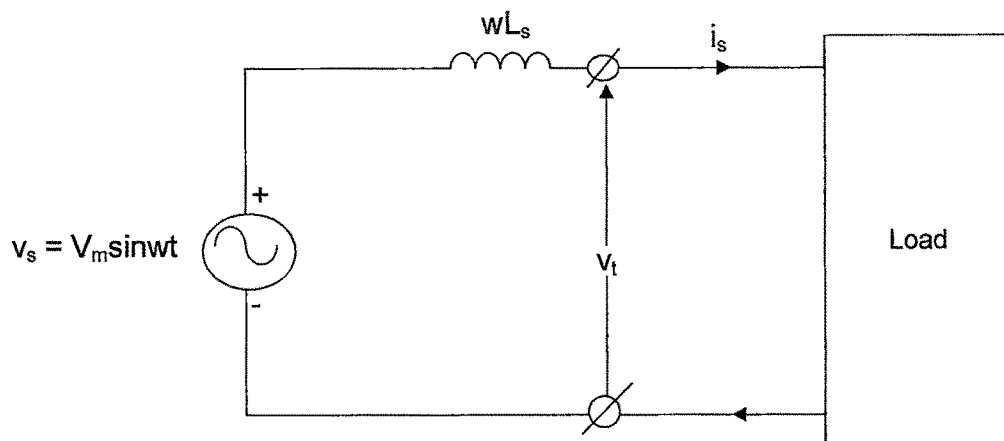


Fig. 3.1 Vector diagram for Capacitive and Inductive compensation

3.2.1 FUNDAMENTALS OF REACTIVE POWER COMPENSATION

Fig. 3.2(a) shows a simple circuit diagram where the load is drawing a fundamental current i_s at a lagging power factor angle " ϕ ". The active component of the current i_s is designated as i_{sa} and the reactive component is designated as i_{sr} . The terminal voltage v_t is also shown in the figure. It lags the supply voltage v_s and has value less than the supply voltage. Based on the short circuit impedance wL_s , the maximum value of the current i_s and the power factor angle " ϕ ", the terminal voltage v_t will assume a locus as shown in fig. 3.2(b). It is clear from the figure that the unwanted reactive power component i_{sr} increases the magnitude of the supply current i_s . This will mean increased losses in the system (transformer and cable losses) and also more kWh consumed by the system. The reactive power drawn by the system decides the instantaneous as well as the average power factor. From economics point of view, it also decides the electricity charges to be paid to the utility. Typically for industrial consumer, if the power factor is below 0.85, the penalty offered by the utility rises sharply. If it is maintained beyond 0.95, the utility offers an incentive to the consumer in many cases. Thus, there is a need to improve the average power factor beyond 0.95.



(a) Source voltage supplying current i_s at lagging power factor ϕ

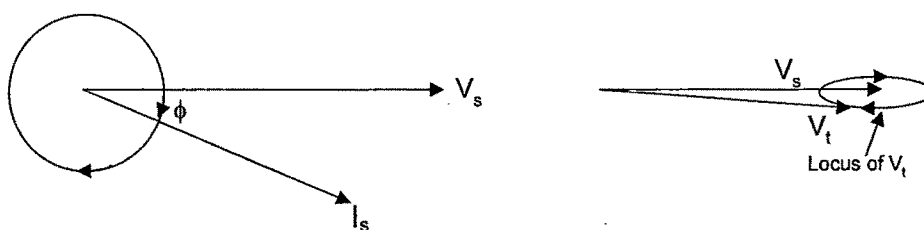


Fig. 3.2 Variation in terminal voltage V_t with supply current i_s at 360° power angle range

Further, a fast fluctuation of the voltage will give rise to flicker in the supply voltage and will perhaps result in mal-operation of other electronic equipment connected on the same supply bus. Such a fast fluctuation is expected because of dynamics associated with many loads as described earlier. The reactive power compensation is hence a major issue for utilities as well as consumers and hence needs to be resolved on the basis of actual dynamics of the load. Apart from voltage fluctuations, reactive power also causes increased power loss in the systems and networks.

Ideally, load reactive power demand should be met dynamically on a continuous basis, so that the supply power factor is maintained close to unity. This brings down losses in the transformers, cables, and transmission lines. Over a period of time, the load dynamics has changed substantially. Load complexities, associated controls, network complexities, and network conditions (especially weak networks) have also undergone considerable changes and become more and more demanding while employing the reactive power compensation. Reliable and tandem working of the compensating equipment without degrading the Power Quality and affecting the performance of other equipment connected on the same network has also become an issue of concern. The network / supply has a limited short circuit capacity at any given coupling point and compensating equipment has to account for it to avoid resonance, amplification of system harmonics, and voltage transients on the supply bus.

In line with the increasing complexity in the networks working with dynamic loads, the reactive power compensation methods also have seen technology based methods which have primarily been evolved in line with the changing needs [218-221].

In terms of topology there have been two approaches for compensation:

- Shunt compensation
- Series compensation

3.2.1.1 SHUNT COMPENSATION

With the help of shunt compensation, the voltage drop over long lines can be kept down to a reasonable level and voltage variations due to the load on the line varying during the day and during the year can be kept within reasonable limits. Some additional attributes for the same are,

- Sudden over voltages can be damped.
- Voltage collapses can be prevented.
- Lack of symmetry between the phases can be compensated.
- Local networks can cope with their local disturbances resulting from industries and network faults.

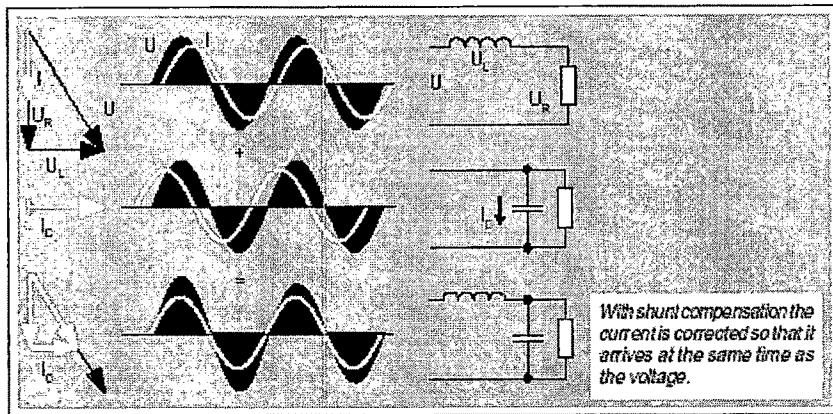


Fig. 3.3 Shunt Compensation

3.2.1.2 SERIES COMPENSATION

With the help of Series compensation, the need to add reactive power is reduced. Some other additional advantages includes,

- The risk that generators and other synchronous machines loose synchronism in the event of a serious short circuit is reduced.
- The route of electric power into a transmission network is controlled.

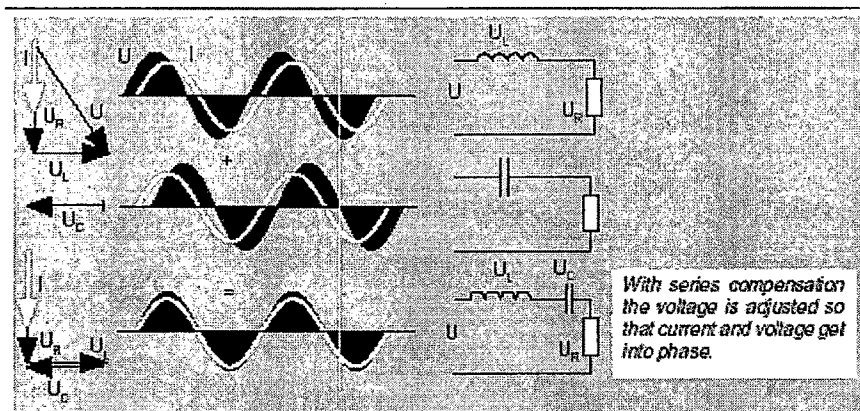


Fig. 3.4 Series Compensation

Further, focus is maintained on shunt reactive power compensation methods.

3.3 TRADITIONAL REACTIVE POWER COMPENSATION METHODS

Traditional reactive power compensations methods are as below

1. Fixed Capacitor (FC)
2. Automatic Power Factor Correction (APFC)
3. Thyristor Switched Capacitor (TSC)

4. Thyristor Controlled Reactor (TCR)

These traditional methods make use of passive elements (capacitor and inductor). Naturally, the component selection is dependent on the network short circuit capacity at the coupling point. They suffer from one or more disadvantages, such as resonance with supply short circuit impedance, voltage transients produced during switching, and poor response time. Listed below are some of the major disadvantages of the above four methods.

3.3.1 FIXED CAPACITOR (FC)

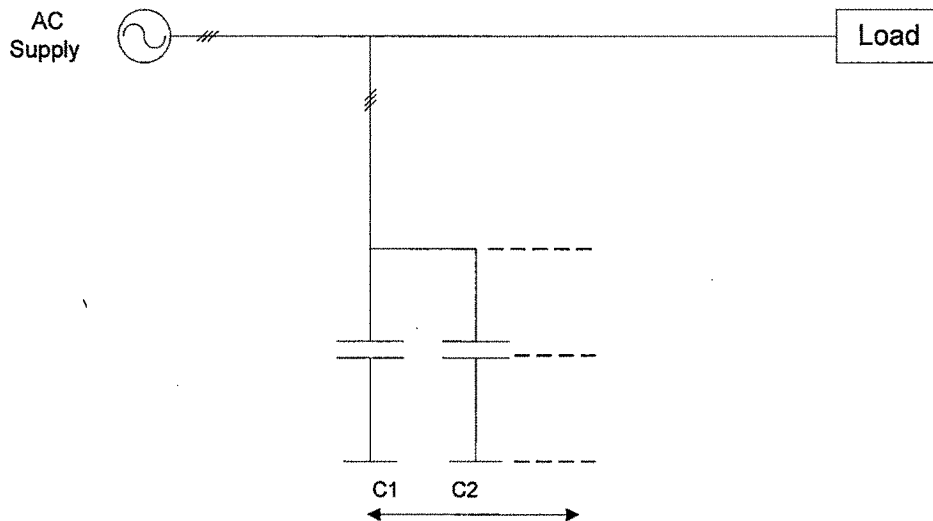


Fig. 3.5 Fixed Capacitor

While the solution is the most simple, it has severe limitations as below:

- There is no dynamics involved, hence suitable only for constant loads
- Considerable under and overcompensation for varying loads
- Resonance with supply network
- Harmonic amplification
- Reactive power delivery is supply voltage dependent (proportional to square of the supply voltage) which produces inaccuracy in overall kVAR compensation
- Ageing problems of capacitors resulting less compensating reactive power
- Considerable maintenance

3.3.2 AUTOMATIC POWER FACTOR CORRECTION (APFC)

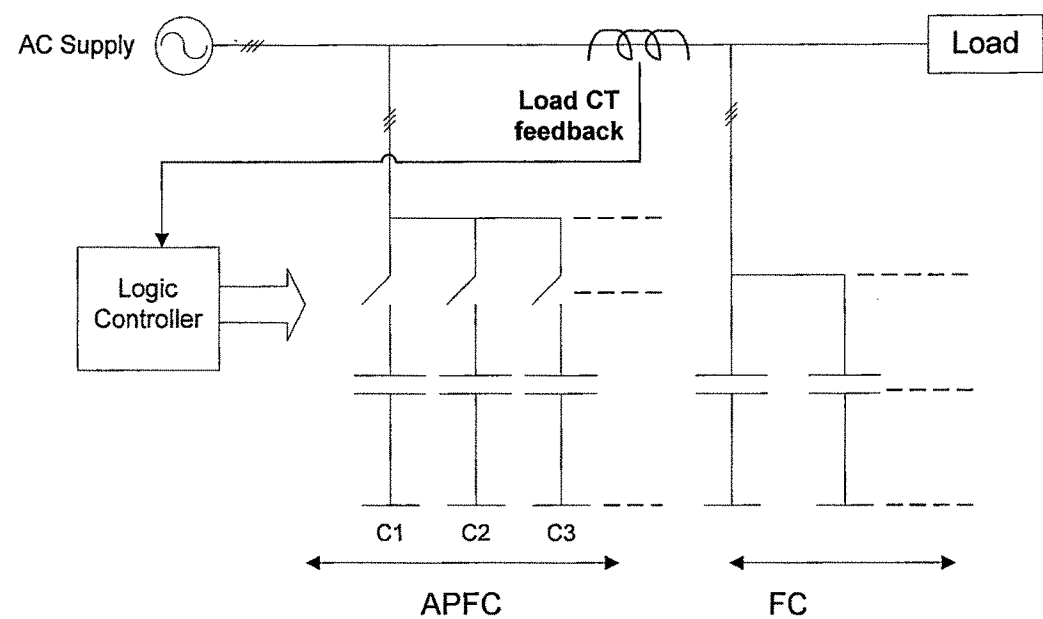


Fig. 3.6 Fixed capacitor and APFC

While the solution is relatively better than the Fixed Capacitor (FC) usage, it still has the limitations as below:

- It supports limited dynamics, hence suitable for slowly varying loads
- Considerable under and overcompensation for varying loads due to step response
- Resonance
- Harmonic amplification
- Inrush currents and voltage transients due to contactor switching affecting life of the capacitors as well as equipment connected on the same bus
- Reactive power delivery is supply voltage dependent (proportional to square of the supply voltage) which produces inaccuracy in overall reactive power compensation
- Ageing problems of capacitors resulting less reactive power compensation and its accuracy
- Considerable maintenance

3.3.3 THYRISTOR SWITCHED CAPACITOR (TSC)

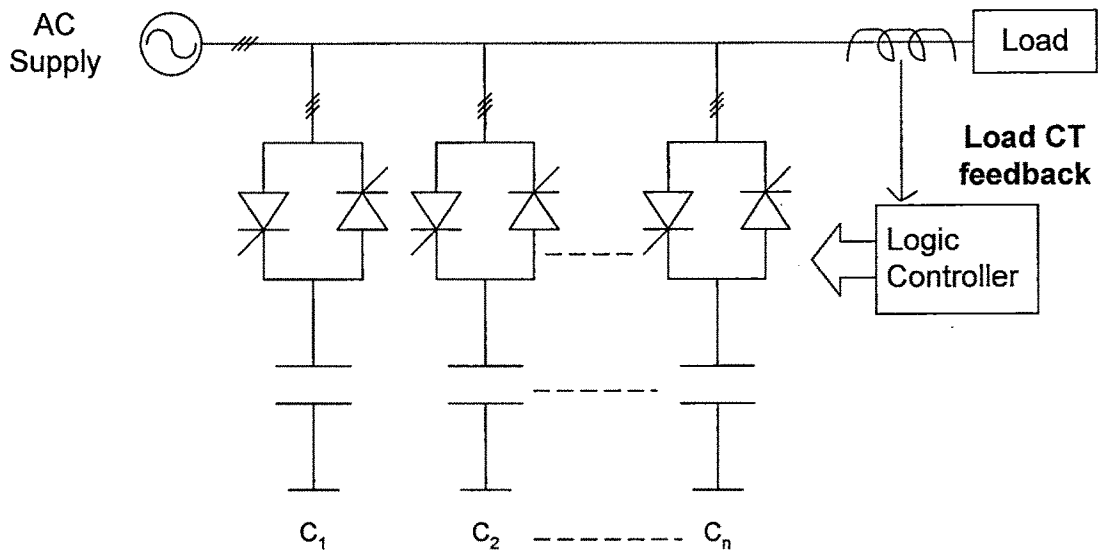


Fig. 3.7 TSC

While this scheme has enjoyed maximum popularity with growth of Power Electronics (PE) based solutions, it still exhibits limitations as below:

- Not suitable for load dynamics of the order of seconds (due to discharge time of capacitors for switching duty) unless zero crossover strategy is employed.
- Considerable under and overcompensation for varying loads due to step response. Number of steps hence required is substantial, to overcome this problem, which ultimately reduces reliability of the TSC. Difficulty in thyristor versus fuse coordination when numbers of sections are increased with different kVAR ratings unless ratings are standardized which increases the cost.
- Resonance
- Harmonic amplification
- Inrush currents and voltage transients (if zero voltage crossover is not employed) affecting life of the capacitors as well as equipment connected on the same bus. Can still cause inrush currents and voltage transients based on accuracy of synchronization network and frequency variations.
- Reactive power delivery is supply voltage dependent (proportional to square of the supply voltage) which produces inaccuracy in overall reactive power compensation

- Ageing problems of capacitors resulting less reactive power compensation and its accuracy
- Considerable maintenance

3.3.4 THYRISTOR CONTROLLED REACTOR (TCR)

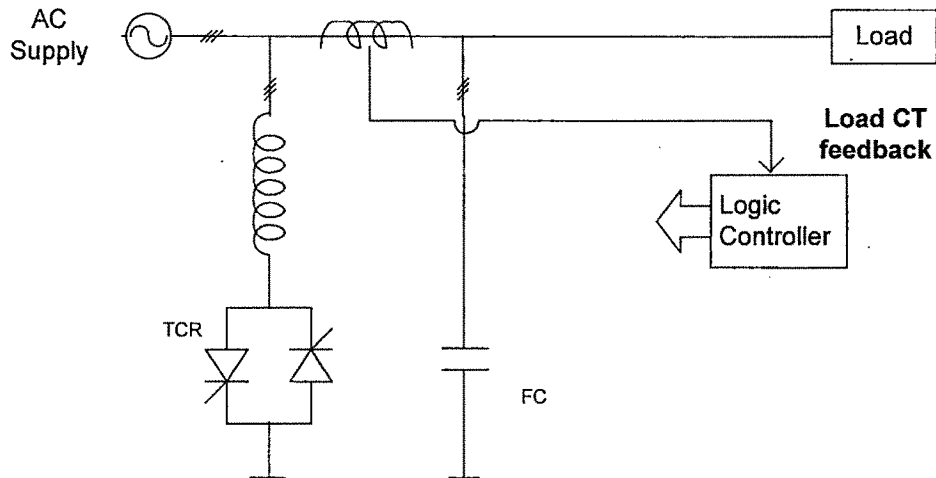


Fig 3.8 TCR with FC

While this is the only scheme which facilitates inductive and capacitive compensation possibility, and also to some extent has smoothened response, it still exhibits limitations as below,

- Suitable for dynamically varying loads demanding response in seconds at the cost double kVAR installed capacity and lower order harmonics produced (normally hence preferred for very high compensation requirements such as 30 MVAR and beyond)
- Resonance
- Harmonic amplification
- Not economical for lower reactive power compensation
- Capacitor reactive power delivery is supply voltage dependent (proportional to square of the supply voltage) which produces inaccuracy in overall reactive power compensation
- Ageing problems of capacitors resulting less reactive power compensation and its accuracy
- Considerable maintenance

3.4 ACTIVE VOLTAGE SOURCE CONVERTER BASED COMPENSATOR (AVSCC)

While the above traditional methods has been in use in last decades, growing Power Quality(PQ) concerns and the limitations as offered by the them, have fuelled the development of active converter based technology, which primarily uses a Voltage Source Converter (VSC), and overcomes all the different disadvantages of the first four methods. This is hence a solution being preferred while dealing with the reactive power compensation for highly dynamic loads under different network conditions. Such a method if designed appropriately can offer, following edge as against the previous methods.

- Dynamic response time of the order of one power cycle. Thus load dynamics can be closely tracked.
- Stepless and smooth response
- No harmonics injected in the network
- Virtually independent of the supply short circuit capacity at the coupling point. Thus changing network conditions can be accommodated easily.
- Can work in both inductive and capacitive mode, without using the passive elements to achieve the functional requirements. Thus the active converter capacity reduces to 50% that of the load compensation requirement while employing fixed 50 % compensation using capacitor bank.
- Can work in tandem with existing capacitors employed for power factor correction and produce an economical solution for compensation
- Compensation is offered based on reactive current requirement and is independent of the incoming voltage
- Method in line with increased demands of the network conditions and load dynamics
- Reliability same as other power devices (thyristors) and better when compared with TSC which needs good number of sections to produce close to stepless response
- Virtually no maintenance

Brief summary for the methods discussed above are summarized in the Table 3.1 below

TABLE-3.1
Comparison of Various Reactive Power Compensation Methods

FEATURE	FC / APFC	TSC	TCR	AVSCC
Range	0 to Q	0 to Q	0 to Q	-Q to Q
			(FC gives +Q and TCR gives -Q)	
Capacity	Q	Q	2Q	Q
Performance dependent on fault level	Yes	Yes	Yes	No
Control Response	Stepwise slow	Stepwise Fast	Smooth Fast (Few cycles)	Smooth Very Fast (One cycle)
Switching Device	Breaker /Contactor	Thyrsitor	Thyrsitor	IGBT,GTO,IGCT etc.
Harmonics Injected	No	No	Yes	No
Approximate cost (%)	100 /120	150	260	220

3.5 STATCON

Reactive power compensator is developed based on Voltage Source Converter. For the sake of convenience, these developed converters are called here as "STATCON". It compensates the load demanded reactive power by drawing equal and opposite reactive power from the supply based on converter principle explained below. This type of compensator also has different names used by different manufacturers worldwide, such as Static VAR Generator (SVG), Advanced Static VAR Compensator (ASVC), Static Compensator (STATCOM), and Static Condenser (STATCON). STATCON, being an active converter (Voltage Source Converter : VSC), possesses all the advantages as listed under the active converter based technology for reactive power compensation.

3.5.1 BASIC OPERATING PRINCIPLE OF STATCON

The basic operating principle of STATCON is given in fig. 3.9 , wherein:

v_s indicates instantaneous supply phase voltage;

v_{i1} indicates fundamental component of the instantaneous switching phase voltage v_i produced by STATCON converter;

i_{L1} indicates instantaneous fundamental component of load current;

i_{s1} indicates instantaneous fundamental component of supply current;

i_{c1} indicates instantaneous fundamental component of STATCON current;

wL_s indicates supply short circuit impedance at supply frequency; and

wL_b indicates STATCON boost Reactor impedance at supply frequency.

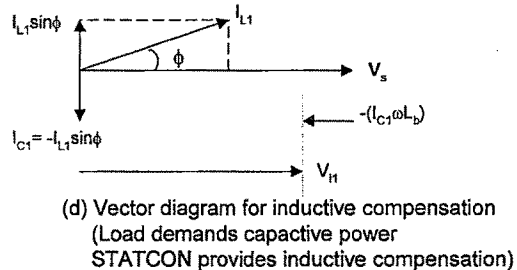
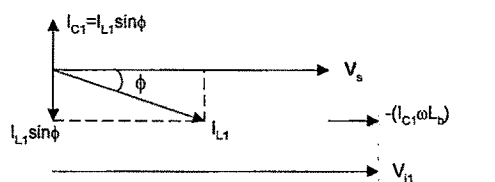
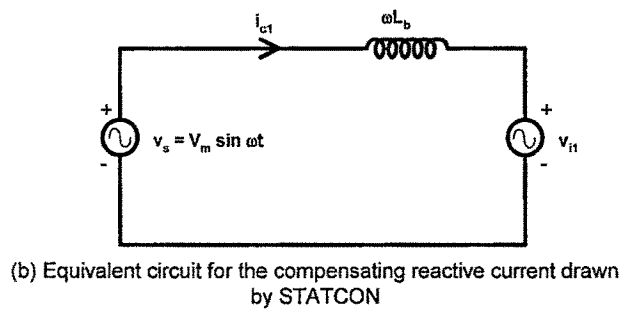
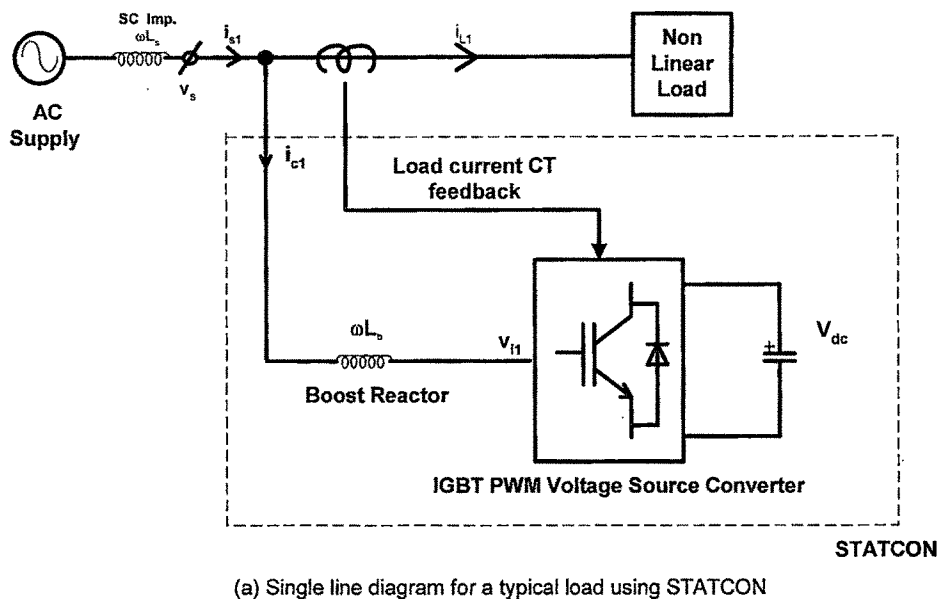


Fig. 3.9 Basic operating principle of STATCON

It is very clear from fig. 3.9 that by controlling the voltage V_{i1} (its amplitude and displacement from supply voltage), STATCON can be made to draw either capacitive or inductive current. The method of current control hence is "Indirect Current Control (ICC)". The load CT gives information of load current from which the reactive current compensation is calculated and v_{i1} then is given by:

$$-V_s \pm (i_{C1} \cdot \omega L_b) + v_{i1} = 0 \quad (1)$$

Where,

+ sign denotes inductive mode operation of STATCON

- sign denotes capacitive mode operation of STATCON

Since STATCON uses active power converter (based on power devices) it will have to support a small but varying power loss in the devices and other power components (elaborated further in equations (3) to (8) and (11) to (14)), the varying loss needs to be accounted by a variable resistor R_v in the equivalent circuit. The equivalent circuit shown in fig. 3.9 (b) gets modified as given in fig. 3.10 (a).

Equation (1) now changes to:

$$-V_s \pm (i_{C1} \cdot R_v) \pm (i_{C1} \cdot \omega L_b) + v_{i1} = 0 \quad (2)$$

The modified vector diagrams are given in figs. 3.10(b) and 3.10(c). It should be noted that the displacement angle ' δ ' is extremely small and could vary within less than 3 degrees as elaborated later.

It should, however, be noted that since the resistance R_v is variable, it needs to be simulated in a closed loop condition. Further, the dynamic placement of vector V_{i1} or its calculated value depends on it.

STATCON controls will have to calculate this R_v continuously and adjust the vector V_{i1} accordingly so that the entire closed loop functions properly to meet the dynamic reactive power requirement of the load. This is explained in details later.

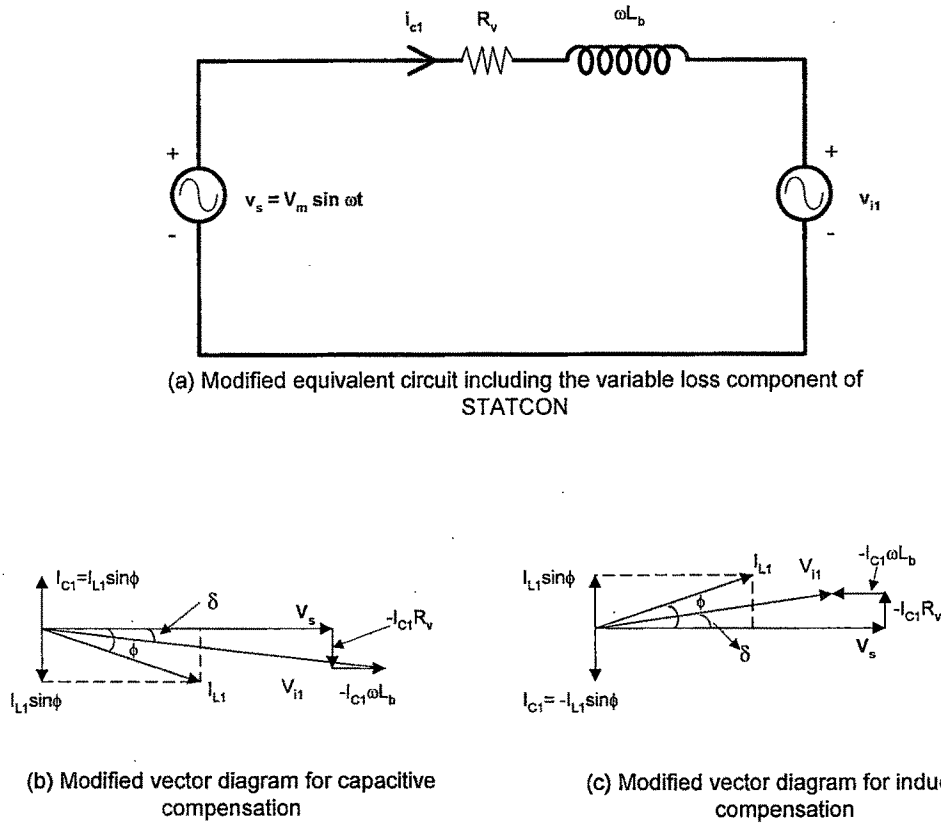


Fig. 3.10 Modified equivalent circuit and vector diagram for STATCON considering variable loss resistor

3.5.2 STATCON : DESIGN DETAILS

Design details are better explained with the help of following figures accompanied by description.

3.5.2.1 THREE-PHASE STATCON

For Three-phase STATCON following figures in the following pages, followed by their description helps for design details:

- Fig. 3.11 Power scheme for the three phase STATCON;
- Fig. 3.12 PWM generation based on SPWM method;
- Fig. 3.13 Circuit diagram for the voltage distortion analysis;
- Fig. 3.14 (a) Control Logic;
(b) Control Electronics;
- Fig. 3.15 Flow chart;
- Fig. 3.16 Signals received and delivered by various control cards;

Fig. 3.17 Block diagram of digital card;

Fig. 3.18 General arrangements of three-phase STATCON;

Fig. 3.19 (a) Inductive mode of operation;
(b) Capacitive mode of operation;

Fig. 3.20 (a) Mode changeover response

Fig. 3.20 (b) Dynamic responses

Note: PWM denotes "Pulse Width Modulation ".

SPWM denotes "Sinusoidal Pulse Width Modulation".

Before the figures are described, certain basic as well as overall aspects with respect to figs. 3.9 and 3.10 and the STATCON operation in relation to the same is described below.

The STATCON is connected in shunt with the load, as in fig.3.9 (a). The load current (i_{L1}) is measured through a current transformer (CT) and its reactive component is established, as in figs. 3.9(b) and (c) and as indicated by $I_{L1} \sin \phi$.

Note: 1. Instantaneous values are mentioned by low case letters, such as i_{L1} , v_{i1} .

2. Root Mean Square (RMS) values are mentioned by I_{L1} , V_{i1} .

STATCON is supposed to nullify or compensate this load component $I_{L1} \sin \phi$ by drawing equal and opposite current ($I_{c1} = - I_{L1} \sin \phi$) from the supply. This is the basic requirement of reactive power compensation and hence that of STATCON.

In STATCON, the power devices used are called as Insulated Gate Bi-polar Transistors (IGBT's). The power converter using these IGBT's (fig. 3.11) is controlled by Pulse Width Modulation (PWM) process in such a way that the three fundamental frequency voltages appearing at the terminals R1, Y1, and B1 of the converter (fig. 3.11) with respect to virtual zero (midpoint of the dc capacitors or voltage V_{dc} in fig. 3.11) are as shown by voltage v_{i1} in fig. 3.12. This fundamental component v_{i1} of the switching voltage v_i in fig.3.12 is controlled by varying the amplitude of the modulating signal in fig. 4. The varying voltage v_{i1} opposes the supply voltage v_s shown in fig. 3.9(b), which is the single-phase equivalent circuit. The difference between the supply voltage V_i and the applied voltage V_{i1} , say ΔV ,

could be positive or negative. Based on whether the ΔV is positive or negative, STATCON will draw inductive or capacitive current from the supply (RMS value as $\Delta V / \omega L_b$), as shown in figs. 3.9(d) and (c) respectively, to compensate the load reactive component $I_{L1} \sin \phi$.

Next requirement is to understand how STATCON generates the voltage V_i and V_{i1} and how many components and subassemblies are required to do so. The IGBT based converter in fig. 3.11 has to have controlled switching of the IGBT devices, based on the required compensation process as explained in figs. 3.9 and 3.10. It should be noted that the fig. 3.10 accounts for small but active power losses in STATCON (power loss in devices, and all other components in the power scheme of fig. 3.11 and modifies figs. 3.9(b), (c), and (d) to figs. 3.10(a), (b), and (c) respectively. Accounting for the small power loss as above, the STATCON has to dynamically solve and find out value of V_{i1} continuously.

The voltage V_{i1} is produced by superimposing the carrier wave of necessary frequency (in this case 2.8 kHz) with the varying modulating signal corresponding to required V_{i1} as shown in fig. 3.12. The various components and subassemblies required to establish the control over this voltage V_{i1} and hence on the compensating current I_{c1} are given and explained in the figures below.

The converter in fig. 3.11 finally produces the voltage V_{i1} at its terminals R1, Y1, and B1 with respect to the virtual zero (midpoint of the dc capacitors or the voltage V_{dc}).

The digital controller, which is part of the Control Electronics (CE), sequences the converter and the power scheme. However, the Control Electronics and the Control Logic control the sequencing and interlocking operations of the complete STATCON as a whole. Thus, the power scheme and its components, the Control Electronics and the Control Logic form major parts of STATCON.

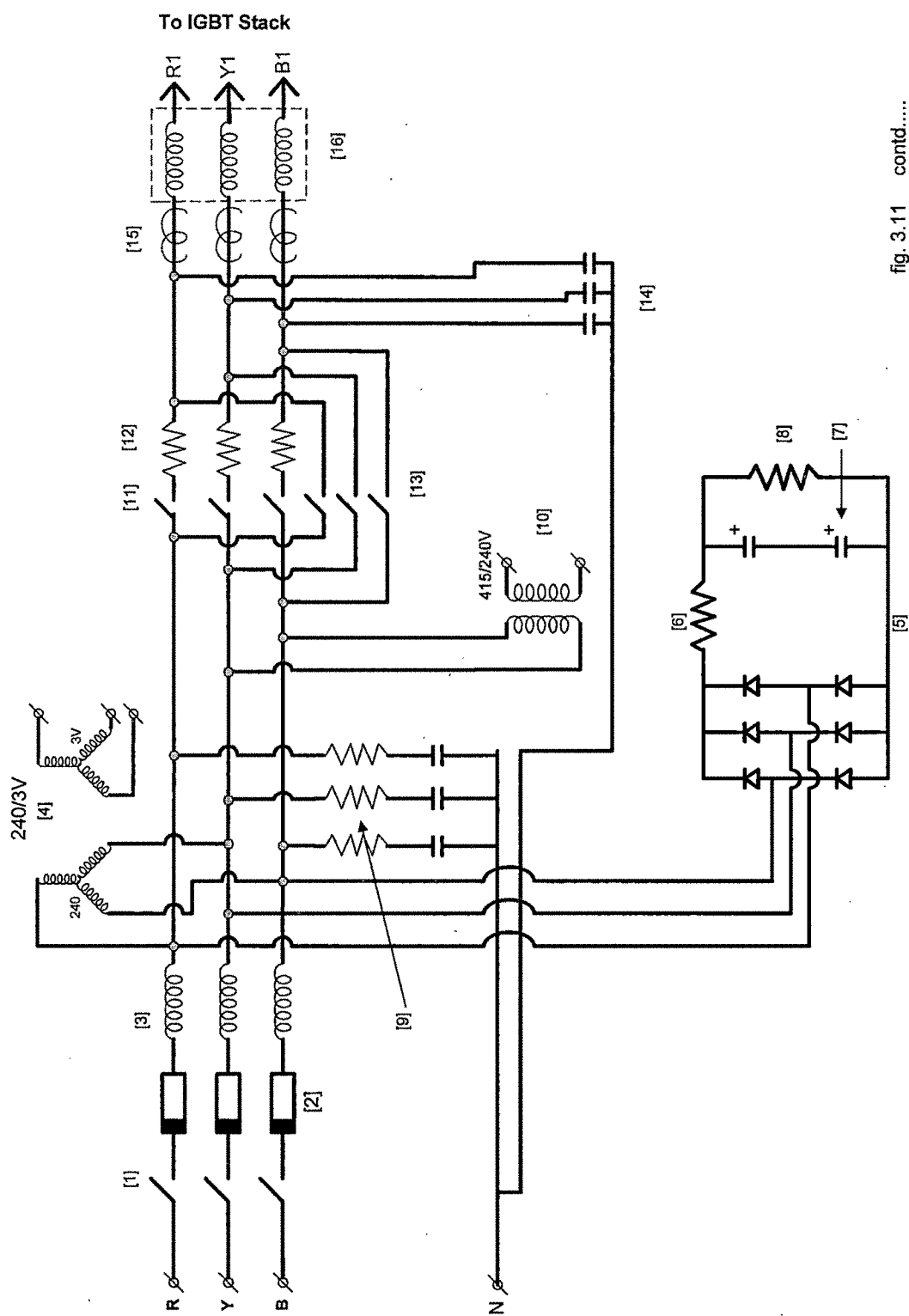
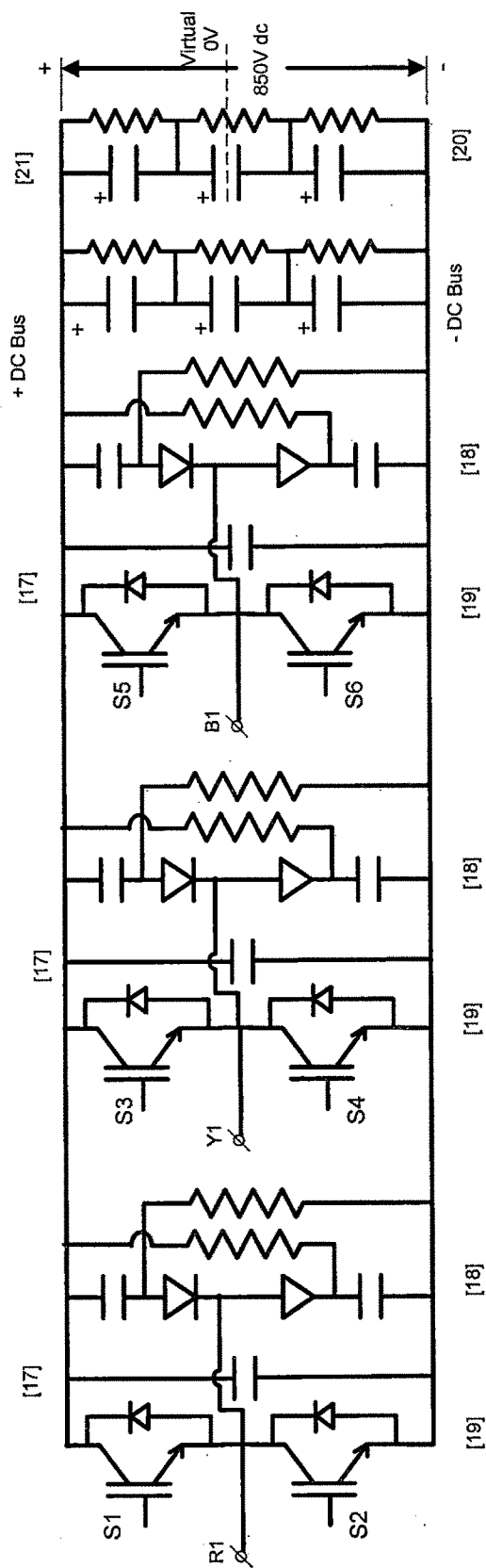


fig. 3.11 contd.....



CONVERTER

Fig. 3.11 contd.....

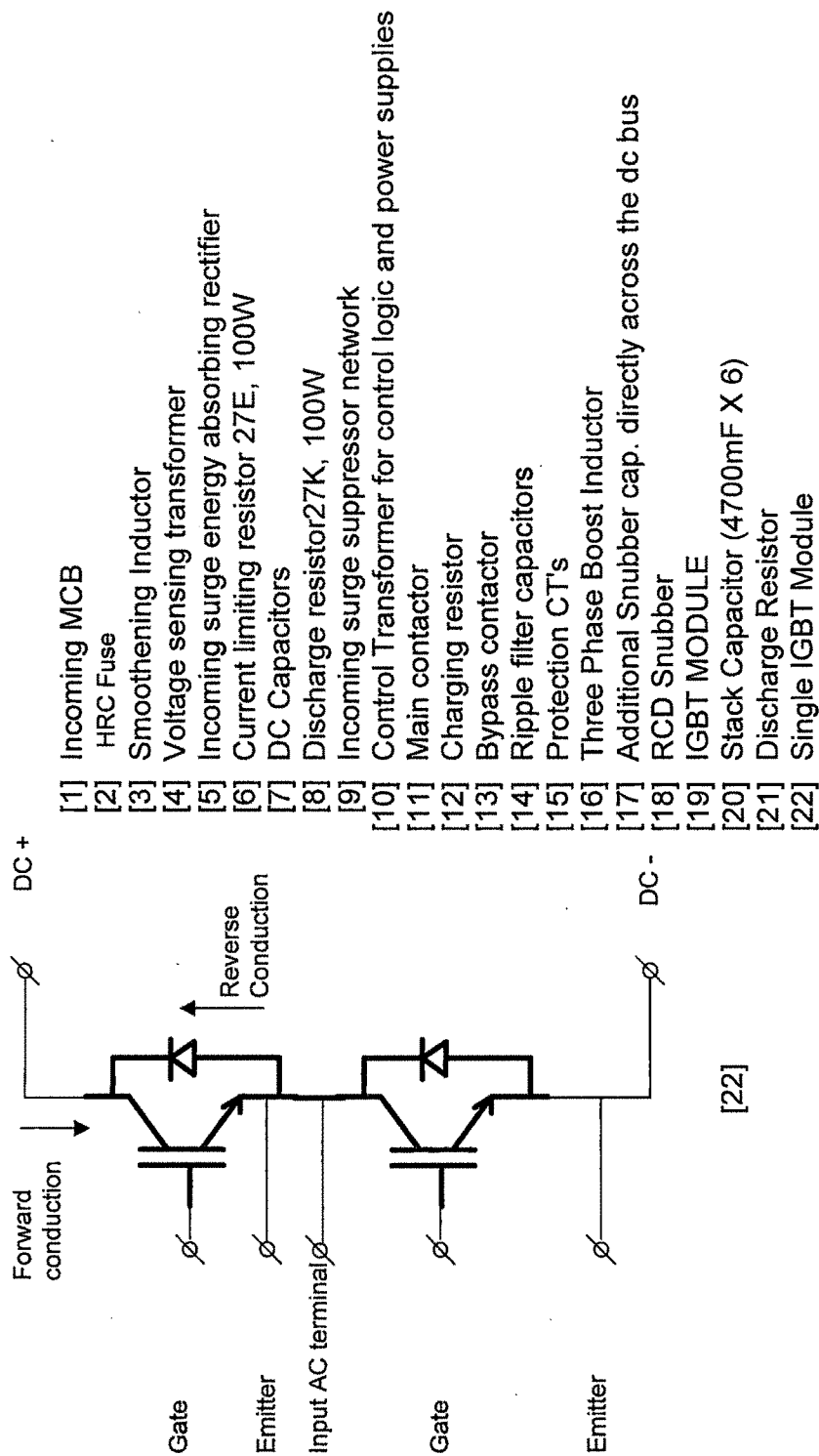


Fig. 3.11 Power Scheme for the three phase STATCON

Description for

Fig. 3.9(a)

This figure gives a typical single line diagram of connecting the STATCON (three-phase or single-phase) in parallel with the load while receiving a load CT feedback and compensating the load reactive power. From the load current, required compensation for the inductive or capacitive load current component is calculated by STATCON and same compensating current is then drawn from the supply. Please refer figs. 3.9(c) and (d) and figs. 3.10 (b) and (c).

Fig. 3.9 (b)

This figure is for understanding the fundamental frequency voltage loop including the supply voltage, the fundamental component V_{i1} of the switching voltage V_{it} of the STATCON and the boost reactor. This leads to proper understanding of figs. 3.9 (c) and (d).

Fig. 3.9 (c) and fig. 3.9(d)

These figures explain the vector relationship amongst the supply voltage, the fundamental component of the switching voltage of the STATCON and the current drawn by the STATCON when it works in either capacitive mode or in inductive mode.

Fig. 3.10 (a)

This is modified fig. 3.9(b) incorporating the variable power loss component of STATCON. The power loss component is denoted by R_v . This loss resistance depends upon the actual active loss in the components of the power scheme given in fig. 3.11.

Fig. 3.10(b) and fig. 3.10 (c)

These are modified vector diagrams given in figs. 3.9(c) and (d) incorporating the variable power loss resistor R_v of STATCON.

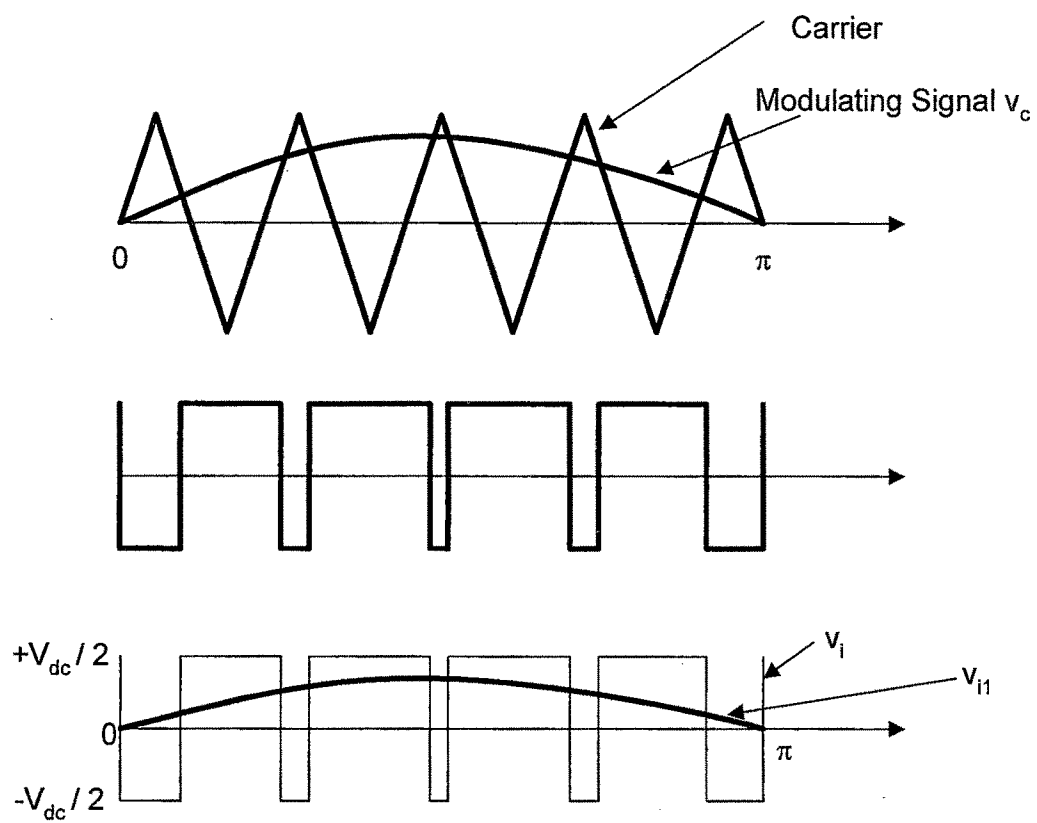


Fig. 3.12 PWM generation based on SPWM method

Fig. 3.11

This is the power scheme diagram for the three phase STATCON which includes all the power components starting from acceptance of input power supply to the IGBT power stack. Basically, it uses a three-phase half bridge construction for the Voltage Source Converter. It also shows ac voltage sensing transformer, control transformer for control logic and electronic cards, power supplies, incoming diode rectifier for surge absorption, incoming voltage spike or surge suppressor, R-C-D snubber arrangement, and the power contactor arrangement.

When the main Moulded Case Breaker (MCB) [1] is closed, it gives the three-phase power to STATCON and impressing the three-phase voltage across its input terminals. The HRC fuses [2] are meant for short circuit protection. The incoming smoothening inductors [3] and the diode rectifier based surge energy absorber [5,6,7,and8] are effective when there is a sudden power failure. The rectifier output capacitors absorb trapped energy in the network and save the STATCON from any damage due to overvoltage or voltage transients. The R-C based surge suppressor [9] absorbs transients on the incoming supply network. The main contactor [11] closes initially and charges the DC capacitor stack [20] to peak of incoming phase to phase voltage (approximately 587 V for a three phase supply of 415 V) through the charging resistor [12] with a limit on the supply current drawn. These DC capacitors are also provided with discharge resistors [21] across their terminals to discharge them when the power fails or STATCON is switched off for any reason. The bypass contactor [13] closes when the micro-controller releases the command for it to operate. It then bypasses the main contactor and carries the supply line currents. Once the bypass contactor is closed, the IGBT converter or STATCON as a whole is ready to perform, but will be controlled by the micro-controller in the digital card. It then charges the DC bus voltage from the nominal voltage of 587 V to 850 V dc (called as boost charging of the DC capacitor stack) and subsequently the converter or STATCON performs as the reactive power compensator. The control transformer 240 / 3 V [4] is meant for providing incoming voltage information to control electronics. The 415 / 240 V transformer [10] is used for supplying isolated power to control logic and control electronics. The filter capacitors [14] after the bypass are meant for filtering the input current ripple generated by the switching of the IGBT devices. The protection Current Transformer (CT's) [15] measure the input currents and provide information to be used for sensing over-current in

supply lines. The boost reactors [16] allow boost charging of the stack to 850 V dc and isolate the incoming supply from the IGBT converter. The IGBT switches, as shown by [19 and 22], are bi-directional allowing the current to flow in both directions. In forward direction, the switch is controlled based on pulse delivery to the IGBT gate with respect to its emitter, while the reverse direction conduction depends on the IGBT not having a pulse to its gate and the diode being forward biased. The snubber devices (R-C-D) [18] are meant for providing dv / dt , di / dt and hole storage / reverse recovery protection for the IGBT's. Additional protection for the devices is also given using snubber capacitors [17] across the positive and negative DC bus of the converter and located near each IGBT module. The capacitor stack is maintained at 850 V dc during running condition of the STATCON. Since the output dc ripple current is small, only two dc parallel capacitor sections are used to filter the same.

Fig. 3.12

This figure shows how switching Pulse Width Modulated (PWM) voltage is produced at the terminals (R1, Y1, B1 terminals marked in fig. 3) of the converter using Sinusoidal Pulse Width Modulation process. It uses a 2.8 kHz carrier and a sinusoidal modulating waveform and reflects the comparison in terms of the switching voltage as shown in the figure. The switching voltage, as explained earlier, is expressed as $\pm V_{dc} / 2$ with respect to the virtual zero (midpoint of the dc side capacitors [21] in fig. 3.12. The fundamental component V_{i1} of the switching voltage V_i is as discussed in figs. 3.9 and 3.10.

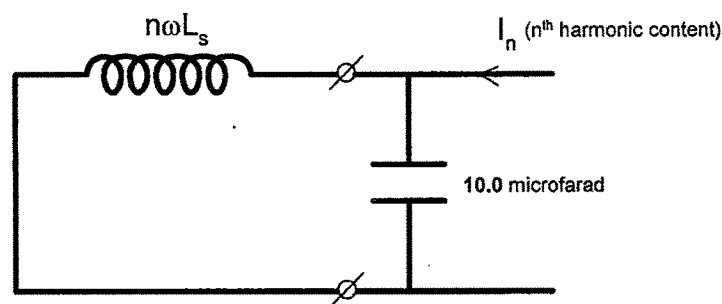


Fig. 3.13 Circuit diagram for the voltage distortion analysis

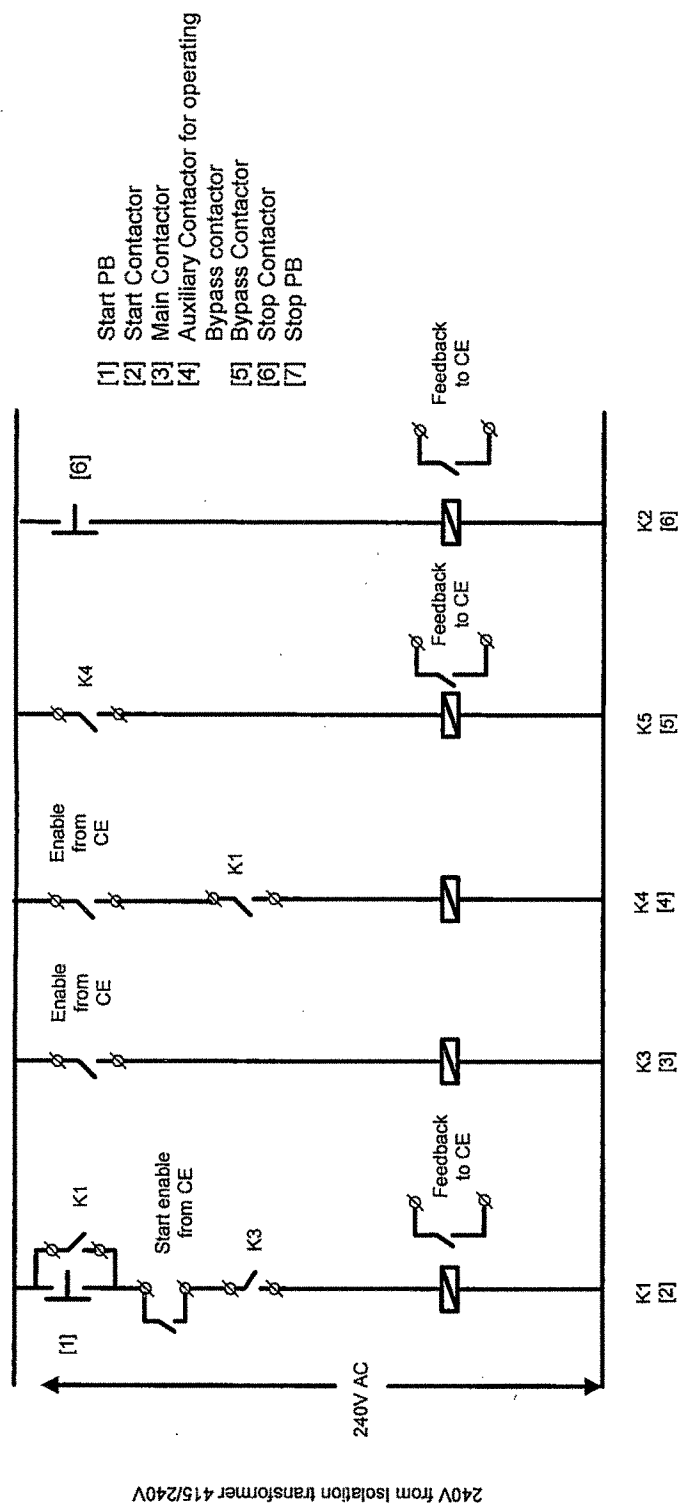


Fig. 3.14 (a) Control Logic

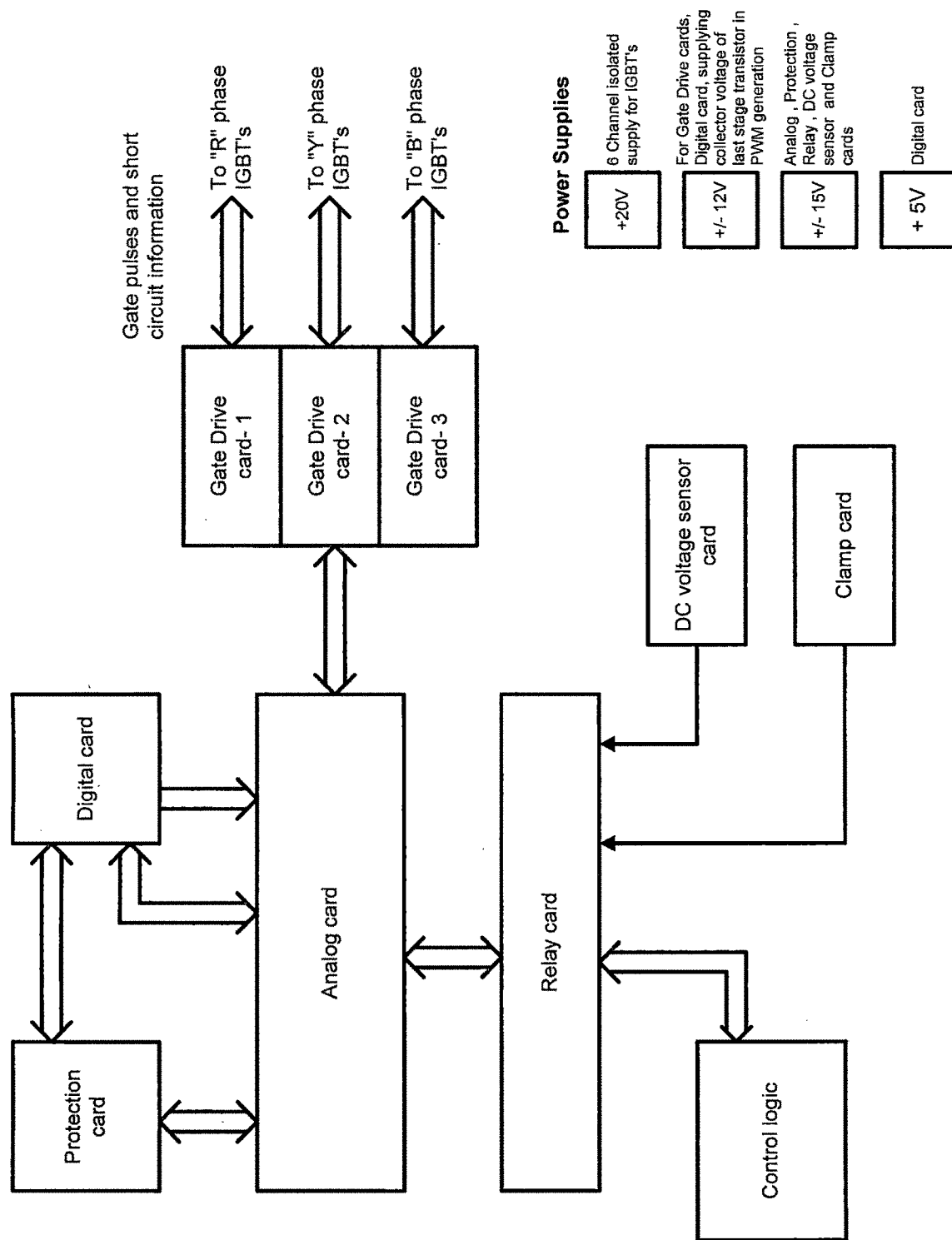


Fig. 3.14(b)contd

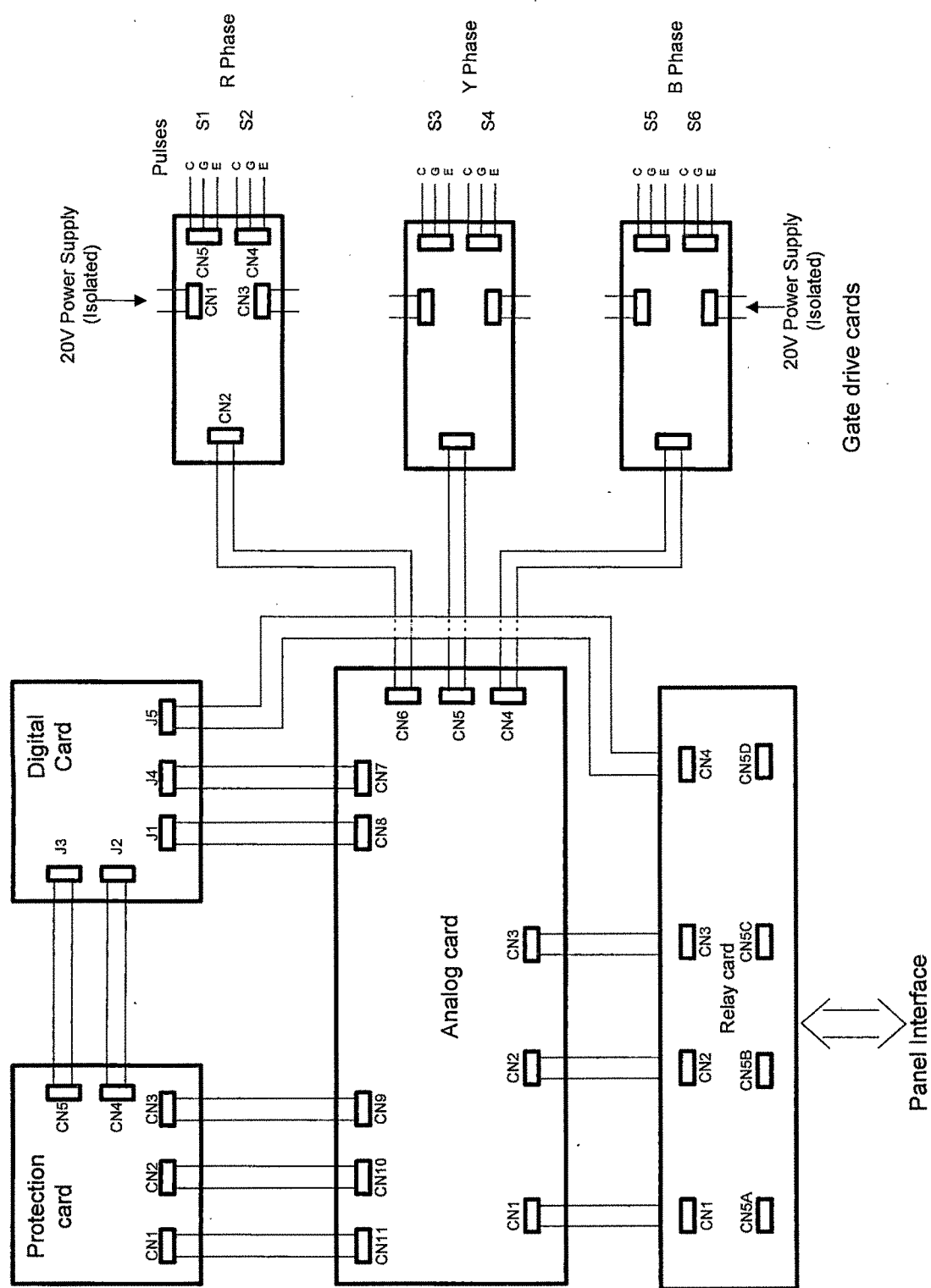
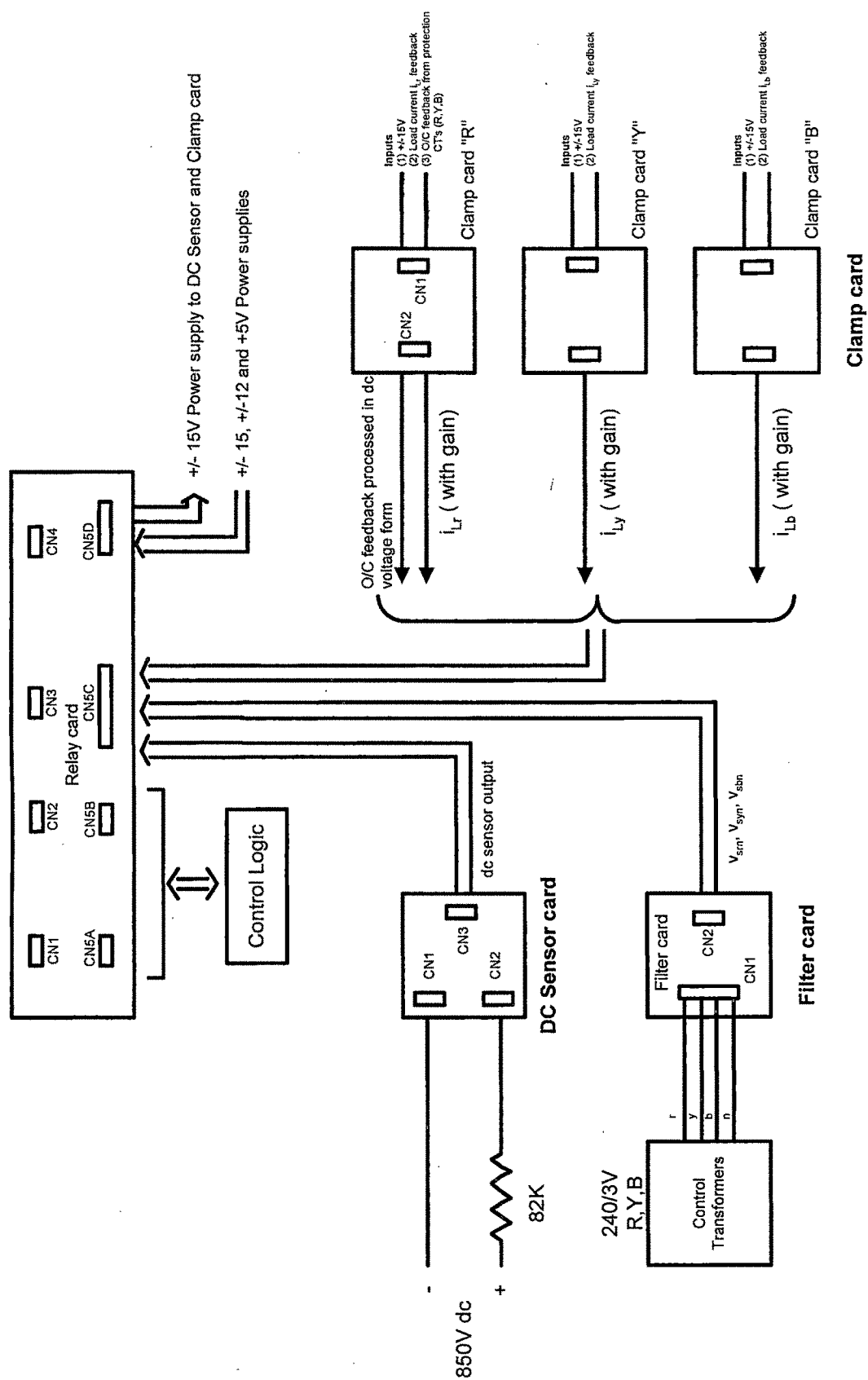


fig. 3.14 (b) contd.....



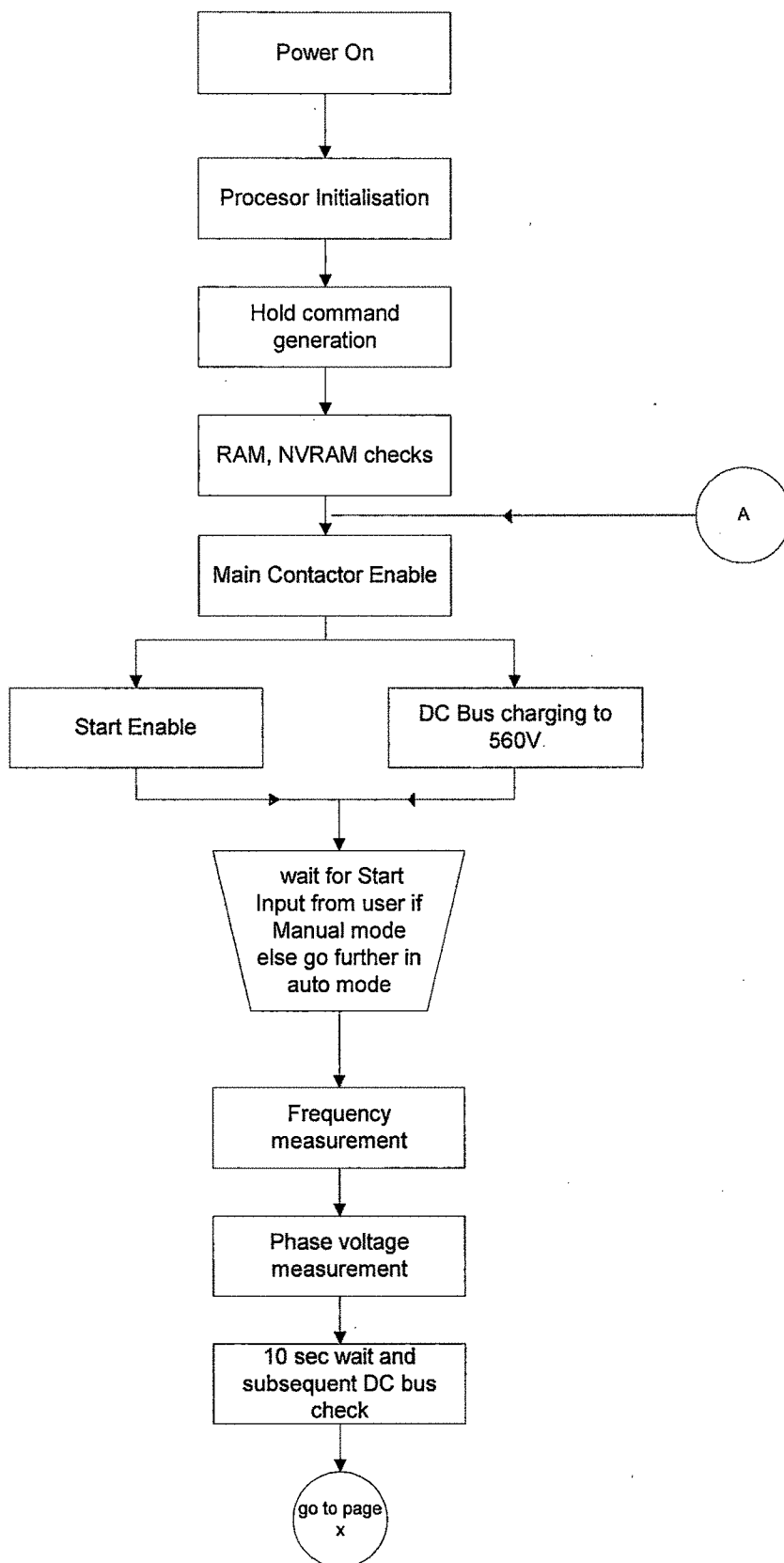


Fig. 3.15 Contd.....

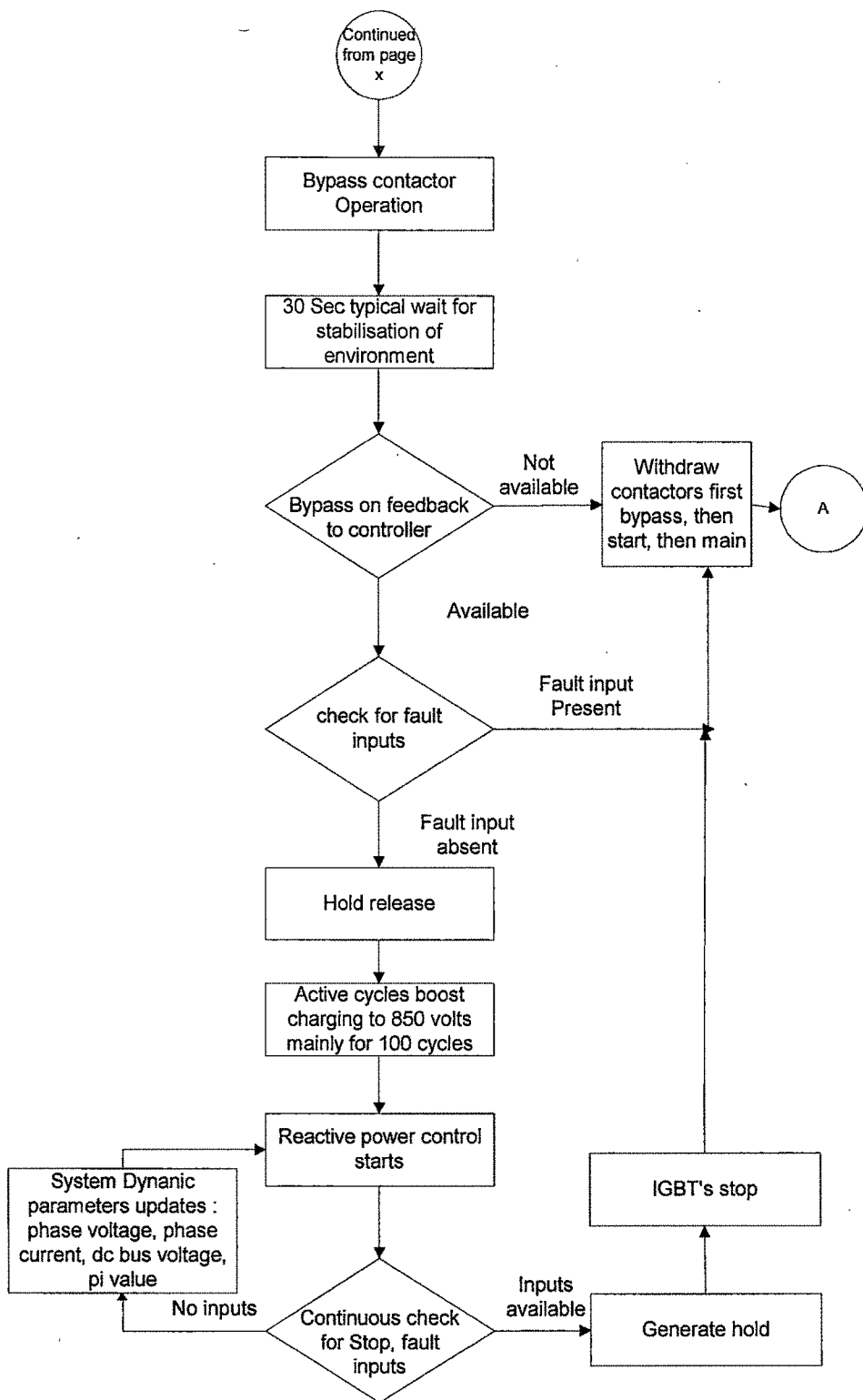


Fig. 3.15 Flow chart

1. DC voltage sensor card

Fig. 3.16 Starts.....

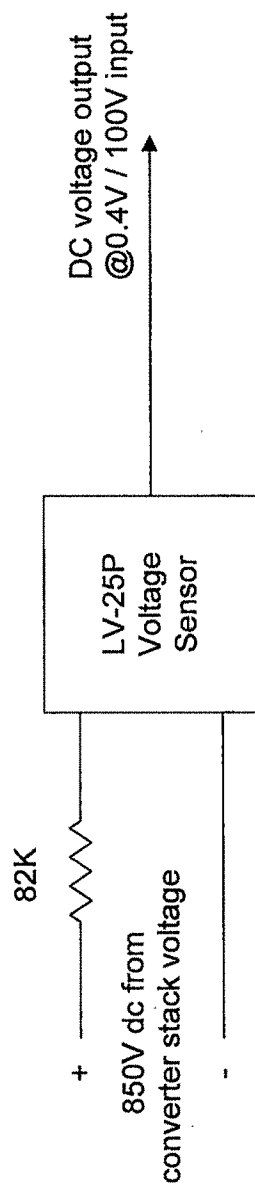


Fig. 3.16 contd.....

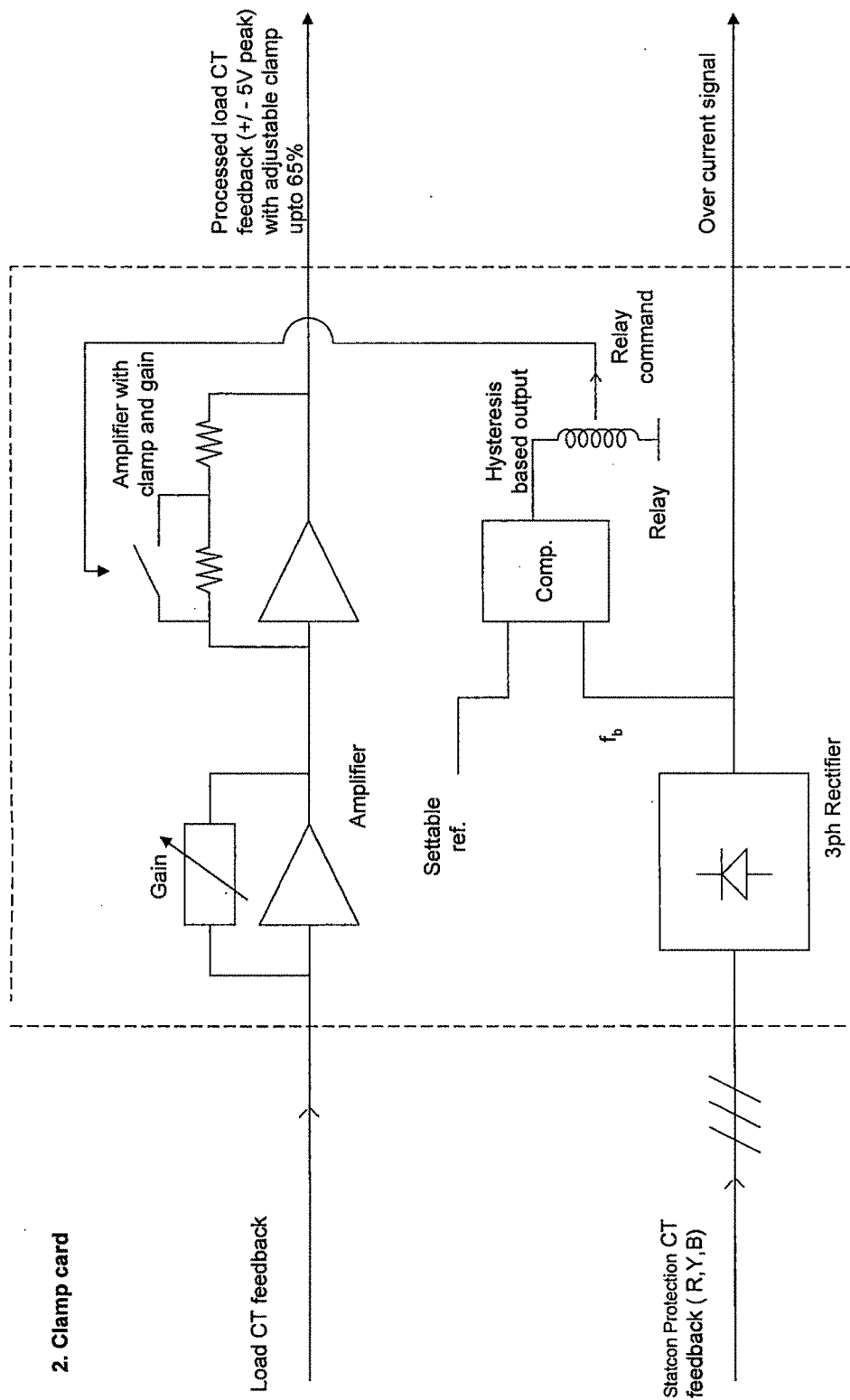


Fig. 3.16 contd.....

3. Relay card

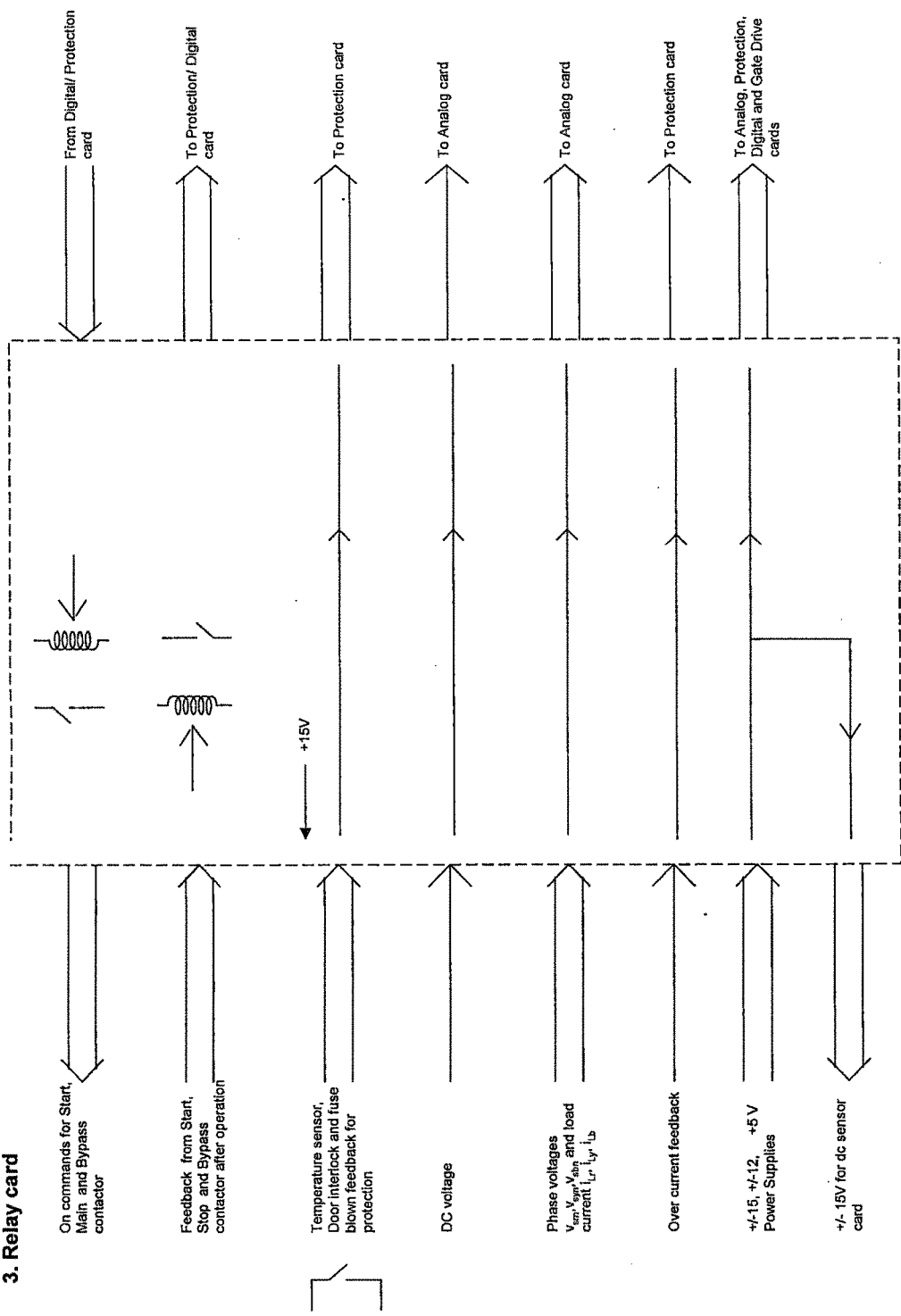


Fig. 3.16 contd.....

4. Analog card

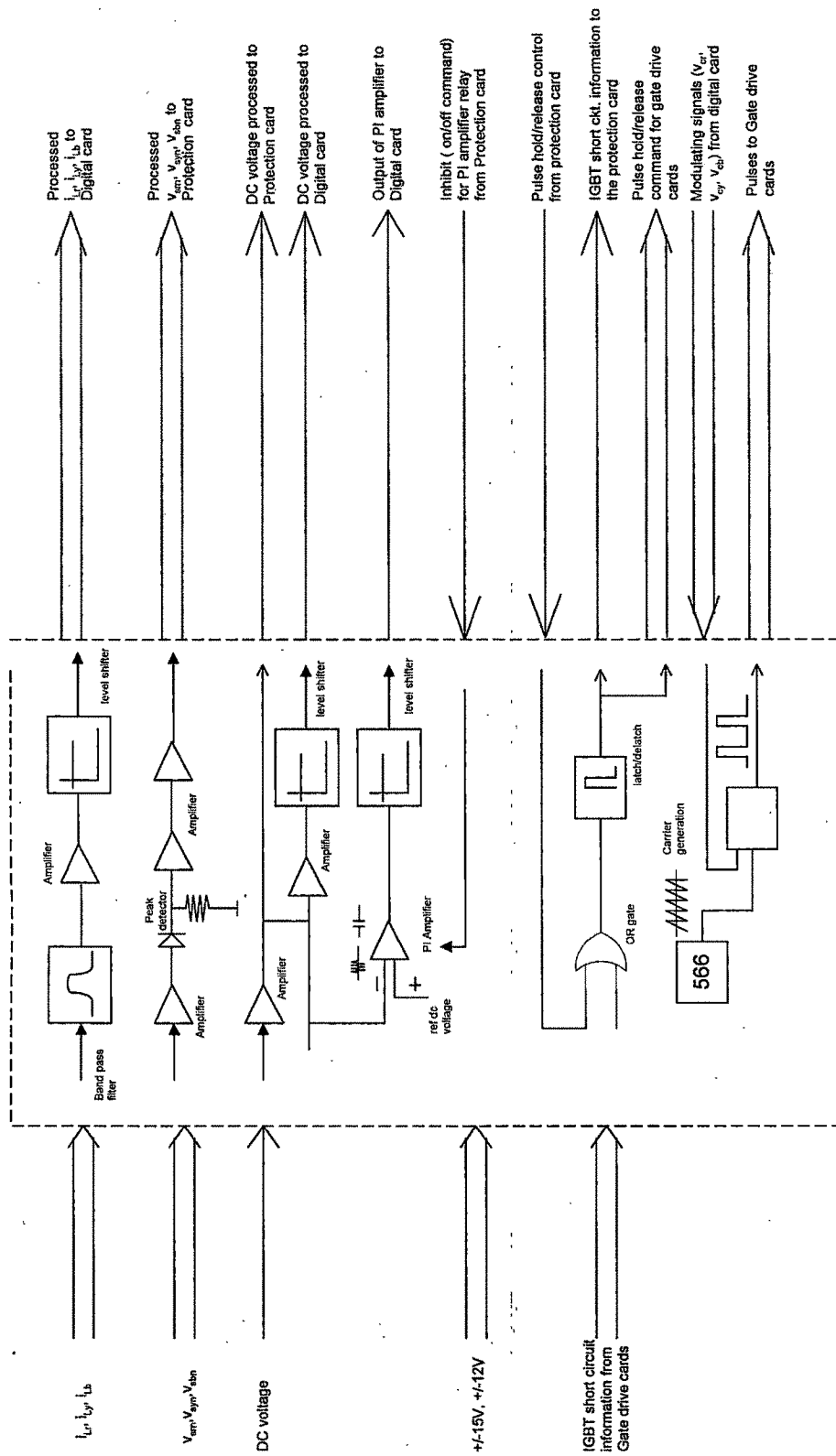


Fig. 3.16 contd.....

5. Protection card

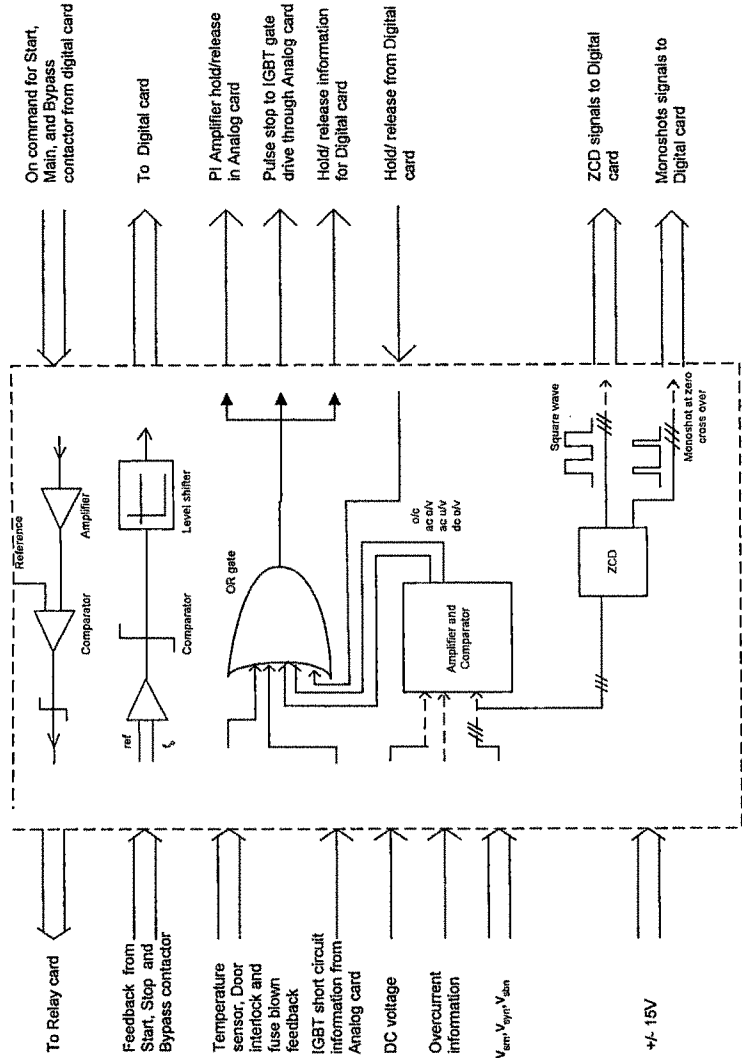


Fig. 3.16 contd.....

6. Gate drive card

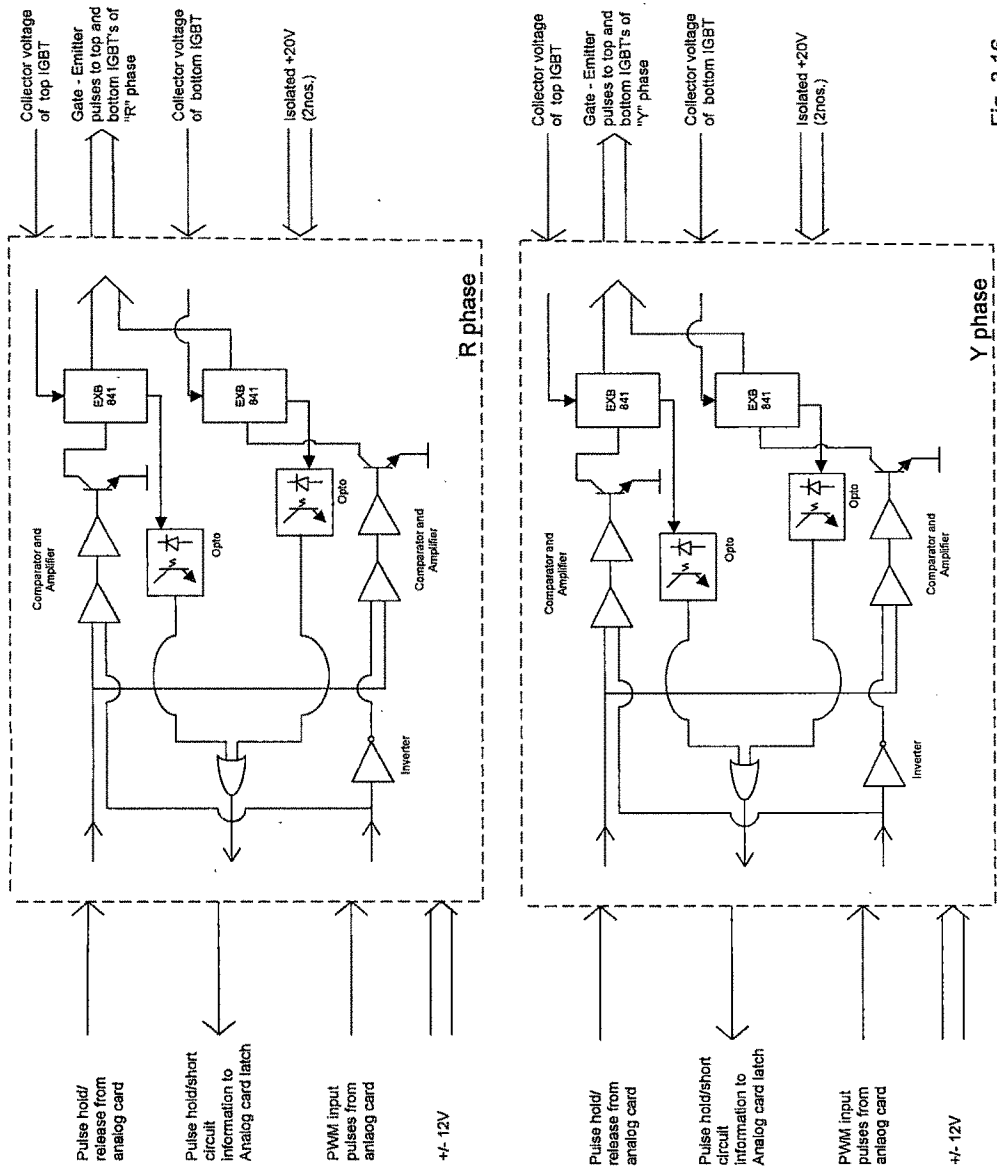


Fig. 3.16 contd....

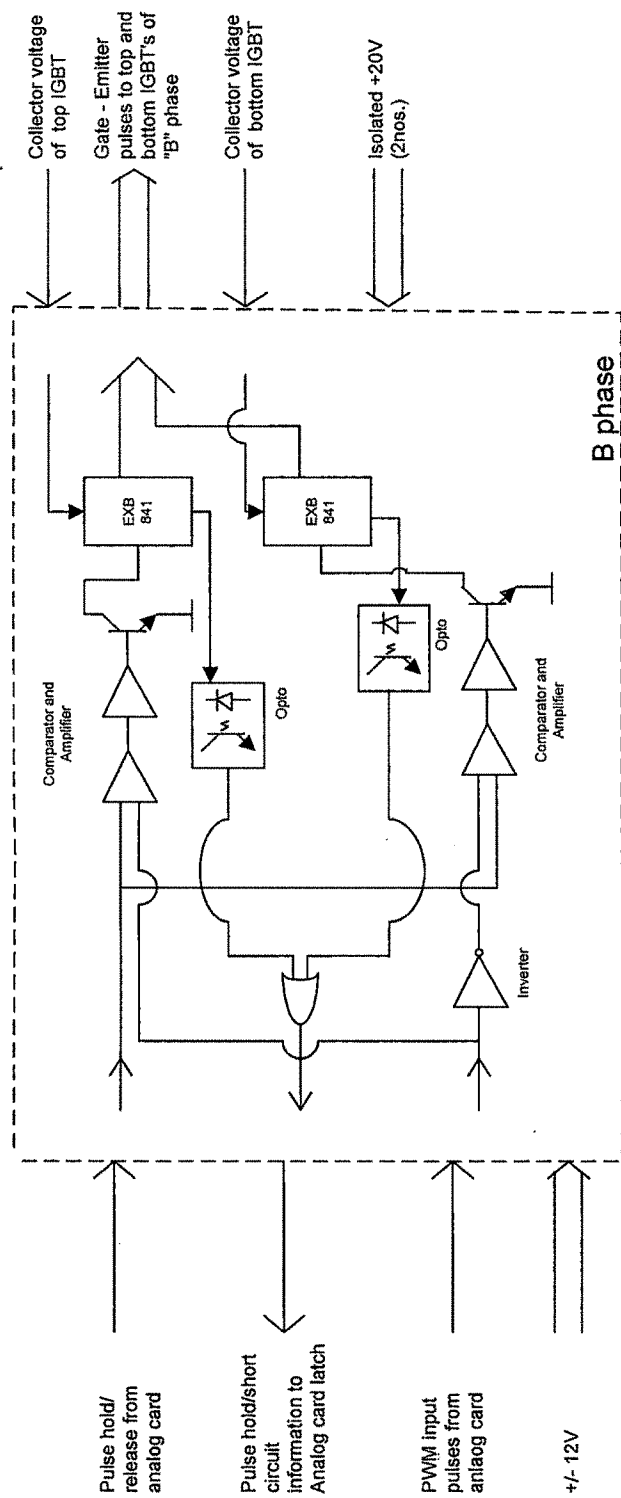


Fig. 3.16 contd.....

7. Digital card

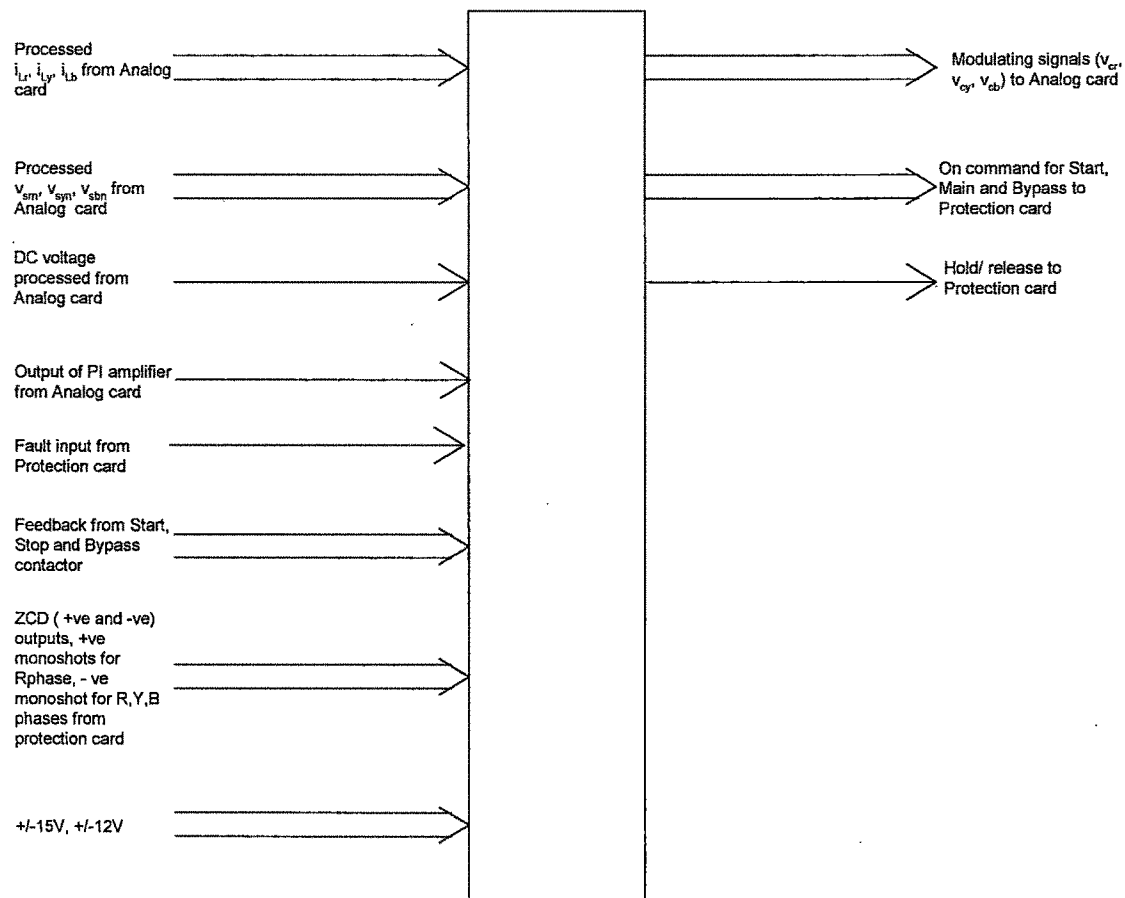


Fig. 3.16 Signals received / delivered by various control cards

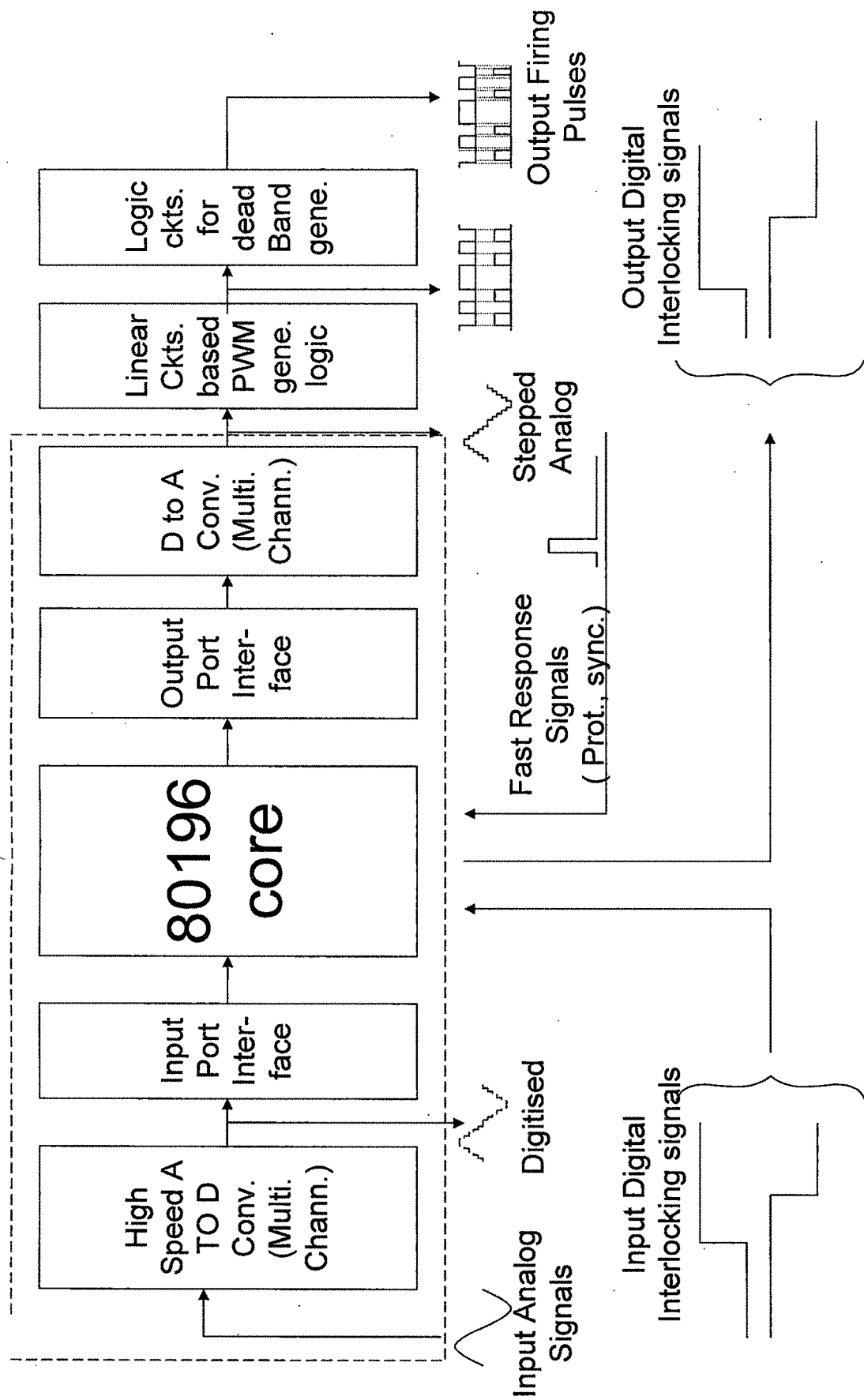
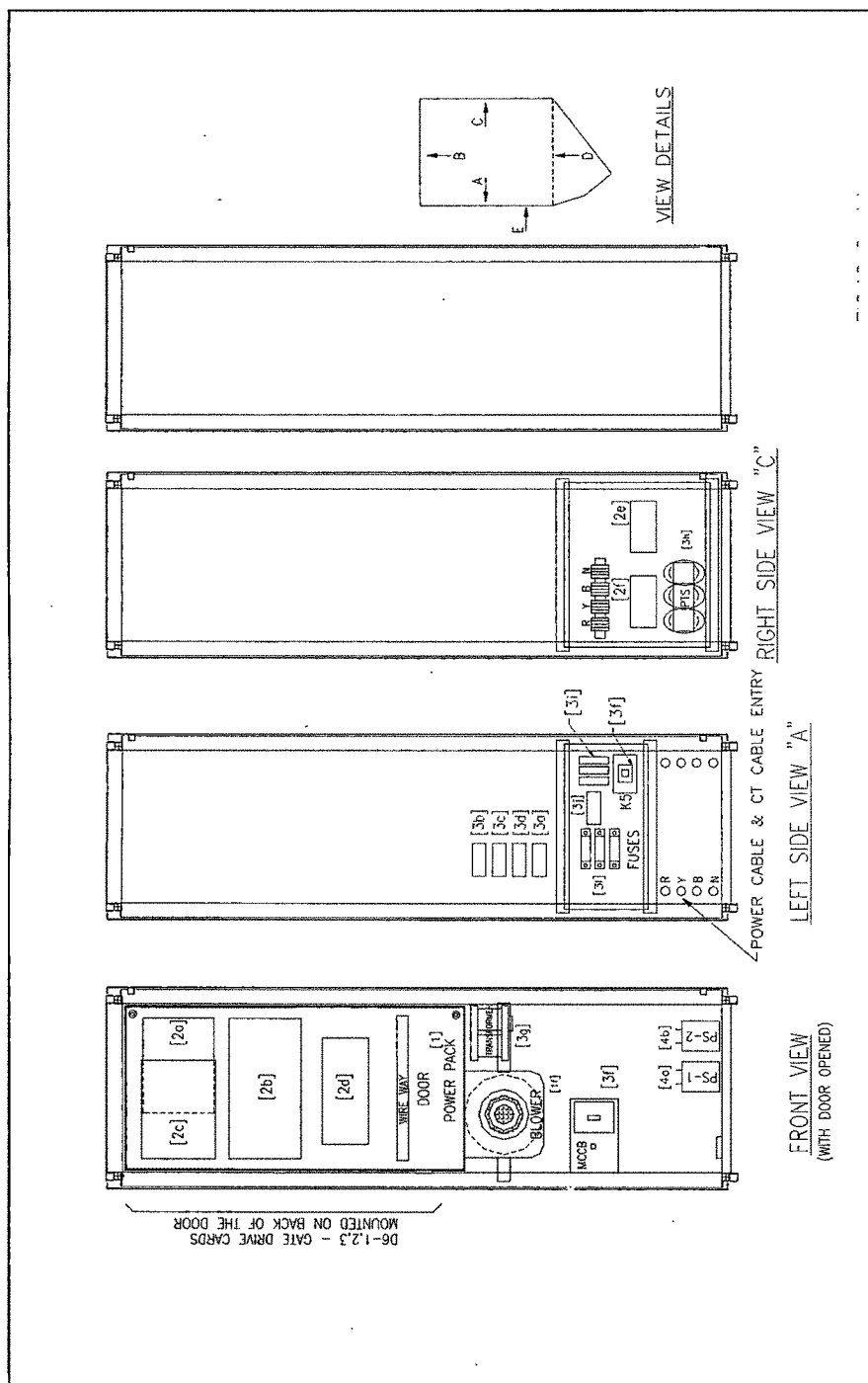


Fig. 3.17 Block diagram of Digital card

POSITION	DESCRIPTION	QTY
[1] POWER PACK	[1a] IGBTs [1b] SNIIBER R-C-D [1c] DC CAPACITOR STACK [1d] DC VOLTAGE SENSOR CARD [1e] HEAT SINK [1f] BLOWER FOR COOLING [1g] POWER PACK CUBICLE [1h] THERMOSTAT [1i] DC RESISTOR FOR VOLTAGE SENSOR CARD [1j] DISCHARGE RESISTOR	3 Nos. 6 Sets 6 Nos. 1 No. 1 No. 1 No. 1 No. 1 No. 1 No. 1 No. 6 Nos.
[2] CONTROL CARDS	[2a] DIGITAL CARD [2b] ANALOG CARD [2c] PROTECTION CARD [2d] RELAY CARD [2e] LOAD CT/CLAMP CARD [2f] FILTER CARD [2g] GATE DRIVE CARDS	1 No. 1 No. 1 No. 1 No. 1 No. 1 No. 3 Nos.
[3] SWITCHGEAR SECTION	[3a] AUXILIARY BYPASS CONTACTORS [K4] [3b] START CONTACTOR [K1] [3c] STOP CONTACTOR [K2] [3d] MAIN CONTACTOR [K3] [3e] POWER (BYPASS) CONTACTOR [K5] [3f] MCCB/MCB [3g] ISOLATION TRANSFORMER FOR CONTROL LOGIC & ELECTRONICS [3h] POTENTIAL TRANSFORMER (VOLTAGE SENSING) [3i] PRECHARGING RESISTOR [3j] INCOMING FILTER CAPACITOR & RESISTOR [3k] SMOOTHING REACTOR & SURGE ABSORPTION [3 Ph. DIODE RECTIFIER BASED] [3l] INCOMING HRC FUSES	1 No. 1 No. 1 No. 1 No. 1 No. 1 No. 1 No. 3 Nos. 3 Nos. 3 Nos. 3 Nos. 3 Nos. 3 Nos. 3 Nos. 3 Nos.
[4] CONTROL POWER SUPPLY	[4a] +5V POWER SUPPLY (PS-1) +12V POWER SUPPLY (PS-1) +15V POWER SUPPLY (PS-1) [4b] +20V POWER SUPPLY (PS-2) ISOLATED POWER SUPPLIES FOR GATE DRIVE CARDS	1 No. 1 No. 1 No. 1 No.
[5] PWM BOOST REACTOR CUBICLE	[5a] THREE PHASE PWM BOOST REACTORS [5b] FILTER CAPACITOR [5c] PROTECTION & METERING CT	1 No. 3 Nos. 3 Nos.
[6] OUTER PANEL	[6a] AMMETER FOR STATCON LINE CURRENT [6b] VOLTMETER FOR INCOMING VOLTAGE [6c] START PUSH BUTTON [6d] STOP PUSH BUTTON [6e] AMMETER SELECTOR SWITCH [6f] VOLTMETER SELECTOR SWITCH [6g] NAME PLATE	1 No. 1 No. 1 No. 1 No. 1 No. 1 No. 1 No.

Fig. 3.18 Contd..



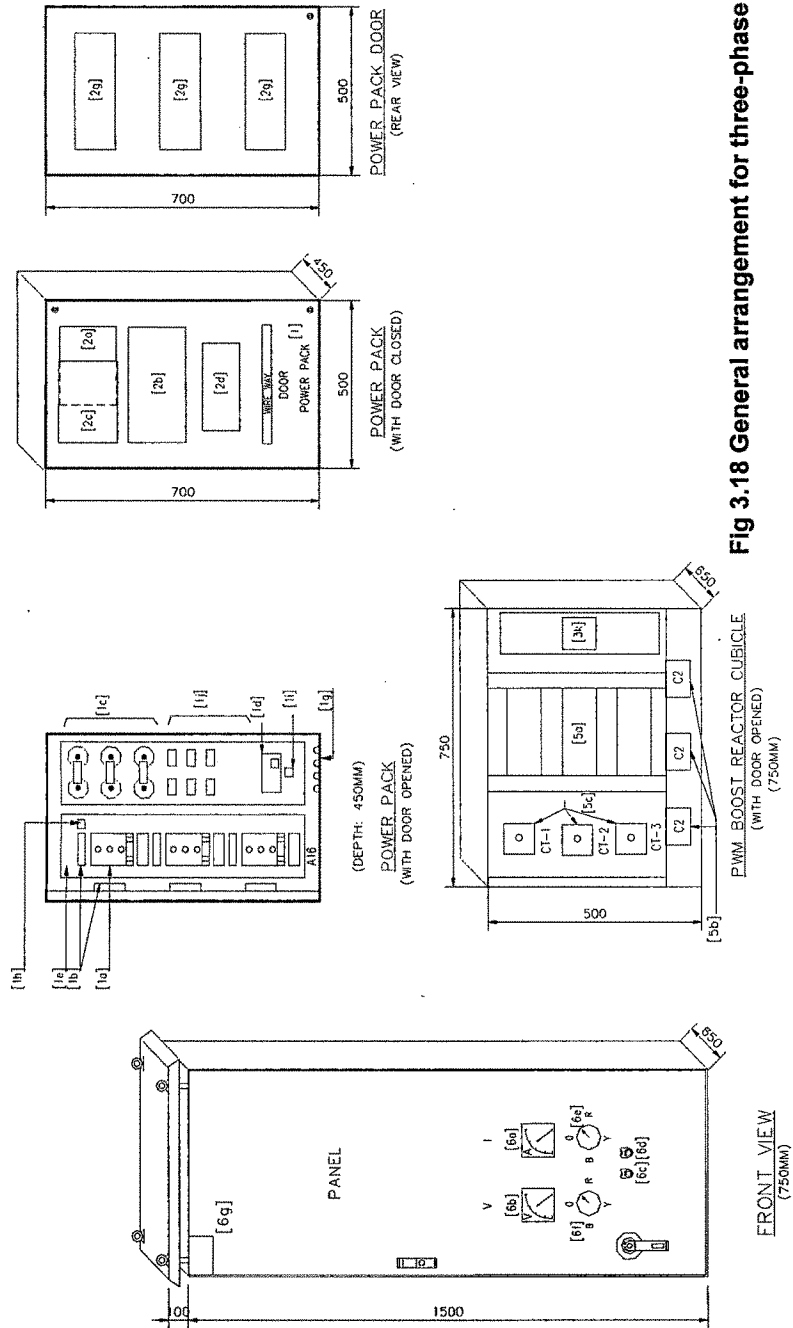


Fig 3.18 General arrangement for three-phase STATCON

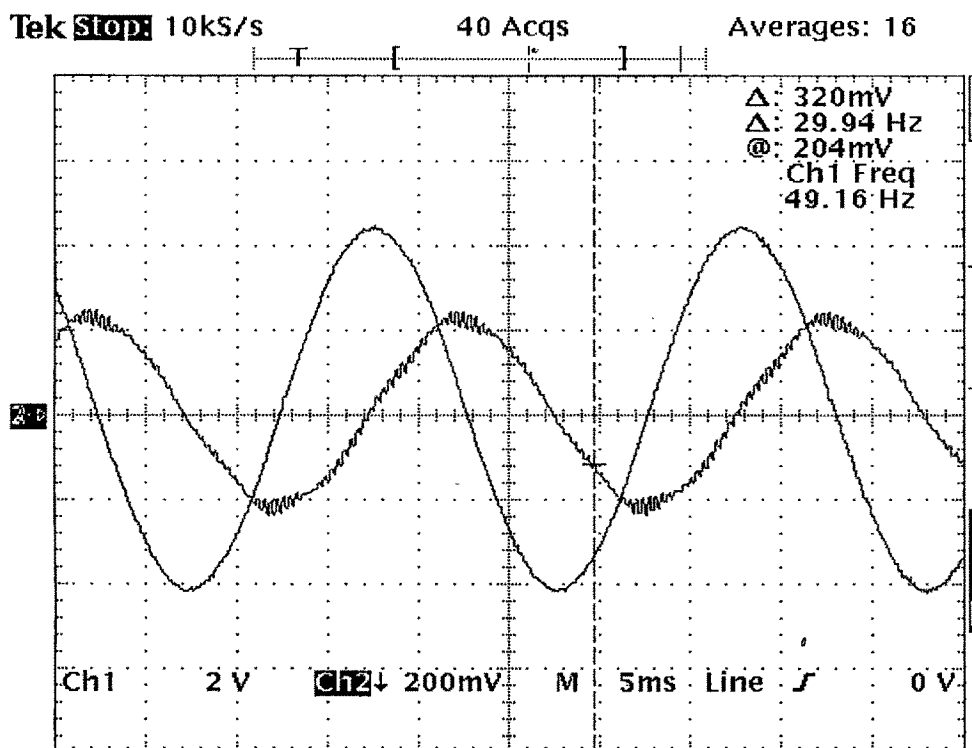


Fig. 3.19 (a) Inductive Mode of Operation

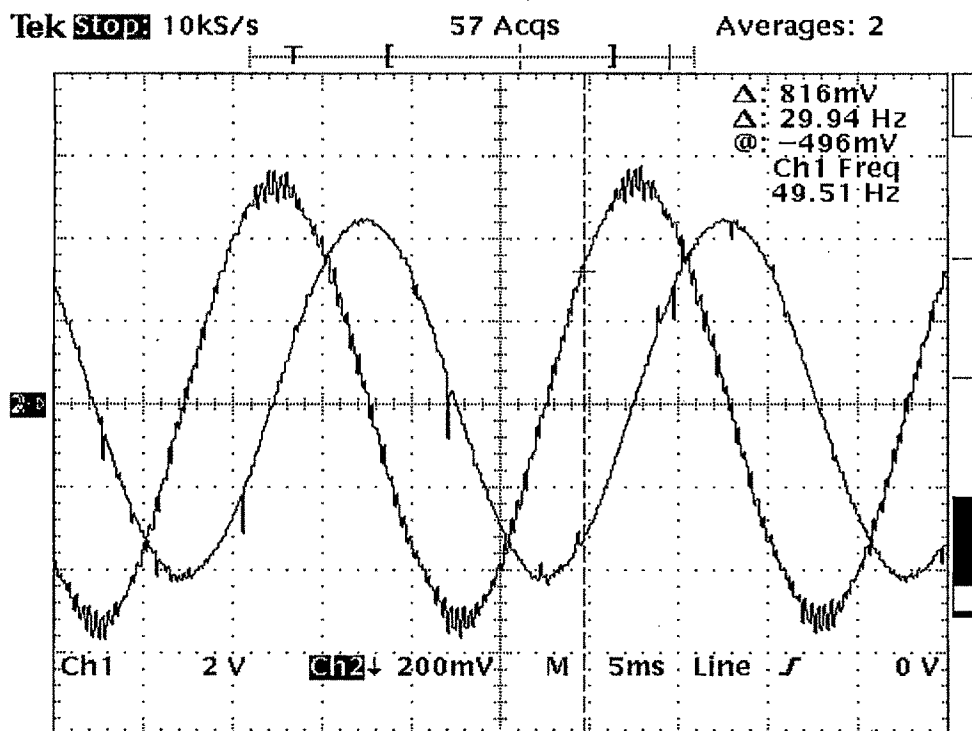


Fig. 3.19(b) Capacitive Mode of Operation

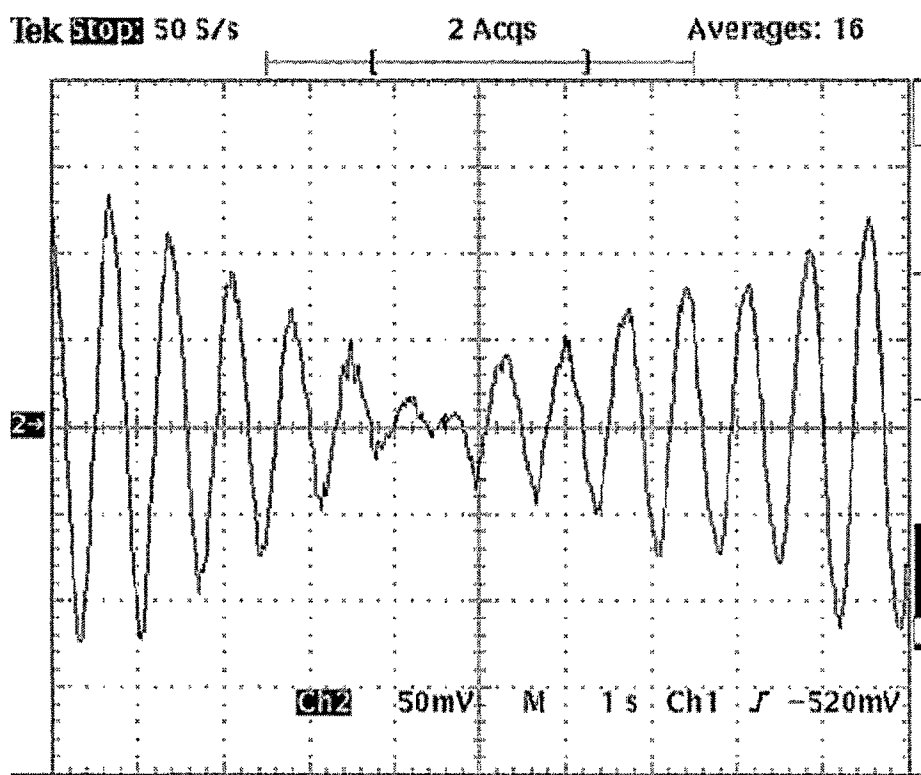


Fig. 3.20 (a) Mode changeover response

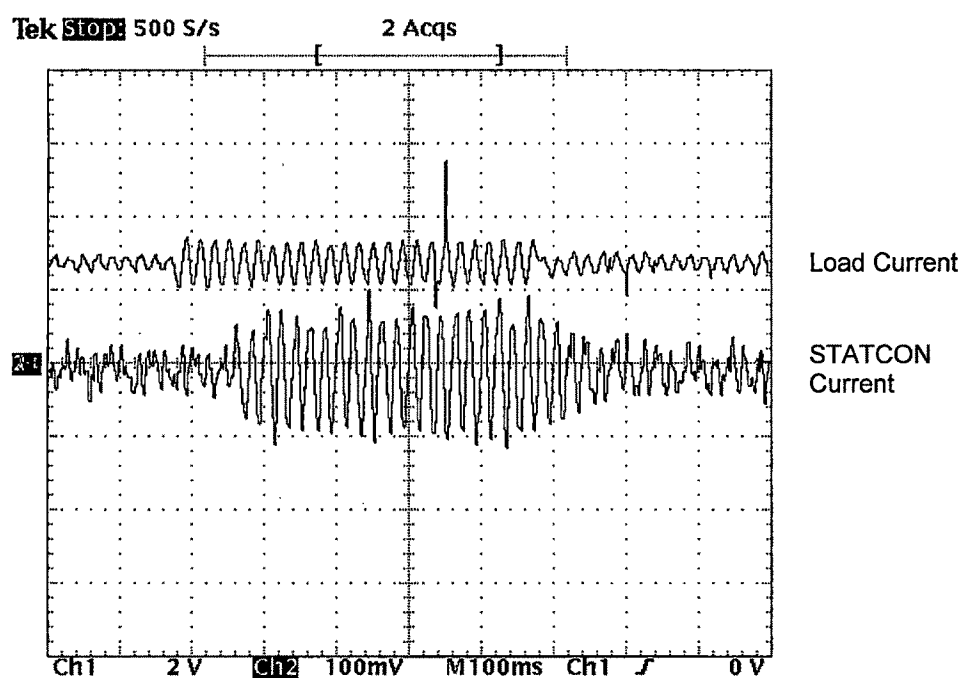
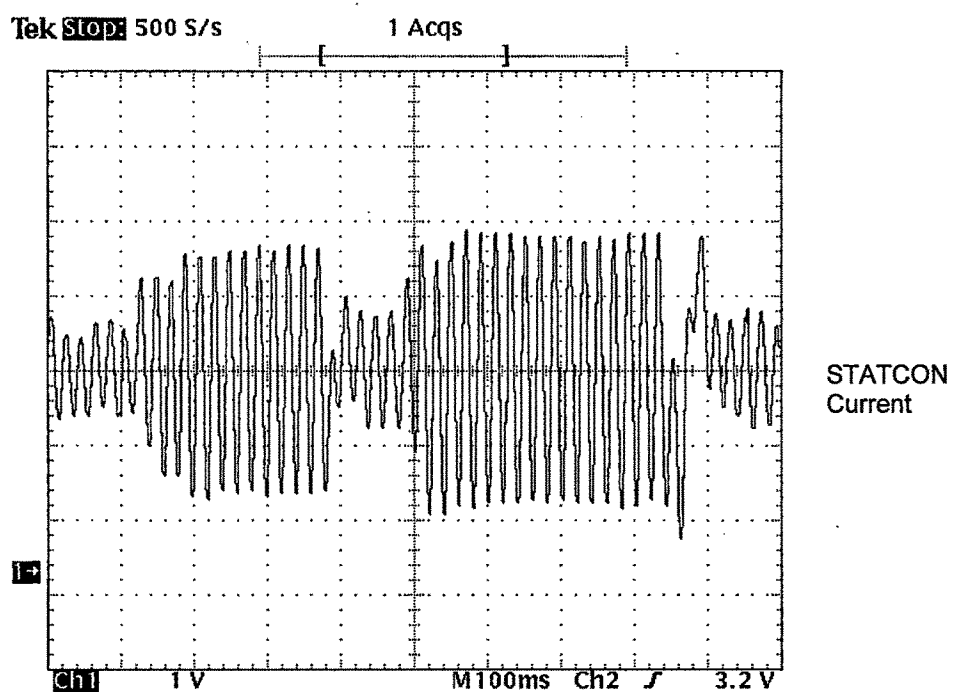


Fig. 3.20 (b) Dynamic response

Fig. 3.13

This figure is used for calculation of the supply voltage distortion based on 'n'th harmonic current ripple fed to the supply and being filtered through an appropriately sized capacitor connected in shunt with the supply terminals. The capacitor presents relatively a small impedance ($1/n\omega C$) to the 'n'th harmonic frequency as compared to the short circuit impedance of the supply network ($n\omega L_b$) and hence restricts the harmonic current flowing into the supply network.

Fig.3.14 (a)

This figure gives the Control Logic (sequencing and interlocking operations) for the three phase STATCON fed through a 240 V isolation transformer. The logic is simple and utilizes basically control contactors and relays (from Relay card).

On receipt of the start command through a start push button [1], the start contactor [2] closes. Then the micro-controller gives command for the main contactor [3] to operate to charge the capacitor stack of the converter. Further, the micro-controller will give command for the bypass contactor [5] to close to allow the STATCON function as a reactive power compensator. On receipt of stop command, given from a stop push button [7], or sensing of any fault, the micro-controller will first stop the IGBT firing, bring down the supply currents to zero value, and give command for the bypass contactor [5] to open. It will then give command for the main contactor [3] to open. The auxiliary contactor [4] is used for operating the bypass contactor coil. The stop contactor [6] operates when stop command is delivered by a stop push button.

Fig. 3.14 (b)

This figure explains how the Control Electronics is interfaced with the Control Logic, regulated / isolated IGBT Gate power supplies, DC voltage sensor, filtered incoming ac voltage and the



Gating for the IGBT's. It also shows the connections within various control cards. These cards and their functions are explained later. The required controlled / regulated power supplies for the control cards are as given below.

+5 V dc for the Digital card

+/- 12 V dc for the Digital card, Gate Drive cards, and Analog card

+/- 15 V dc for the Analog card, Protection card, Clamp card, and DC Voltage sensor card

+ 20 V dc, 6 numbers isolated power supplies for the IGBT triggering / firing.

All the power supplies are routed through the Relay card, except six numbers of the + 20 V dc power supplies. The major interconnections are done using flat cables between the cards.

Fig. 3.15

This is the flow chart for the sequence and interlocking operations of the three phase STATCON as executed by the micro-controller through its controlling software. It broadly explains the actions taking place in the STATCON after the power is switched on through the incoming MCB, and various checks the micro-controller carries out at different stages of the operation, till the required operation of reactive power control is effected. It also gives the information on how the STATCON folds back if there is any fault sensed.

Fig. 3.16

This figure is for providing the understanding of basic inputs and outputs of each card of the Control Electronics. It also establishes and explains how the incoming signals are received processed at various cards and finally how the output signals are delivered to the Gate drive cards, which control the IGBT firing.

The analog signals vary between +/- 10 V , +/- 5 V or 0 to +5 V while the digital signals have maximum value + 5 V dc.

This figure also gives block level schematic and understanding of each control card. The input / output and functional details of the cards are given later.

Fig. 3.17

This figure explains the architecture of the Digital card in a block form and also explains input / output relationship of the signals received / delivered by the card. Input / output and functional details of this card are given in chapter 4.

Fig. 3.18

This figure gives the general arrangement of various components and subassemblies within the three-phase STATCON panel or cubicle. These are numbered and explained. It gives an impact of how a panel / cubicle housing the complete STATCON assembly looks like. The panel / cubicle are basically of IP 31 protection class in construction but needs deration for higher protection classes (typically up to 35% when the class reaches IP54).

Fig. 3.19(a) and fig. 3.19(b)

These figures depict the basic operation of the STATCON while working in Inductive mode and Capacitive mode and confirm that the current drawn is at 90 degrees lagging or leading with respect to the supply voltage.

Fig.3.20 (a)

This figure gives the dynamic response of the three-phase STATCON when it changes mode of operation. The response is programmable and can be tuned with the load demanded response.

Fig. 3.20 (b)

This figure gives the dynamic response of the three phase STATCON current with respect to the load current. This response can be tuned and made to track the load current demand as close as possible based on demand and / or based on the system needs.

3.5.2.2 THREE PHASE STATCON: VITAL DESIGN ASPECTS

3.5.2.2.1 POWER SCHEME AND COMPONENT SELECTION

The three phase STATCON has following basic specifications.

- 415 V ($\pm 10\%$), ± 50 Hz ($\pm 5\%$), ± 85 A
- Incoming supply as 4 wire (3 phases and one neutral)
- All the internal power supplies to be derived from the incoming supply only
- Dynamic response time close to one cycle

The power scheme is given in fig. 3.11. It uses a three phase half bridge construction for the power converter. The power converter produces terminal voltage v_{li} (v_{lr} , v_{ly} , v_{lb} with respect to the neutral or the midpoint of the output capacitor bank voltage V_{dc}), as can be seen from fig. 3.12. Fundamental component of this voltage is v_{li} , (v_{lr} , v_{ly} , v_{lb}), as can be seen from the same figure. Each power switch (in this case IGBT, i.e. Insulated Gate Bi-polar Transistor) is

bi-directional. The converter configuration is Current-controlled Voltage Source Converter operating in boost mode. In this case input current i_s (i_{sr} , i_{sy} , i_{sb}) is controlled indirectly by controlling the voltage v_{i1} . Hence, current control method deployed is "Indirect Current Control (ICC)". The dc voltage V_{dc} needs to be more than the peak of supply phase to phase voltage so that the supply current can be forced in both the directions.

3.5.2.2.2 VARIOUS FORMULAE TO BE USED IN THE COMPONENT SELECTION OF THE CONVERTER AND THEIR RELEVANCE

1. Maximum v_{i1} required for capacitive operation

$$= (415 * 1.15) / \sqrt{3} + (85 * \omega L_b)$$

2. Minimum v_{i1} required for inductive operation

$$= (415 * 0.8) / \sqrt{3} - (85 * \omega L_b)$$

Design factor is 15% overvoltage and 20% undervoltage.

3. Peak ripple in the supply current at 50% duty ratio of the terminal switching voltage v_i switching between the levels $\pm V_{dc}/2$ is given by

$$(2 * V_{dc}) / (\pi * m_f * \omega L_b)$$

where

m_f = ratio of switching frequency of the IGBT devices to supply frequency.

Note that the switching frequency is also the same carrier frequency as explained above.

4. The converter equation (2) given earlier can be rewritten as

Capacitive mode

$$v_{i1} = V_m \sin \omega t + (I_{cm} * \omega L_b) \sin \omega t - (I_{cm} * R_v) \cos \omega t \quad (3)$$

Inductive mode

$$v_{i1} = V_m \sin \omega t - (I_{cm} * \omega L_b) \sin \omega t + (I_{cm} * R_v) \cos \omega t \quad (4)$$

or

Capacitive mode

$$v_{i1} = (V_m + I_{cm} * \omega L_b) \sin \omega t - (E) \cos \omega t \quad (5)$$

Inductive mode

$$v_{i1} = (V_m - I_{cm} * \omega L_b) \sin \omega t + (E) \cos \omega t \quad (6)$$

Here $I_{cm} = 85 * \sqrt{2} \text{ A}$

$$= 120 \text{ A}$$

Error E decides the angle ' δ ' in fig. 3.10 or the angular displacement of voltage V_{i1} from the supply voltage. The switching voltage v_i and hence the v_{i1} voltage is produced by using comparison of a triangular wave with a fundamental frequency signal ' v_c ' as shown in fig. 3.12. The converter thus uses Sinusoidal Pulse Width Modulation (SPWM) method for producing the switching voltage v_i .

The ratio of amplitude of v_c to the amplitude of the triangular waveform is modulation index (M_i). It should normally be below 1.0. However, over modulation is done using a third harmonic injection on the modulating signal v_c . The third harmonic being injected in phase with the fundamental signal v_c , has its amplitude 1/6th as that of the v_c . This gives around 15.5% increased v_{i1} for the same fundamental modulation index M_i .

Since the loss component $I_{cm} * R_v$ or E in equations (5) and (6) is quite small, the displacement angle ' δ ' of v_{i1} is also quite small. It is hence not necessary to consider both sine and cosine components of the third harmonic and one can consider only sine component only.

Thus 1/6th of the fundamental amplitude sine term, i.e. $(V_m \pm I_{cm} * \omega L_b) \sin 3\omega t$ needs to be added to equations (5) and (6). These equations hence get modified as under.

Capacitive mode

$$v_{i1} = (V_m + I_{cm} * \omega L_b) \sin \omega t + (1/6) * (V_m + I_{cm} * \omega L_b) \sin 3\omega t - (E) \cos \omega t \quad (7)$$

Inductive mode

$$v_{i1} = (V_m - I_{cm} * \omega L_b) \sin \omega t + (1/6) * (V_m - I_{cm} * \omega L_b) \sin 3\omega t + (E) \cos \omega t \quad (8)$$

These equations, Digital card micro-controller solves on a continuous basis. The STATCON basic functioning is based on these equations.

With only v_c considered superimposed on the triangular waveform, the V_{i1} voltage is given by

$$V_{i1} = (M_i * V_{dc}) / (2 * \sqrt{2}) \quad (9)$$

With superimposition of 1/6 the third harmonic, as discussed earlier, this voltage V_{i1} is given as

$$V_{i1} = 1.155 * (M_i * V_{dc}) / (2 * \sqrt{2}) \quad (10)$$

The linear relation between M_i and V_{i1} is valid for m_f (switching frequency to fundamental frequency ratio) greater than nine.

3.5.2.2.3 CONVERTER COMPONENT SELECTION

The converter component selection is an interactive process based on

- Formulae given above
- Various IGBT devices available and their characteristics
- Proving the power stack for requisite rating integrating the devices, the snubber components, dc capacitors and the forced cooling etc.
- Switching frequency choice related to above
- Integrated protection approach for the IGBT turn off within less than 12 microseconds
- Digital card developed around 80196 micro controller and its clock frequency, and
- Few other parameters

The component and parameters selected are as under (please see power scheme in fig. 3.11 and fig. 3.18 also).

Components

1. IGBT 200 A, 1400 V (Fuji make 2MBI 200PB -140, 2 in one with isolated base).
2. DC capacitors 4700 μ F, 450 V dc used for the IGBT stack.
3. Three phase, boost reactor 1.65 mH, 120 A.
4. Snubber - Diode 3A , 2000V , type UF 5408 , 2 groups in series with each having four in parallel. (Resistor 11 ohms, 100 W Capacitor 0.1 μ F, 2000V dc)
The snubber is connected across each device. Further, there is also 0.33 μ F, 2000 Vdc capacitor connected across the dc terminals of each IGBT module.
5. Blower – Single phase , 240 V , 500 cubic feet / min.
6. Heatsink - AFCOSET 80 AD (645 H * 126 W * 136.D) anodized.
7. DC cap. discharge resistor – 15 K , 25 W.
8. Main MCB – 415 V, 150 A, 3 pole.
9. Main contactor – 415 V, 40 A, 3 pole with 240 V ac coil.
10. Bypass contactor – 415 V, 150 A, 3 pole with 240 V ac coil.
11. Pre-charging resistor – 10 Ohms, 200 W.
12. Ripple filter capacitor – 12.5 μ F, 2000 V dc per phase.
13. Incoming R-C filter – 5 Ohms, 100 W and 4 μ F, 660 V.
14. Incoming smoothening inductor 20 μ H, 120 A (three phase).

15. Incoming surge energy absorption
 - Diode 70A, 2000 V (3 modules with 2 in one with isolated base or 6 nos.).
 - Current limiting resistor 27 ohms, 100W
 - DC capacitor 1000 μ F, 450 V dc, 2 nos.
 - Discharging resistor 27 K, 100 W.
 - All of these are mounted on a small anodized heatsink (300 H * 150 W * 60 D)
16. Heatsink temperature sensor type N/C operating at 90 degrees.
17. HRC fuse in supply lines rating 125 A , 500 V.
18. Protection CT in each line rating 200 A / 1 A suitable for 415 V supply voltage.
19. Control / Isolation transformer for feeding the Control Logic and power supplies for Control Electronics. This is 415 V / 240 V , with 3 kVA rating.
20. Three numbers of control transformers for the purpose of sensing incoming phase voltages. These are 240 / 3 V , with 6 VA rating each.

Parameters

1. Digital processor N80 C 196 KC 20 (16 bit) operated at 12 MHz
2. Switching frequency of IGBT (carrier frequency) 2.8 kHz
3. IGBT stack cooling. Forced cooled with specified blower
4. Modulating waveform optimized to 24 pulse (15 degrees per step) in each 15 degrees, the controller computes the modulating signal level based on fresh information of all the parameters.
5. In each cycle (before its completion) all information related to voltages, current, frequency and associated operating limits (dynamic) are updated. Correct synchronization is maintained. Thus, every cycle resynchronization with updated parameters takes place. However, the response of the converter is just a little over one cycle (less than 1 cycle and 15 degrees).
6. 'R' phase is considered as the master phase. Computations related to 'Y' and 'B' phases are based on 120 and 240 degrees relationship with respect to the 'R' phase.

Results based on iterations

1. The converter dc voltage has been finally selected as 850 V dc. The switching frequency selected is 2.8 kHz.

2. Input current ripple (peak)

$$= (2 * 850) / (\pi * (2800/50) * 2 * \pi * 50 * 1.65 \times 10^{-3})$$

$$= 18.64 \text{ A at 2.8 kHz}$$

3. V_{i1} variation required (per phase)

$$(240 * 1.1 + 85 * 1.65 * 10^{-3} * 2 * \pi * 50) = 308 \text{ V}$$

$$(240 * 0.8 - 85 * 1.65 * 10^{-3} * 2 * \pi * 50) = 148 \text{ V}$$

Thus the variation is from 308 V to 148 V AC.

At 850V dc, it means modulation index M_i varying from

$$\text{from } (308 * 2 * \sqrt{2}) / (1.155 * 850) = 0.89$$

$$\text{to } (148 * 2 * \sqrt{2}) / (1.155 * 850) = 0.426$$

The restricted modulation index M_i to a maximum of 0.89 allows the modulating signal v_c to remain lower than the triangular waveform amplitude and leaves some margin to account for dynamics of the load.

4. Expected displacement angle

Consider fig. 3.11 (a).

The maximum $I_c * \omega L_b$ drop $(85 * 2 * \pi * 50 * 1.65 * 10^{-3}) = 44 \text{ volts}$

Assume a worst case $I_c * R_v$ drop of 10% of this nature

Thus $I_c * R_v = 4.4 \text{ volts}$

Thus maximum ' δ ' in capacitive mode is given by

$$\tan^{-1} (4.4 / (240 * 1.1 + 44)) = 0.82 \text{ degree.}$$

Similarly maximum ' δ ' in inductive mode is given by

$$\tan^{-1} (4.4 / (240 * 0.8 - 44)) = 1.7 \text{ degree.}$$

It shows that the displacement ' δ ' angle of the vector V_{i1} with respect to the phase voltage V_s (V_{sr} , V_{sy} or V_{sb}) is quite small but is essential for the converter operation. This is in line with what was stated earlier while introducing equations (3) to (8).

5. Incoming voltage distortion (calculated for a typical short circuit capacity of the network)

Assume that at the coupling point of STATCON the short capacity of the network is say 30000 KVA.

Refer fig. 3.13 for the voltage distortion analysis.

Short circuit impedance ($\omega * L_b$)

$$= (3 * 240 * 240) / (30000 * 1000)$$

$$= 0.00576 \text{ Ohms}$$

Therefore, impedance at switching frequency

$$= (2800 * 0.00576) / (50) = 0.265 \text{ Ohms}$$

Further, Filter capacitor impedance at 2.8 kHz

$$= (1000 * 1000) / ((2800/50) * 2 * \pi * 50 * 12.5) = 4.547 \text{ Ohms}$$

Therefore, RMS value of the incoming voltage distortion due for switching frequency will be:

$$= 100 * (18.64 * 4.547 * 0.265) / (240 * \sqrt{4.547^2 + 0.265^2}) * 1.4142$$

$$= 1.263 \%$$

It shows that higher the short circuit capacity of the network, lesser will be the voltage distortion.

1. The converter dc side second harmonic ripple current is expected to be very small. This is because the total ripple current is summation of contribution by each phase of the three phases, which are displaced by 120 degrees.

$$[\cos 2\theta + \cos (4\pi/3 + \theta) + \cos (8\pi/3 + \theta)] = 0$$

3.5.2.2.4 CONTROL SCHEME AND LIST OF FUNCTIONS IN CONTROL ELECTRONICS CARDS

The control scheme is given in fig. 3.14. It basically consists of two parts.

- Control Logic
- Control Electronics

These are given in figs. 3.14 (a) and (b) respectively.

The heart of the system is the micro-controller based Digital card assembly, which performs the following important functions.

- Sequencing and interlocking of the entire STATCON
- Solving the mathematical model given by the equations (7) and (8) and outputting the necessary three modulating signals (v_{cr} , v_{cy} , v_{cb}) for the three phases dynamically.

- Updating of all parameters (voltage, current, dc voltage, frequency, error E in equations (7) and (8) etc.) and sequencing the operation once again at the start of every cycle.
- Checking for receipt of any protection signal and giving an output command for the withdrawal of IGBT gate pulses.
- Checking for its own hardware health.

Fig. 3.15 gives a flow chart, which expresses the complete sequence of operations in the STATCON as controlled by the brain 'micro-controller'. The operational sequence for the STATCON is described here. In fig. 3.14(b), the Relay card is an important card interfacing the Controls Electronics with the Control Logic and the regulated power supplies for the Control Electronics.

It receives feedbacks (three phase voltages, three phase currents, DC voltage sensor output, heat sink temperature monitor, door interlock, and control contactors' on/off conditions) and gives out commands for the operation of control and the power contactor as explained later.

The Control Logic is fed from a separate isolation transformer 415 / 240 V. It takes 415 input from phases "Y" and "B". The 240V power supply input for all the regulated power supplies (+/- 15V, +/- 12V, +5V and +20 V) is also supplied from the same transformer.

The Control Electronics, except for the micro-controller based digital card, uses mainly a single operational amplifier IC (TL084, Quad Opamp) for implementing all the functions like comparator, monoshot, gain amplifier, buffer amplifier, differentiator, zero cross detector etc. The triangular waveform is the only waveform generated by using the IC 566. Thus all functions, protections, signal processing, PWM generation, IGBT pulse release / suppression, level shifting, IGBT deadband generation (minimum delay to avoid simultaneous firing of two IGBT's in the same leg), sequencing and interlocking signal, etc are based on use of this IC TL084 which is the discrete and significant feature of this control electronics.

3.5.2.3 OPERATING SEQUENCE OF THREE-PHASE STATCON PANEL

1. Connect the three phase 415 V supply input with neutral and earth connections to the panel. Source capacity should be at least 200 A.
2. Keep IGBT gate control switch in appropriate ON/OFF condition (as desired during testing).
3. Now panel incoming power source can be switched "ON".

4. Panel incoming MCB to be switched ON.
5. Power supply LED's for 5V,+/-12V, +/-15V, as well as for Gate drive power supply will glow.
6. Processor (micro-controller) initializes.
7. Hold is generated by processor in @6 μ sec after power supply availability during panel switch ON.
8. Main contactor is turned ON by processor after @120 secs, after panel being switched ON.
9. DC bus gets charged to @ 560 V dc.
10. Protection card LED's are to be RESET using respective toggle switch in the Protection card.
11. Two LEDs (L8 and L9) on Protection card glow indicating presence of Hold signal from processor and hold being generated by protection card.
12. Red LEDs on Gate drive card also glow indicating presence of Hold on gate drive outputs.
13. Meantime processor checks health of RAM on the Digital card.
14. Then processor checks health of NVRAM on the Digital card.
15. Processor generates internal start command, which operates corresponding relay on the Relay card (This signal is generated after about 3.3sec subsequent to main contactor being turned ON).
16. Processor waits for START INPUT (given through a push button in the panel) to go to next step.
17. On receipt of start input, Processor executes series of control actions without any user interaction in healthy condition of the panel.
18. Processor measures frequency through available zero crossing signal. If frequency is not found within 45 to 55Hz for next 4 cycles, it declares faulty condition and withdraws the contactor as per withdrawal procedure.
19. Processor measures R phase voltage with available R phase voltage peak detector signal. If voltage exceeds the limiting value 323 V rms, it declares faulty condition after checking for 20 cycles and withdraws the contactor as per withdrawal procedure.

20. After reading R Phase voltage, it generates the limiting values for any subsequent voltage read for R phase as well as Y & B phase (limits: + 20%, - 30%).
21. Processor measures Y phase voltage with available Y phase voltage peak detector signal. If voltage exceeds the limiting value 323 V rms, it declares faulty condition after checking for 20 cycles and withdraws the contactor as per withdrawal procedure.
22. Processor measures B phase voltage with available B phase voltage peak detector signal. If voltage exceeds the limiting value 323 V rms, it declares faulty condition after checking for 20 cycles and withdraws the contactor as per withdrawal procedure.
23. Processor now waits for about 10 sec.
24. Processor measures DC bus voltage. If voltage is below the limiting value 400 V, it declares faulty condition after checking for 20 cycles and then withdraws contactor as per withdrawal procedure.
25. Now processor switches on the bypass contactor (Power contactor to carry STATCON current). This switching ON is about 50 sec from subsequent to START input being made available as mentioned in step 16.
26. On operation of bypass contactor, resistance in the series path of Inductor & IGBT is bypassed in the power circuit and the DC bus voltage changes by @10volts.
27. Processor now waits for further 30 sec so as to allow stabilization of conducted noise due to sudden switch on operation of bypass contactor.
28. Processor now checks receipt of feedback on closing of the bypass contactor and ensures that bypass contactor has operated. If feedback signal is not available it declares faulty condition and withdraws the contactor as per withdrawal procedure.
29. Processor does basic house keeping i.e. update of freq., phase voltage and DC bus voltage. If any of the values are outside the limits as set earlier, it ignores and continues with the last valid value.
30. Processor now is waiting for SYNC interrupt to come. This is generated by R phase positive half cycle start monoshot, which is fed through Protection card to Digital Control card.
31. Processor remains in infinite loop if monoshot is not available.

32. On availability of SYNC interrupt, Processor starts throwing sinusoidal dummy cycles on Modulating Signal output without release of hold signal for about 100 cycles. During this dummy cycles, it checks for presence of tripping signals viz. STOP/Bypass withdrawn/Start withdrawn signal. If it finds so, it declares faulty condition and withdraws the contactor as per withdrawal procedure.
33. Subsequent to dummy cycles, Processor releases Hold so as to facilitate generation of Gate drive pulses and switching ON of power devices, *i.e.* IGBT.
34. Release of hold marks beginning of active cycles with reactive current magnitude considered as ZERO for about 40 cycles. During this time when active cycles are released, it checks for presence of tripping signals viz. STOP/Bypass withdrawn/Start withdrawn/ Fault signal. If it finds so, it declares faulty condition and withdraws the contactor as per withdrawal procedure.
35. Subsequent to completion of active cycles, Processor is ready for generating demanded Reactive Compensation. Before entering into this final Core operating mode, it checks for DC bus voltage has been boosted during Active cycles *i.e.* beyond reference value 750V. If it finds the value below the set value, it declares faulty condition and withdraws the contactor as per withdrawal procedure.
36. Now processor enters in the final control mode of "Dynamic Statcon Current Generation Cycle", *i.e.* infinite loop of control by generating appropriate Modulating Signals based on available current feedback in accordance with respective phase voltage and appropriate internally generated Error Signal (PI). During this control of Core-Reactive Cycles, it checks for presence of tripping signals viz. STOP/Bypass withdrawn/Start withdrawn/ Fault signal. If it finds so, it declares faulty condition and withdraws the contactor as per withdrawal procedure

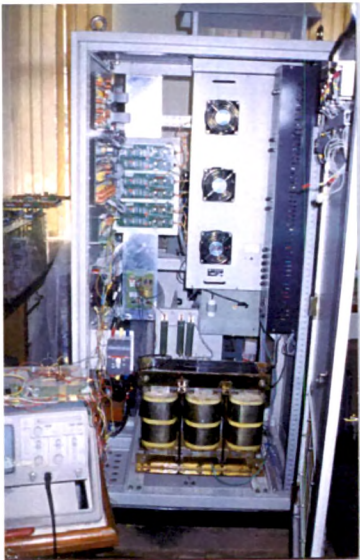
Withdrawal procedure

1. Generation of Hold signal immediately on detection of fault/tripping condition
2. Waiting period of 3 sec
3. Withdrawal of start contactor
4. Waiting period of 5 sec
5. Withdrawal of Bypass contactor (If in energised condition)

6. Waiting period of 5 sec
7. Withdrawal of main contactor
8. Waiting period of 38 sec
9. Loop back to step 16 where processor waits for start Input

3.5.2.4 PRODUCT PHOTOGRAPHS AND FIELD RESPONSES

Photograph of initial prototype panel for three phase operation



3.21 (a) Photograph of Prototype Three phase STATCON panel

Scheme for typical installation in windmill is as below

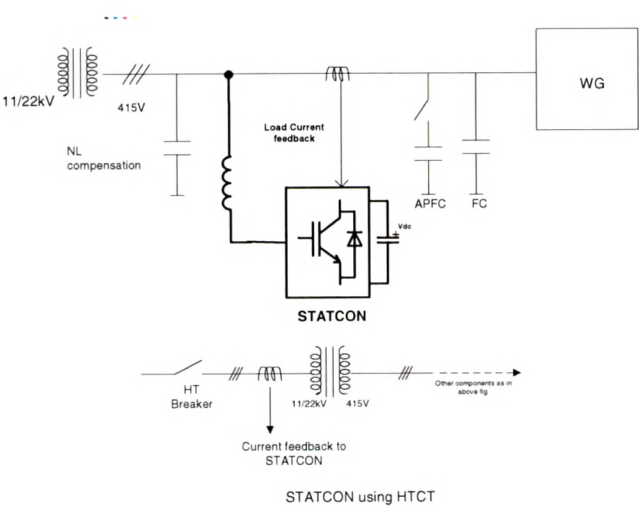


Fig. 3.21 (b) STATCON based compensation scheme for windmill



Fig 3.21 (c) STATCON installation in site at Nagercoil (TN), India on 250kW windmill

The field responses taken for a 225 kW Windmill is given in figs. 3.19 to 3.20. Some more images for the inductive and capacitive mode of operation are also as below in fig 3.21(d).

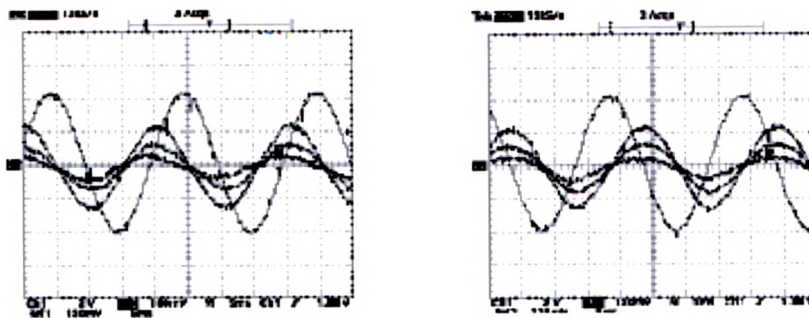


Fig. 3.21 (d) more windmill responses

These cover the modes of operation, mode changeover and dynamics of the three-phase STATCON.

3.5.2.5 SINGLE-PHASE STATCON

For Single-phase STATCON following figures details the design

- Fig. 3.22 Power scheme for the single phase STATCON;
- Fig. 3.23 PWM generation based on SPWM method;
- Fig. 3.24 Circuit diagram for the voltage distortion analysis;
- Fig. 3.25 (a) Control logic;
(b) Control electronics;
- Fig. 3.26 Flow chart;
- Fig. 3.27 Signals received and delivered by various control cards;
- Fig. 3.28 Block diagram of digital card;
- Fig. 3.29 General arrangement of single phase STATCON;
- Fig. 3.30 Dynamic response

Fig. 3.22

This is the power scheme diagram for the single-phase STATCON, which includes all the power components starting from acceptance of input power supply to the IGBT power stack. Basically it uses a single-phase full bridge construction for the Voltage Source Converter with two bridges connected in parallel to improve the kVAR rating. It also shows ac voltage sensing transformer, control transformer for control logic and electronic cards, power supplies, incoming diode rectifier for surge absorption, incoming voltage spike or surge suppressor, R-C-D snubber arrangement, and the power contactor arrangement.

When the main Moulded Case Breaker (MCB) [1] is closed, it gives the single-phase power to STATCON and impressing the single-phase voltage across its input terminals. The HRC fuses [2] is meant for short circuit protection. The incoming smoothening inductor [3] and the diode rectifier based surge energy absorber [5,6,7,and8] are effective when there is a sudden power failure. The rectifier output capacitors absorb trapped energy in the network and save the STATCON from any damage due to overvoltage or voltage transients. The R-C based surge suppressor [9] absorbs transients on the incoming supply network. The main contactor [11] closes initially and charges the DC capacitor stack [20] to peak of incoming phase voltage (approximately 339 V for a single phase supply of 240 V) through the charging resistor [12] with a limit on the supply current drawn. These DC capacitors are also provided

with discharge resistors [21] across their terminals to discharge them when the power fails or STATCON is switched off for any reason. The bypass contactor [13] closes when the micro-controller releases the command for it to operate. It then bypasses the main contactor and carries the supply line currents. Once the bypass contactor is closed, the IGBT converter or STATCON as a whole is ready to perform, but will be controlled by the micro-controller in the digital card. It then charges the DC bus voltage from the nominal voltage of 587 V to 850 V dc (called as boost charging of the DC capacitor stack) and subsequently the converter or STATCON performs as the reactive power compensator. The control transformer 240 / 3 V [4] is meant for providing incoming voltage information to control electronics. The 240 / 240 V transformer [10] is used for supplying isolated power to control logic and control electronics. The filter capacitor [14] after the bypass is meant for filtering the input current ripple generated by the switching of the IGBT devices. The protection CT [15] measures the input currents and provides information to be used for sensing overcurrent in supply lines. The boost reactors [16] allow boost charging of the stack to 600 V dc and isolate the incoming supply from the two IGBT converters operating in parallel. This single phase STATCON uses two converters in parallel to provide the necessary current rating. The IGBT switches, as shown by [19 and 22], are bi-directional allowing the current to flow in both directions. In forward direction, the switch is controlled based on pulse delivery to the IGBT gate with respect to its emitter, while the reverse direction conduction depends on the IGBT not having a pulse to its gate and the diode being forward biased. The snubber devices (R-C-D) [18] are meant for providing dv / dt , di / dt and hole storage / reverse recovery protection for the IGBT's. Additional protection for the devices is also given using snubber capacitors [17] across the positive and negative DC bus of the converter and located near each IGBT module. The capacitor stack is maintained at 600 V dc during running condition of the STATCON. Since the output dc ripple current is high, five dc parallel capacitor sections are used to filter the same.

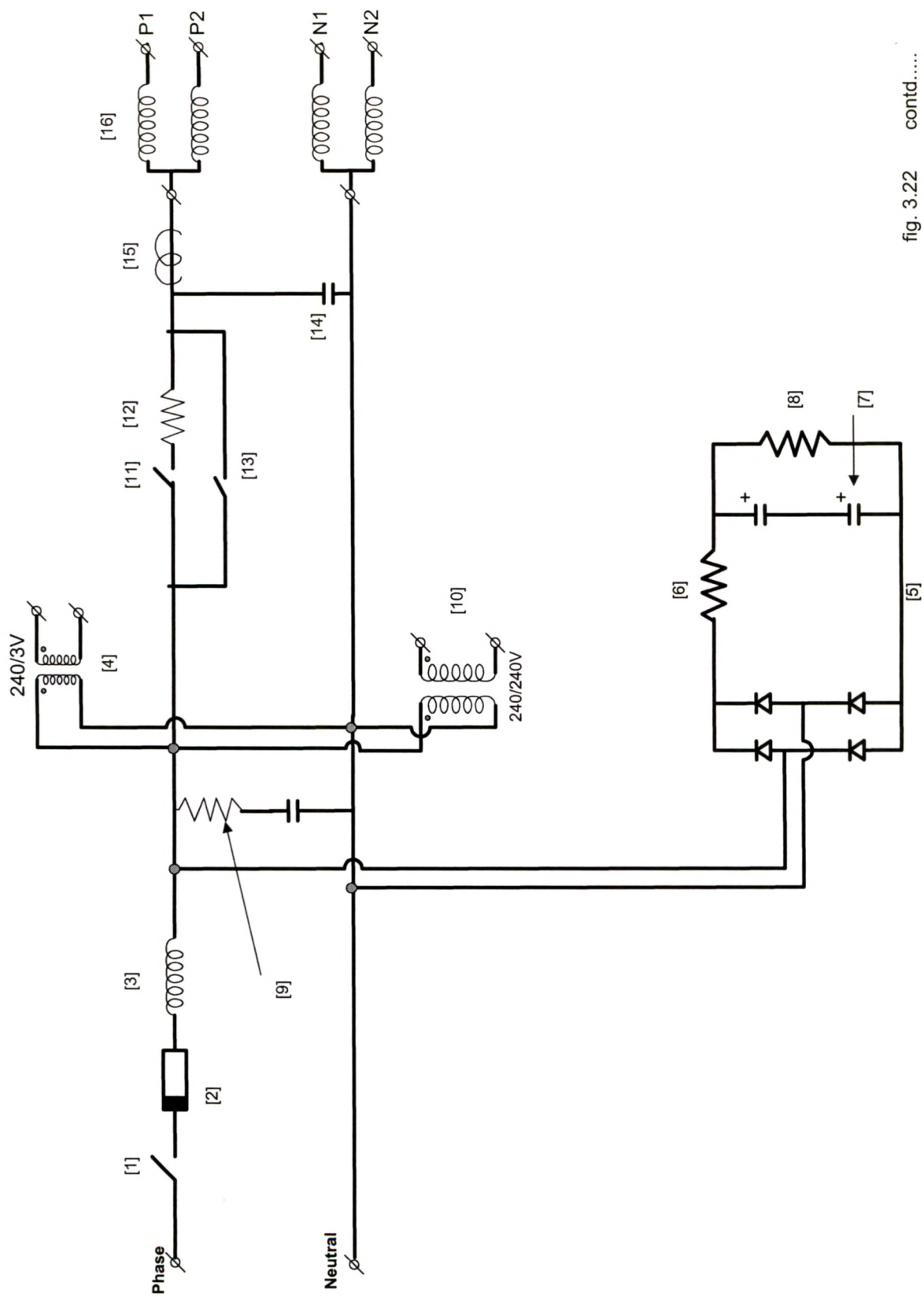


fig. 3.22 contd.....

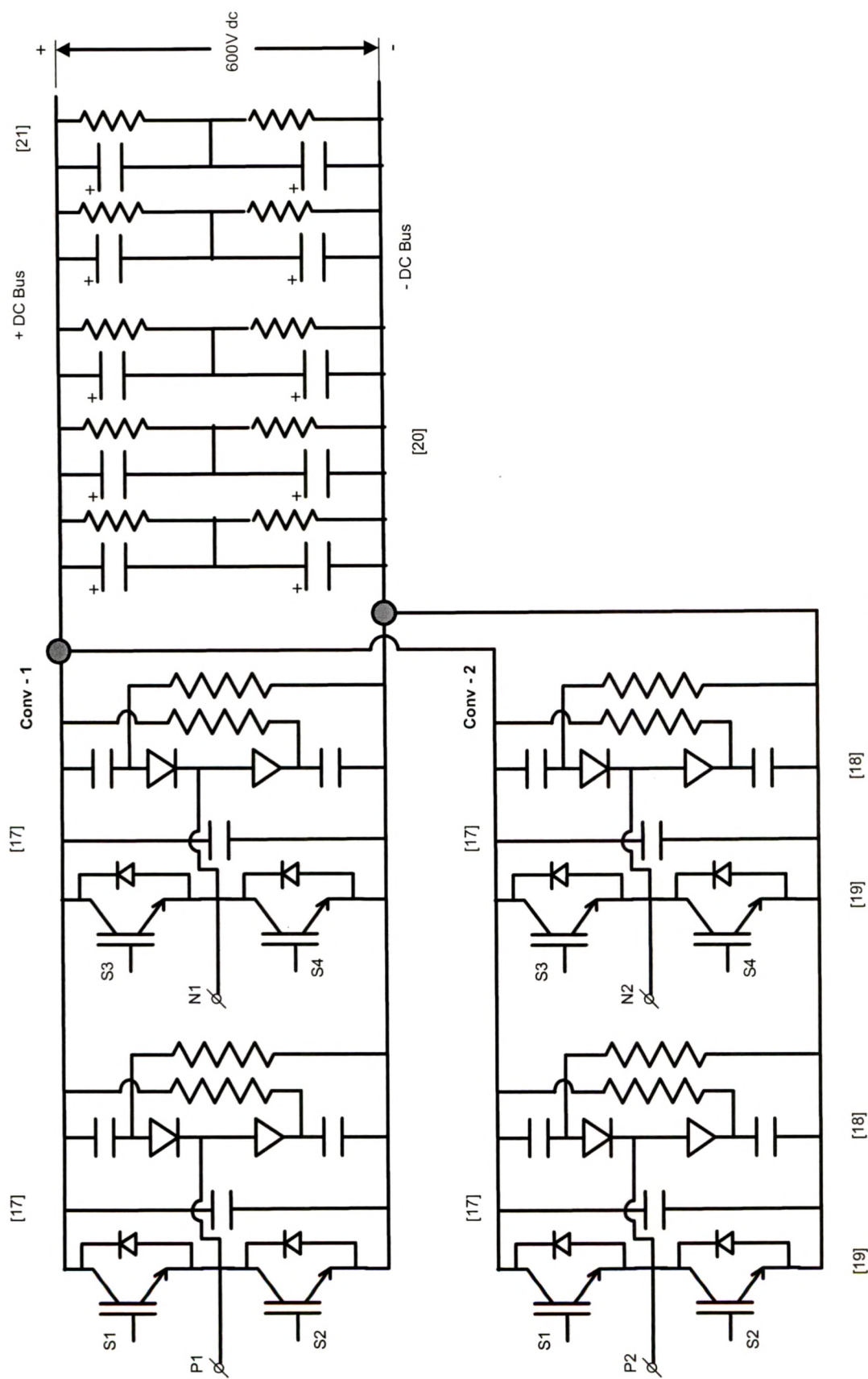


Fig. 3.22 contd.....

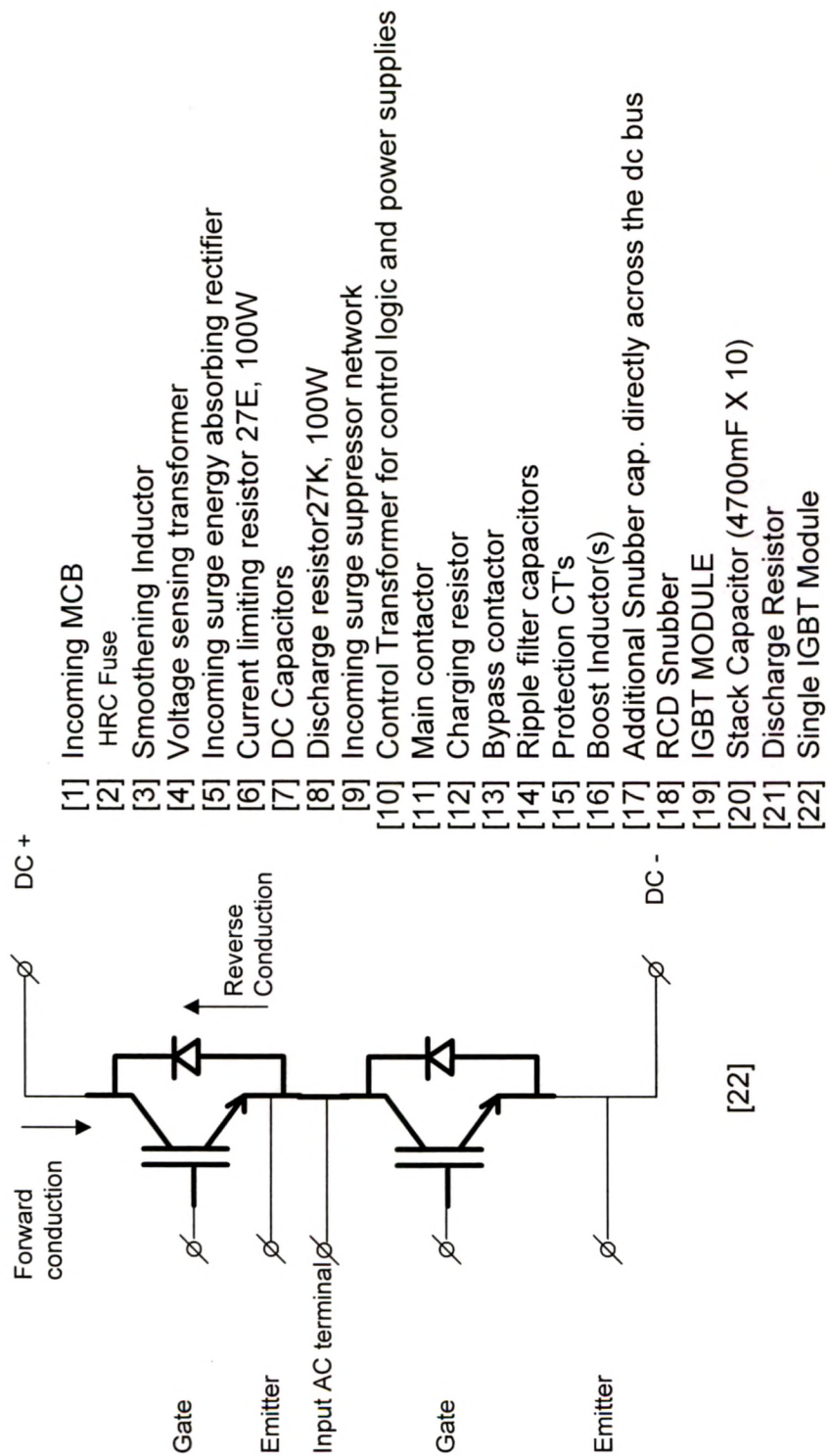


Fig. 3.22 Power Scheme for the single phase STATCON

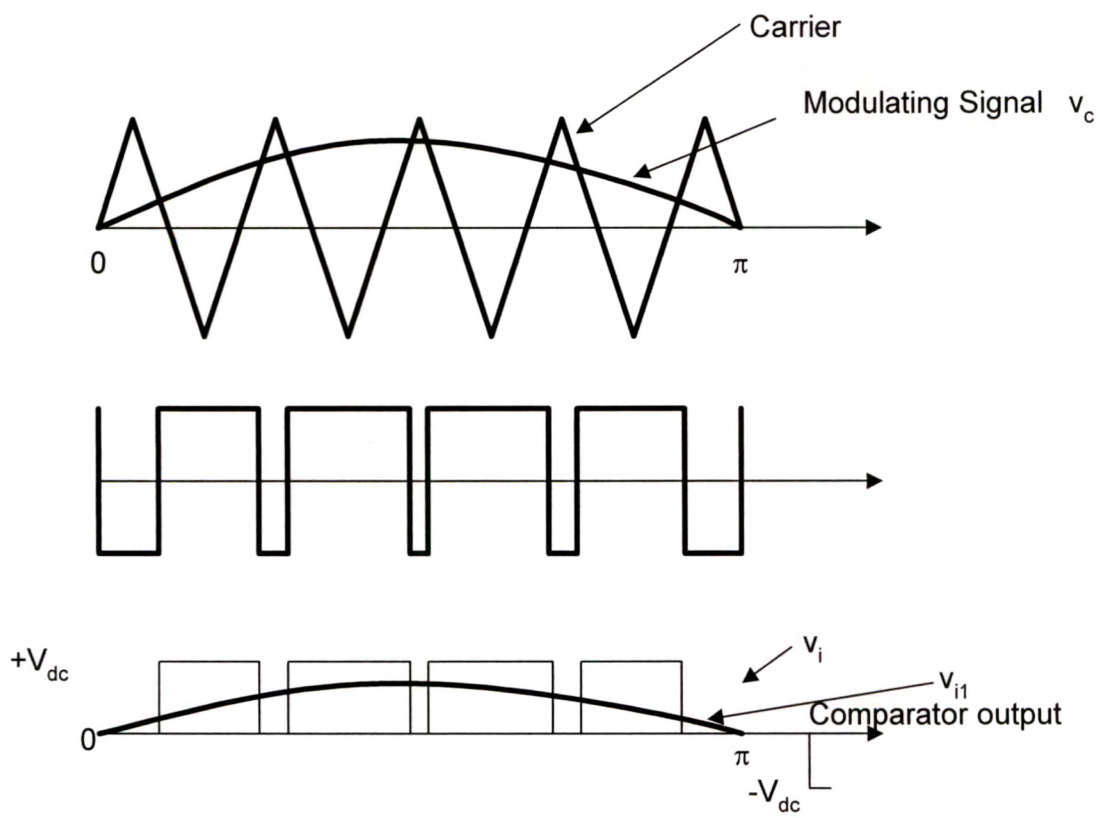


Fig. 3.23 PWM generation based on SPWM method

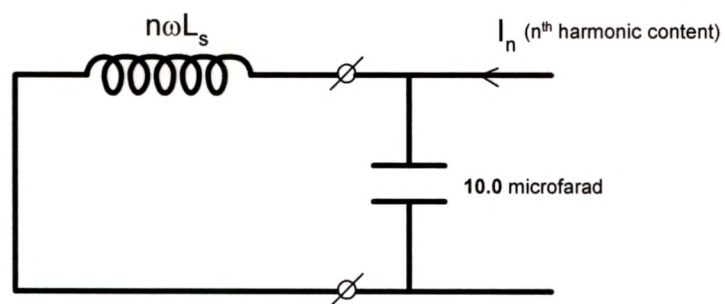


Fig. 3.24 Circuit diagram for the voltage distortion analysis

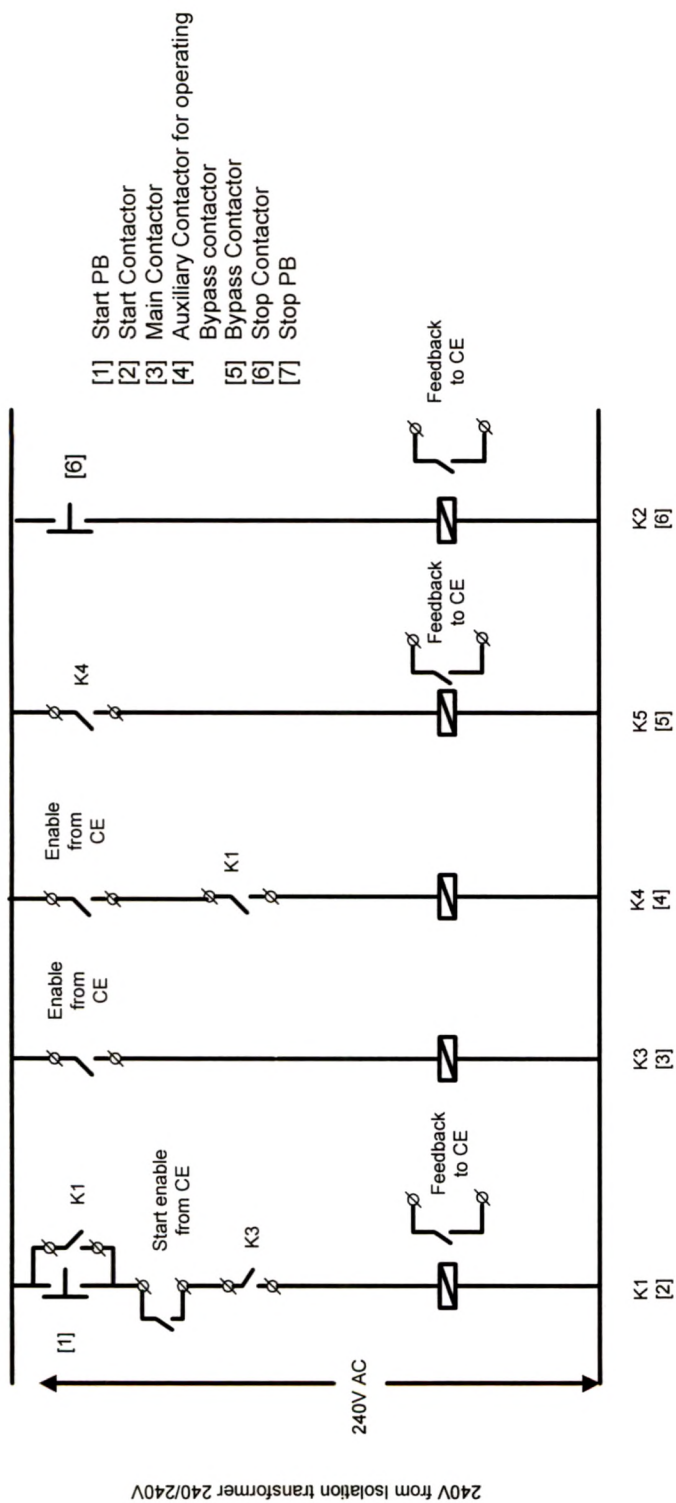


Fig.3.25 (a) Control Logic

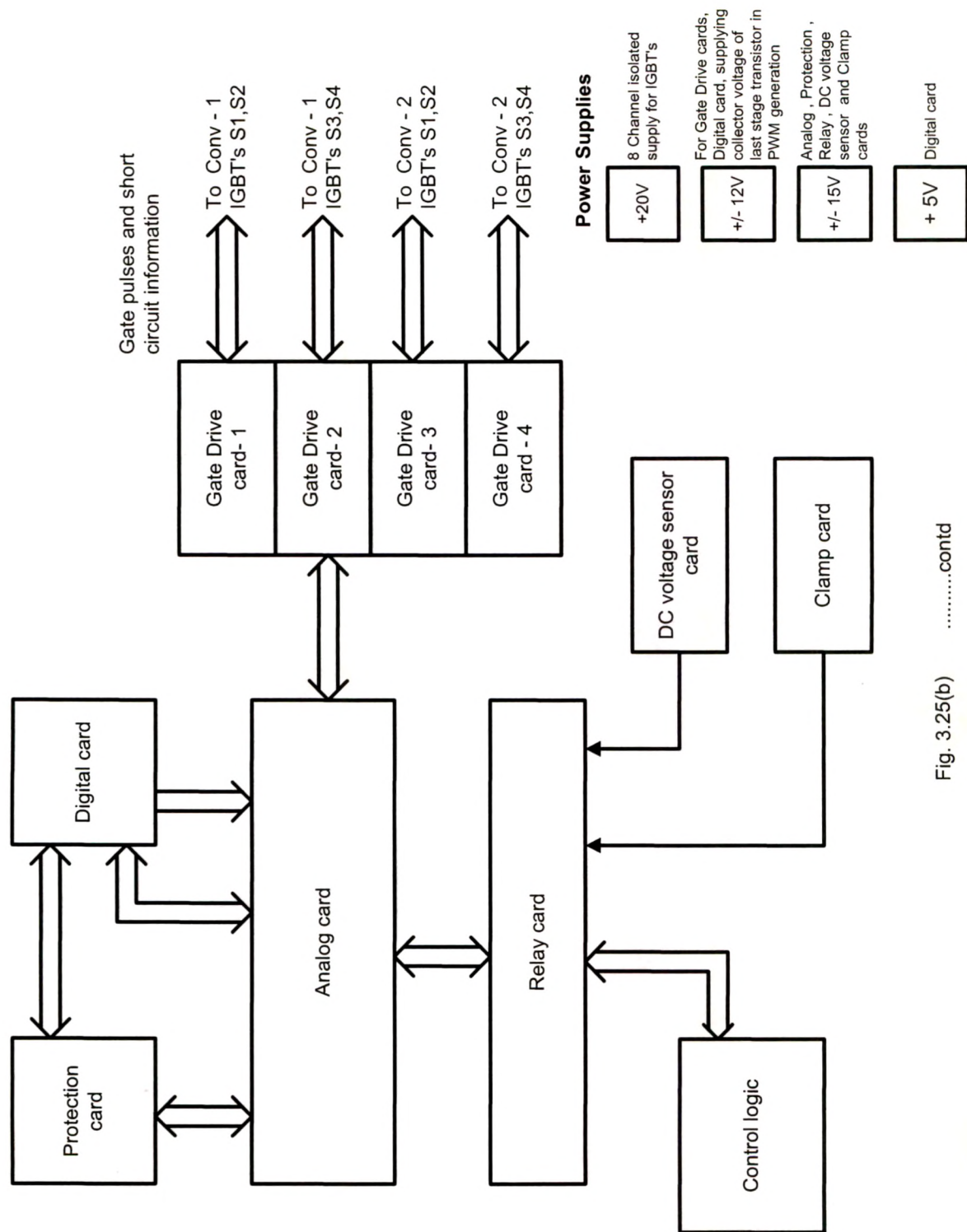


Fig. 3.25(b)contd

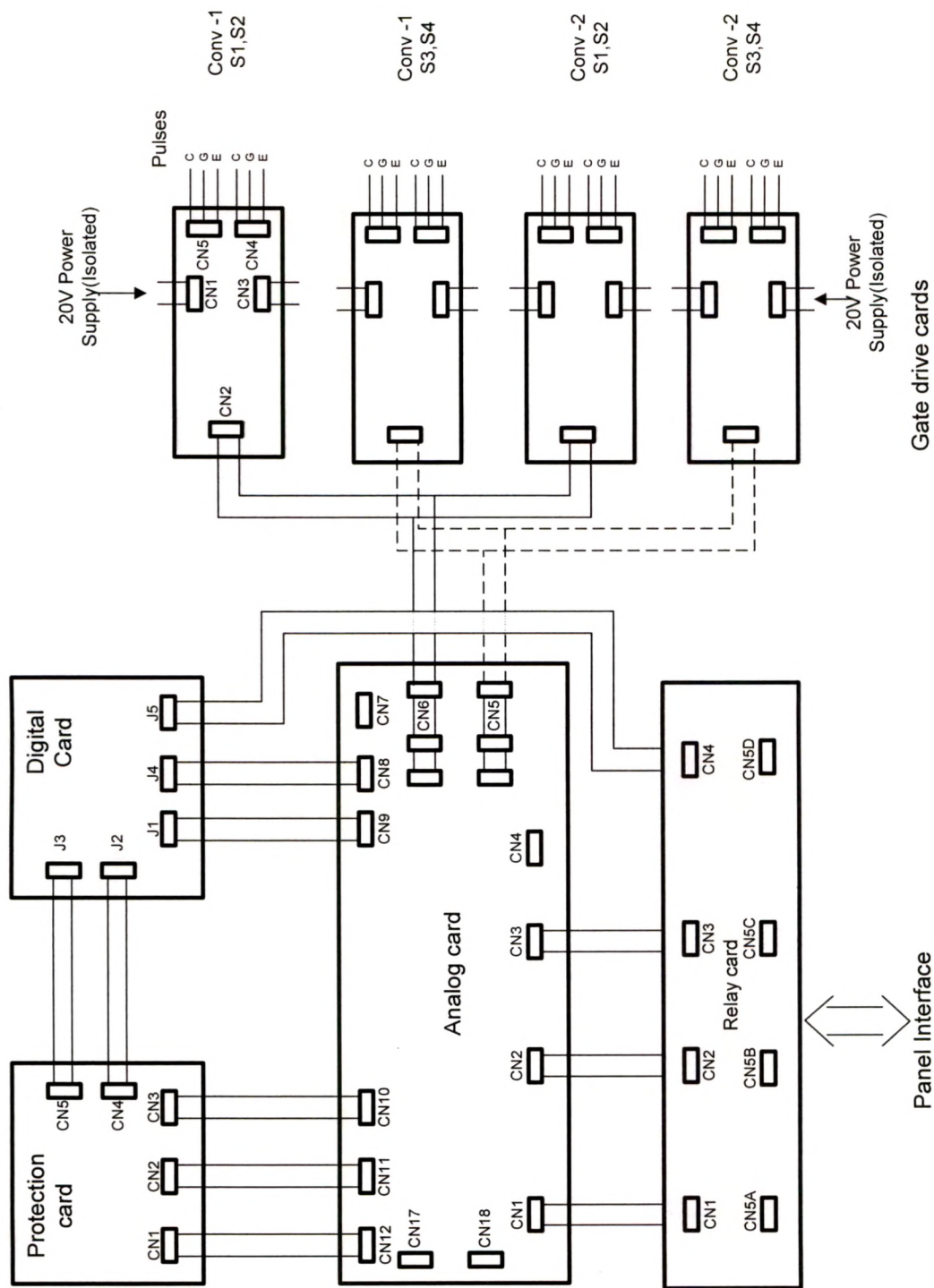


fig. 3.25 (b) Contd.....

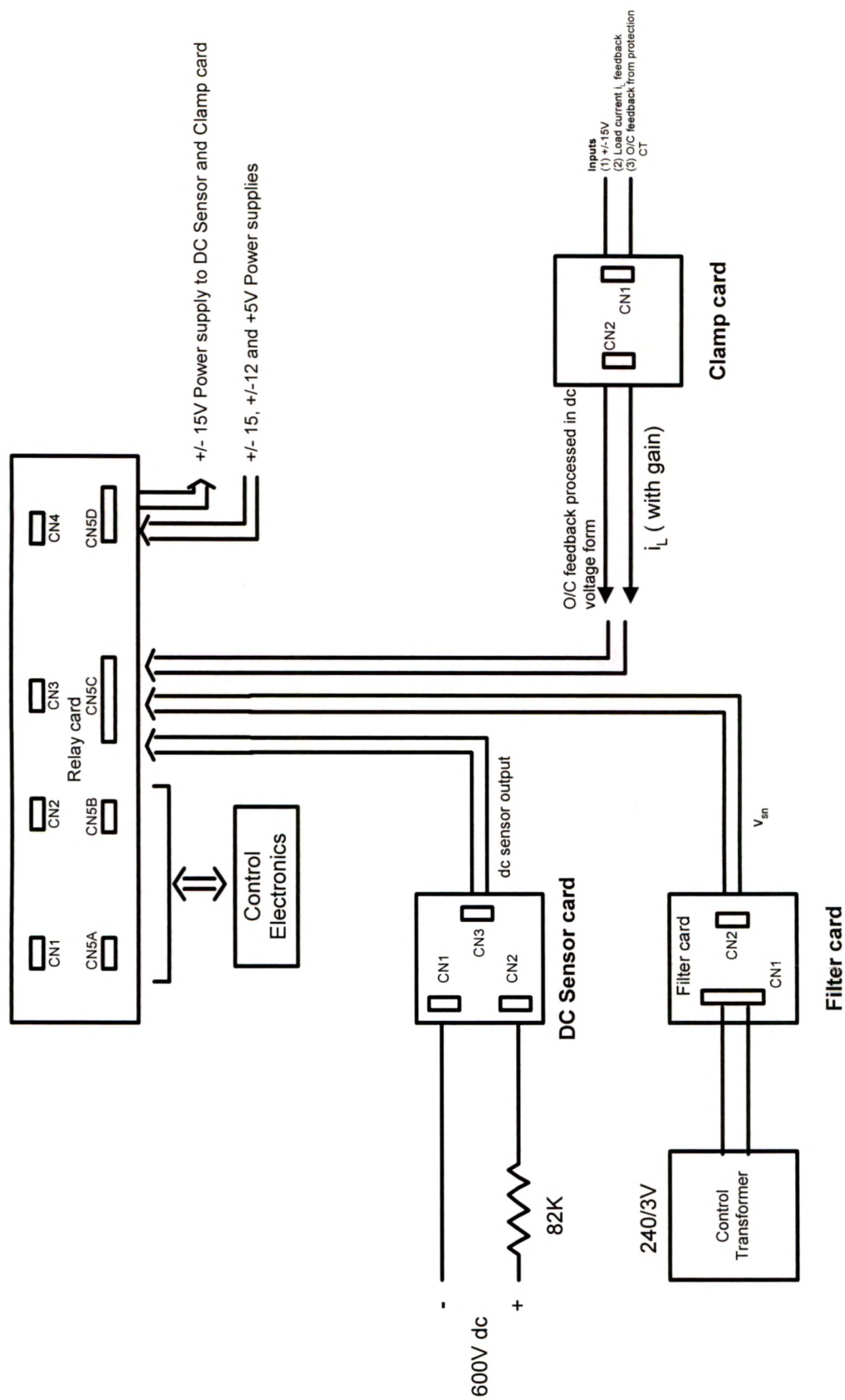


fig. 3.25(b) Control Electronics

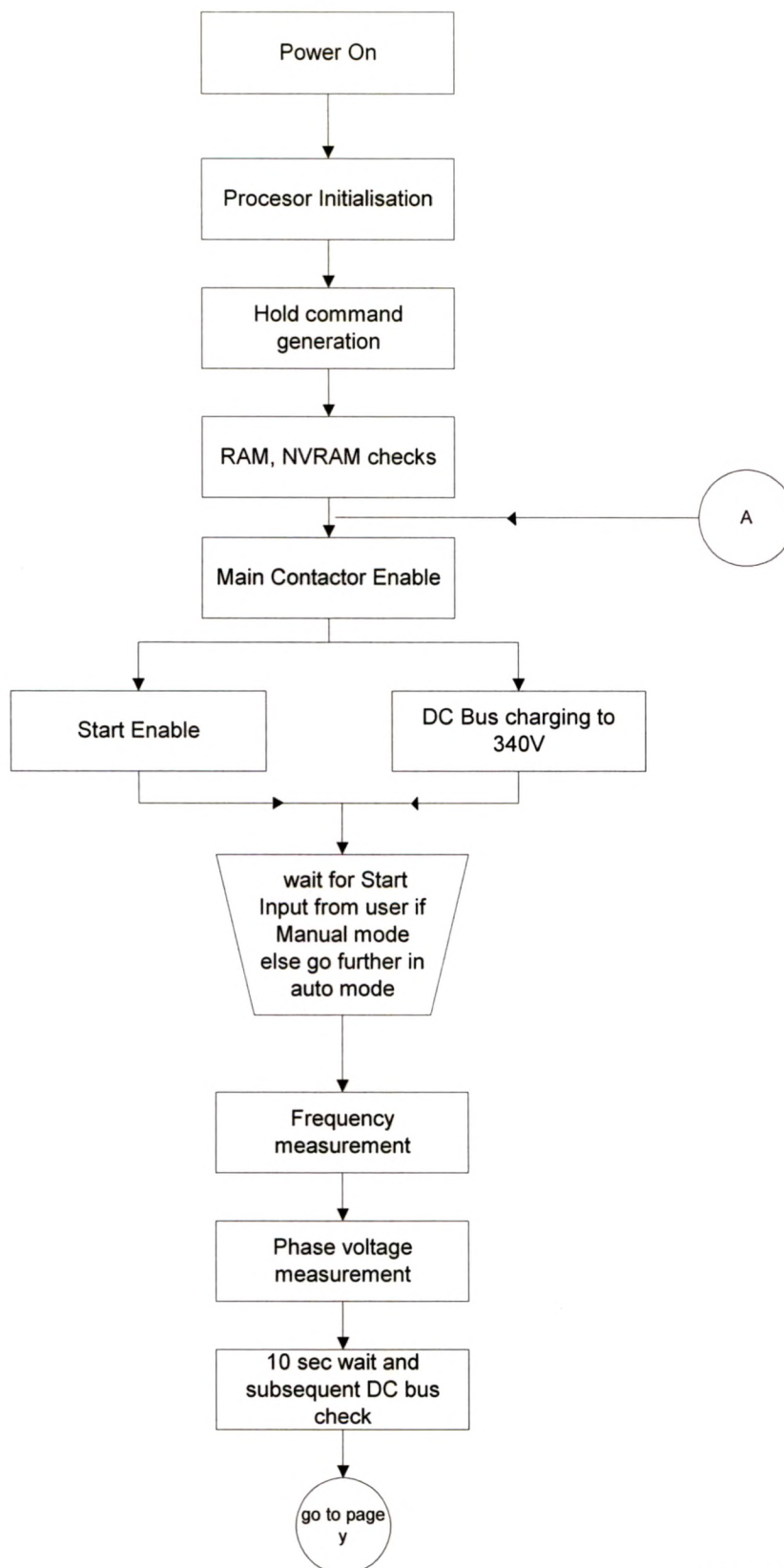


Fig. 3.26 Contd.....

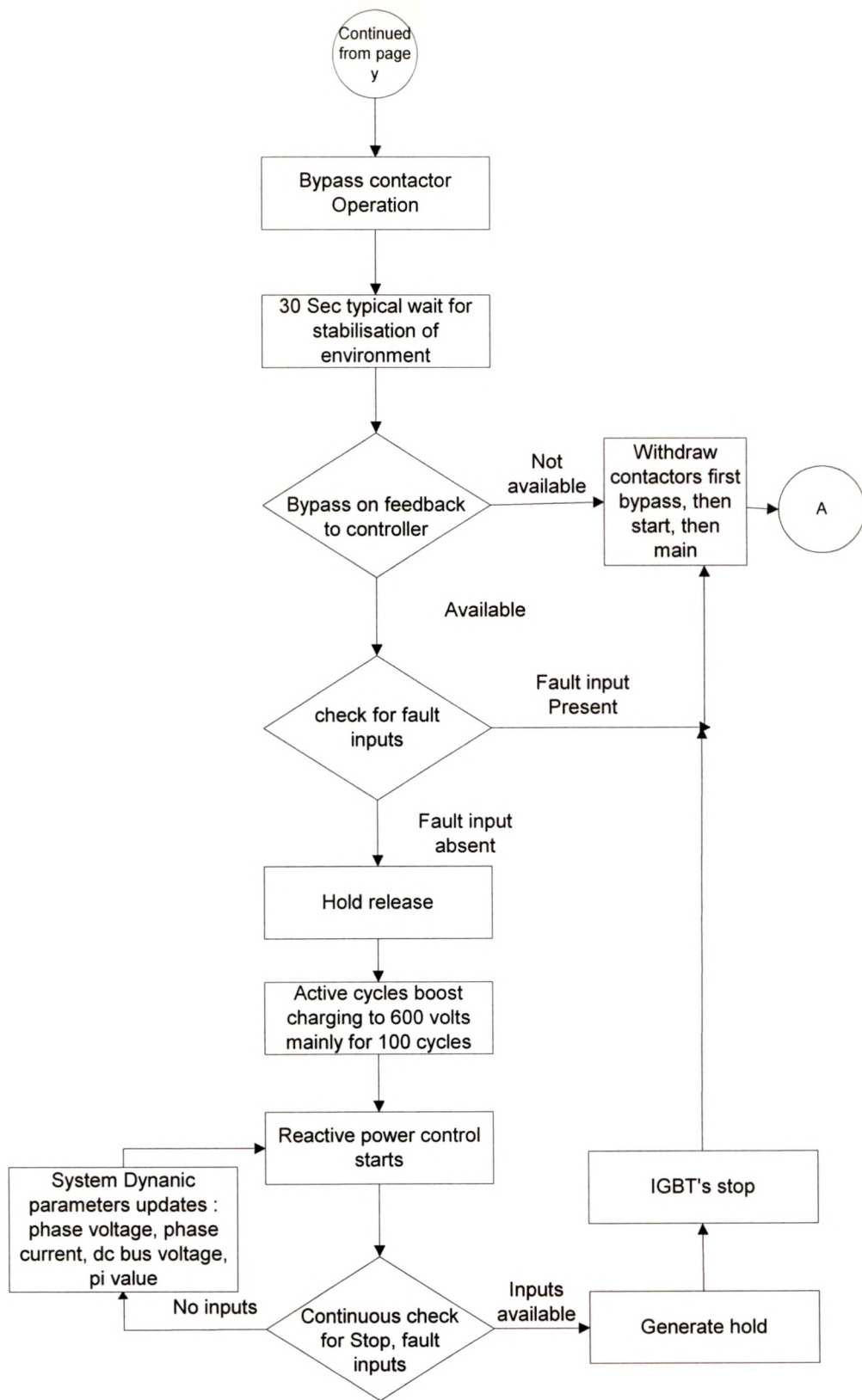


Fig. 3.26 Flow chart

Fig. 19 Starts.....

1. DC voltage sensor card

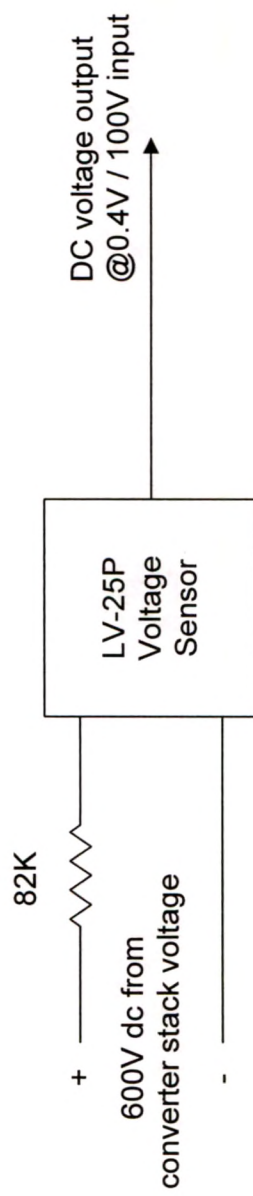


Fig. 3.27 contd.....

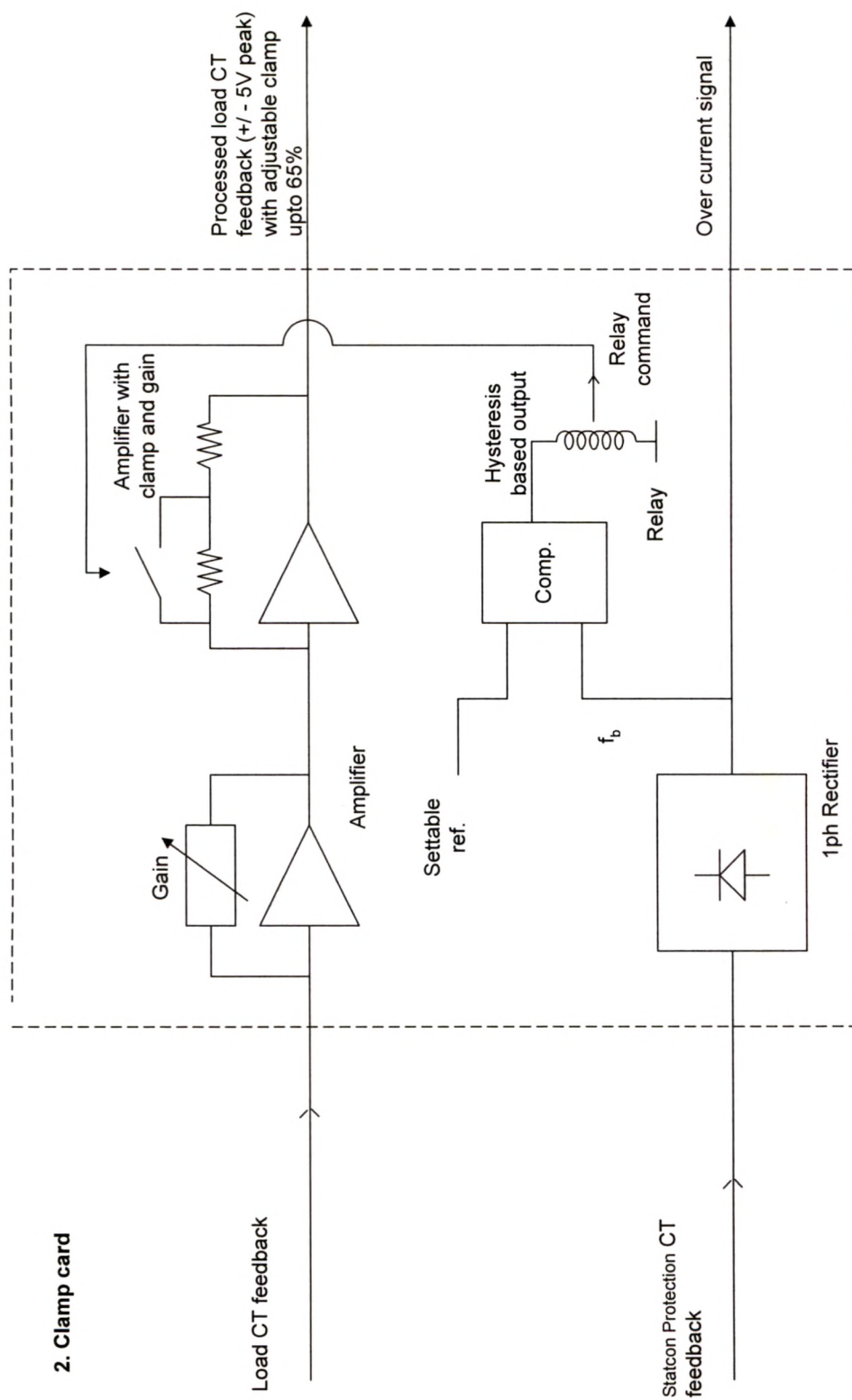


Fig. 3.27 contd.....

3. Relay card

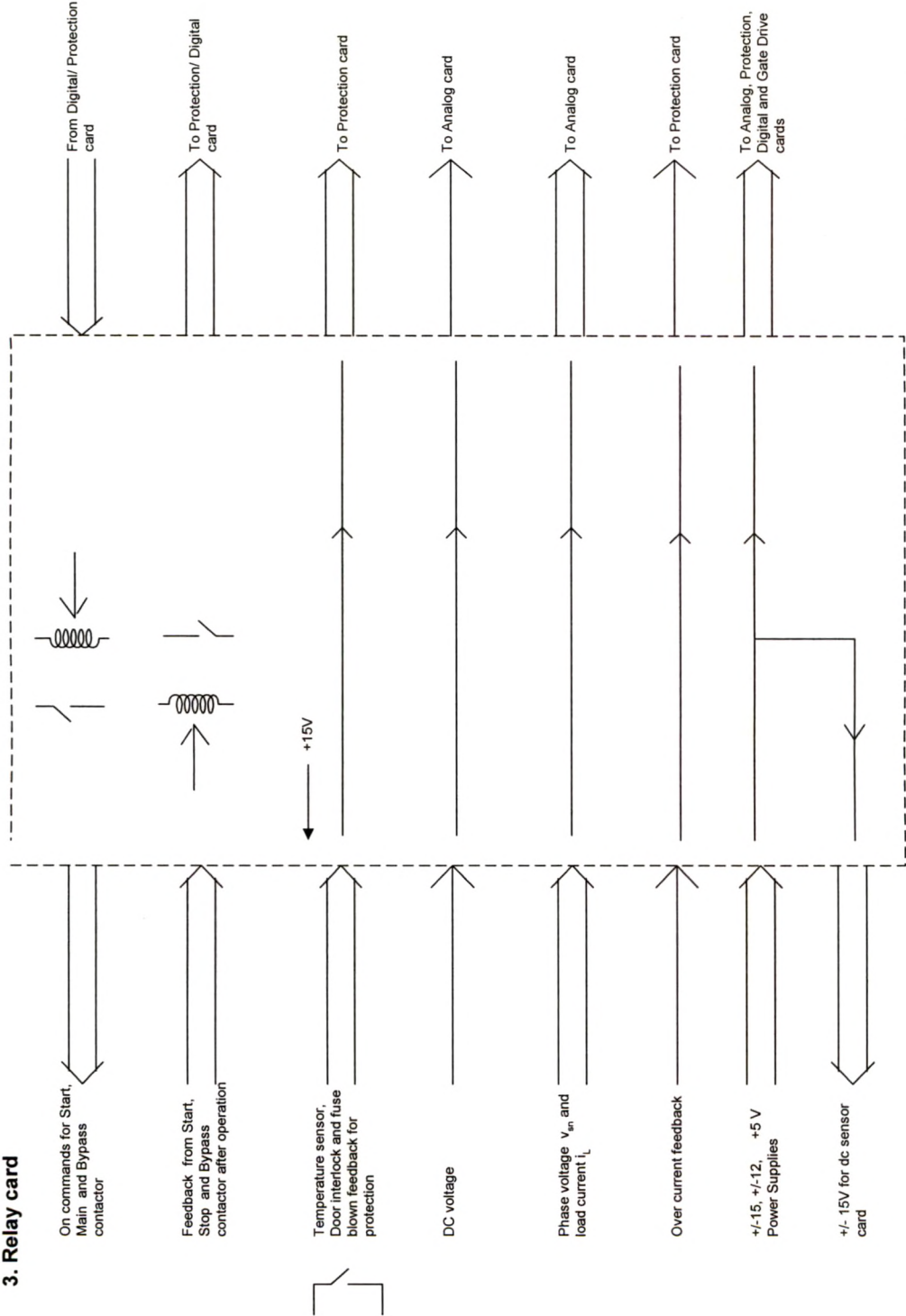


Fig. 3.27 contd.....

4. Analog card

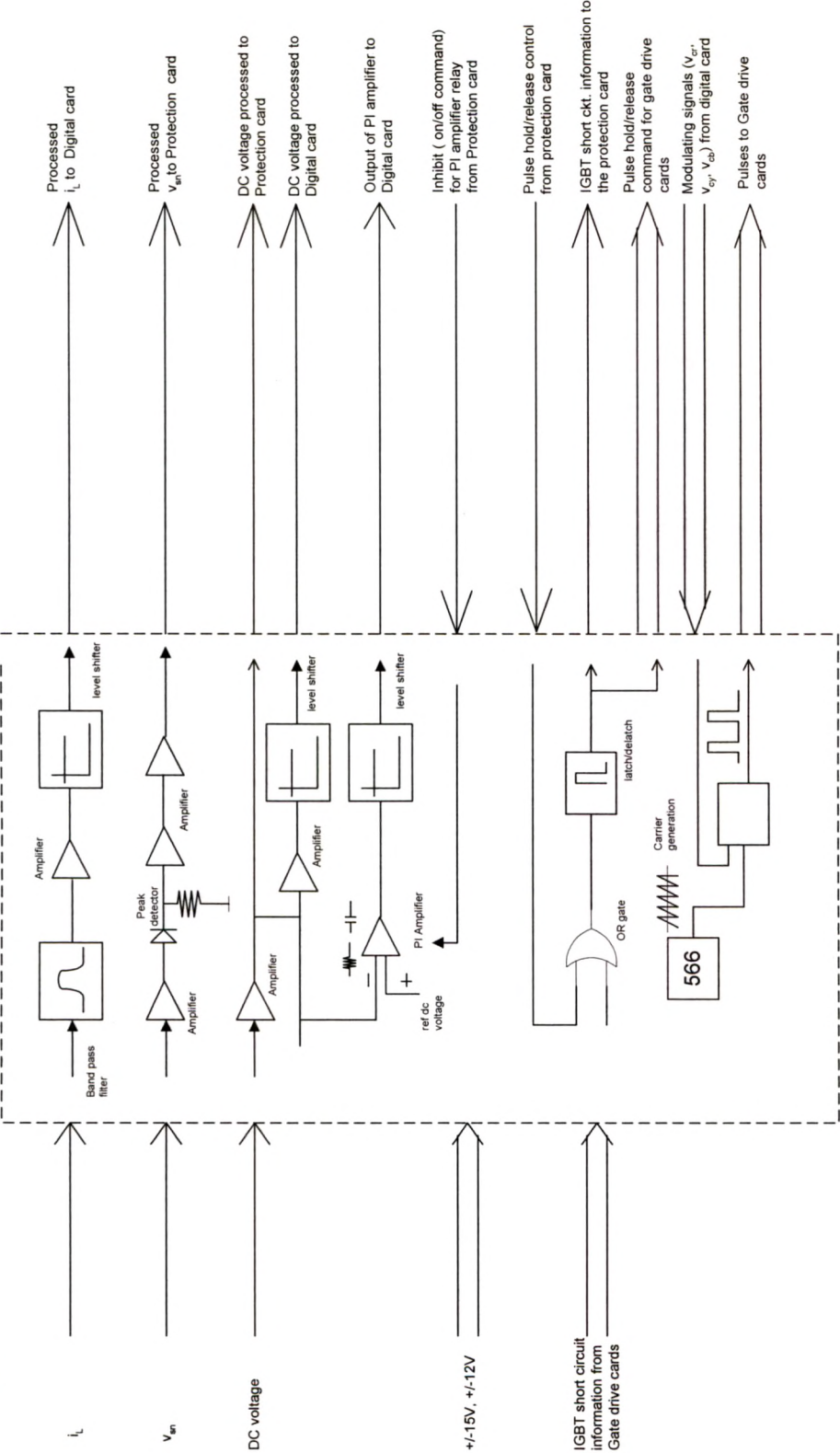


Fig. 3.27 contd.....

5. Protection card

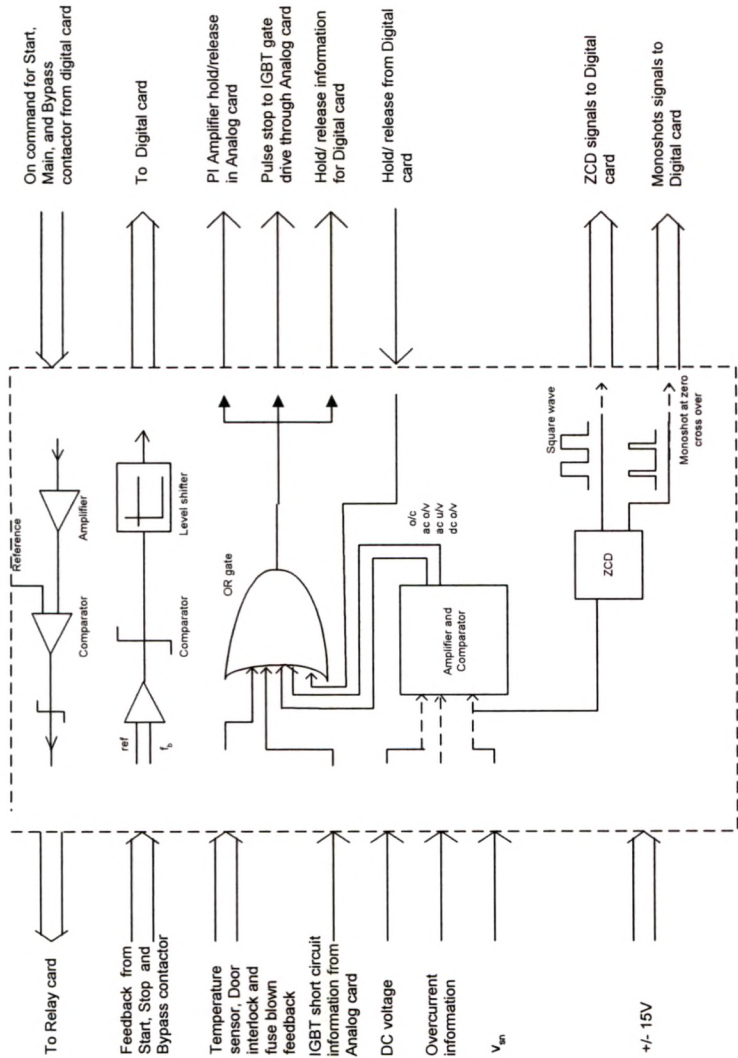


Fig. 3.27 contd.....

6. Gate drive card

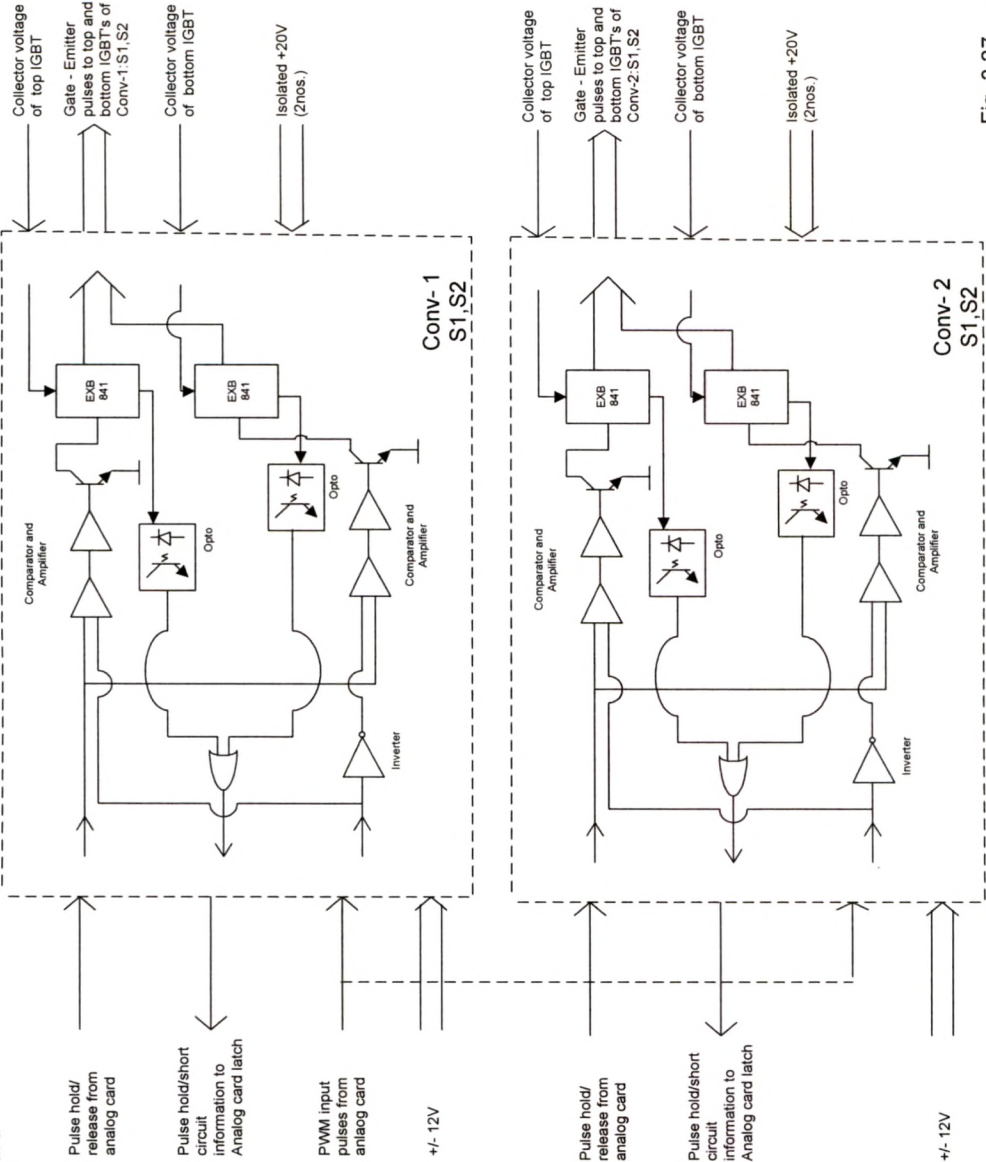


Fig. 3.27 contd.....

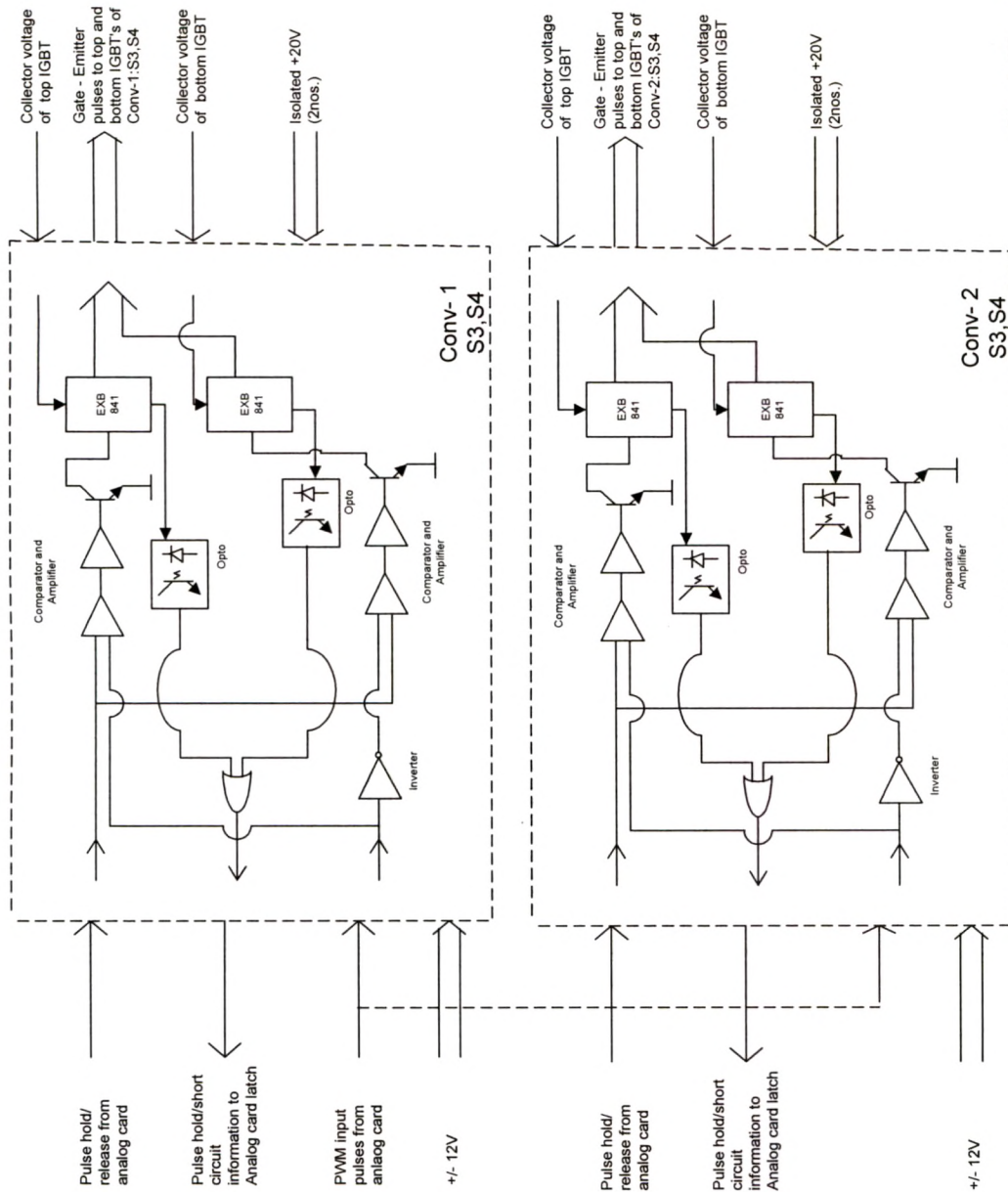
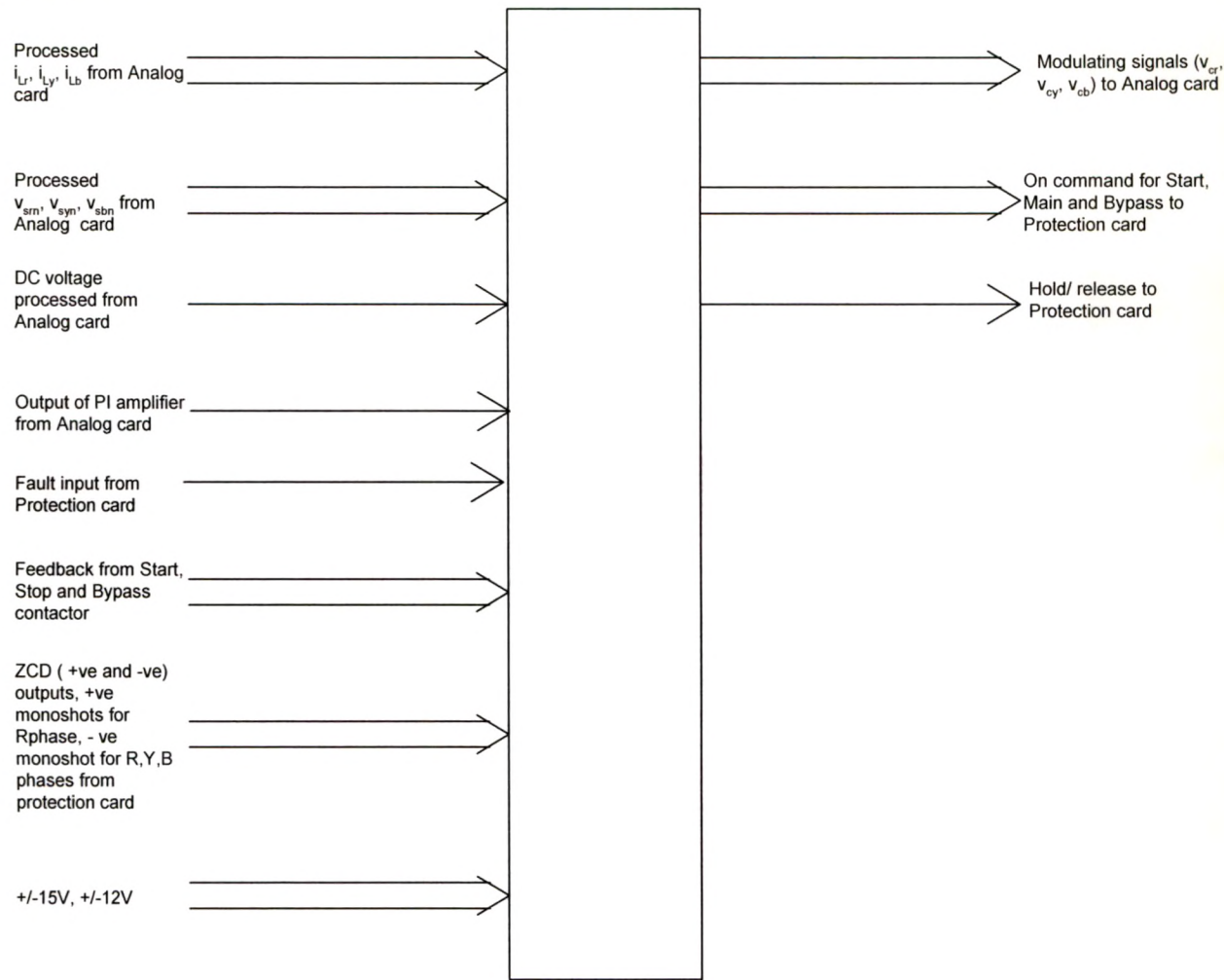


Fig. 3.27 contd.....

7. Digital card



Note : Channels for Phase Y and B are not used while working on single phase eventhough the channel interface exists. Siince the same control electronics designed for threle-phase is adopted for single phase application

Fig. 3.27 Signals received / delivered by various control cards

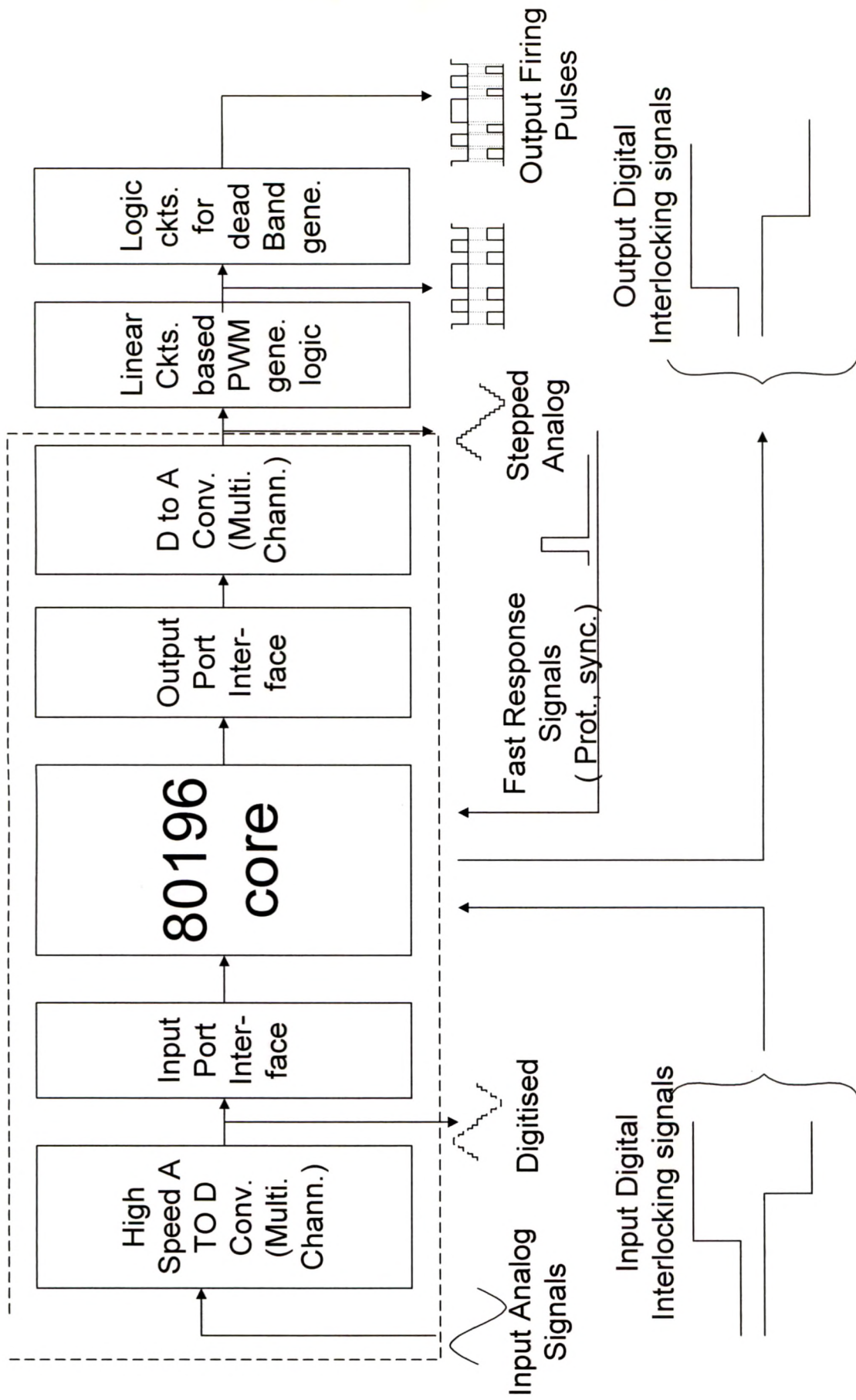


Fig. 3.28 Block diagram of Digital card


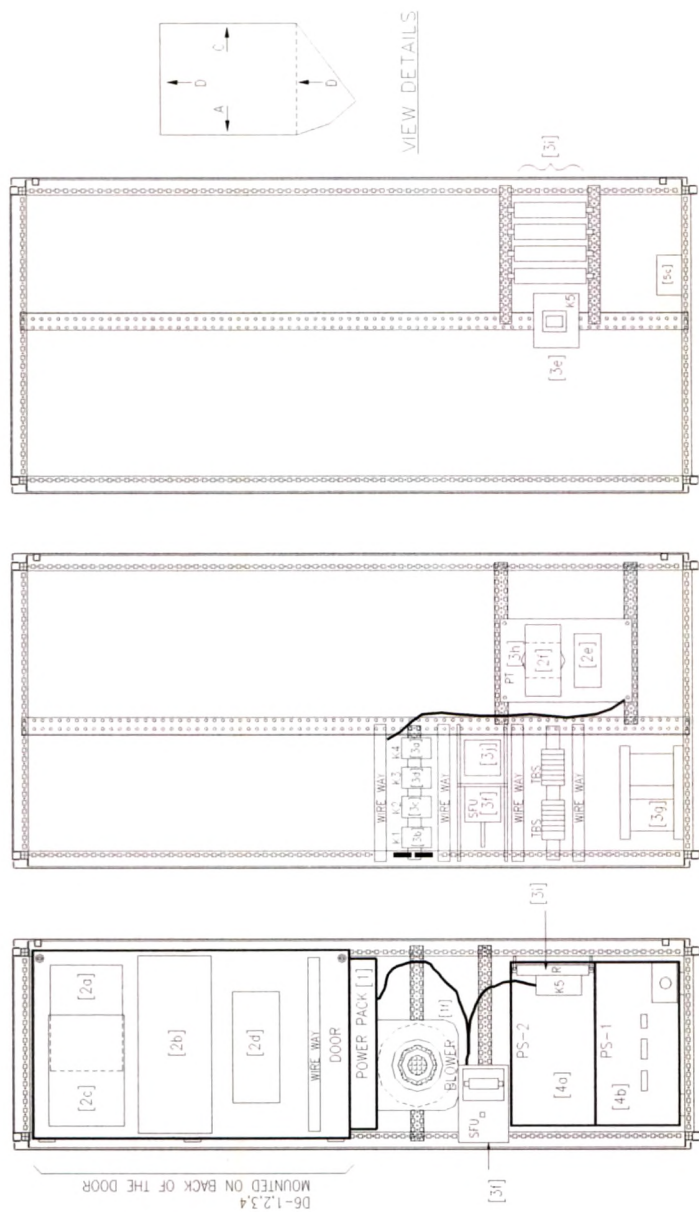
POSITION	DESCRIPTION	QTY
[1] POWER PACK	[1a] IGBTs	4 Nos.
	[2a] SNUBBER R-C-D	4 Nos.
	[1c] DC CAPACITOR STACK	10 Nos.
	[1d] DC VOLTAGE SENSOR CARD	1 No.
	[1e] HEAT SINK	1 No.
	[1f] BLOWER FOR COOLING	1 No.
	[1g] POWER PACK CUBICLE	1 No.
	[1h] THERMOSTAT	1 No.
	[1i] DC RESISTOR	1 No.
	[1j] DISCHARGE RESISTOR FOR VOLTAGE SENSOR	10 Nos.
[2] CONTROL CARDS	[2a] DIGITAL CARD	1 No.
	[2b] ANALOG CARD	1 No.
	[2c] PROTECTION CARD	1 No.
	[2d] RELAY CARD	1 No.
	[2e] LOAD CT/CLAMPCARD	1 No.
	[2f] FILTER CARD	1 No.
	[2g] GATE DRIVE CARDS	4 Nos.
[3] SWITCHGEAR SECTION	[3a] AUXILIARY BYPASS CONTACTOR	1 No.
	[3b] START CONTACTOR	1 No.
	[3c] STOP CONTACTOR	1 No.
	[3d] MAIN CONTACTOR	1 No.
	[3e] POWER (BYPASS) CONTACTOR	1 No.
	[3f] SWITCH FUSE UNIT/MCB	1 No.
	[3g] ISOLATION TRANSFORMER (A15) FOR CONTROL LOGIC & ELECTRONICS	1 No.
	[3h] POTENTIAL TRANSFORMER (VOLTAGE SENSING)	1 No.
	[3i] PRECHARGING RESISTOR	1 No.
	[3j] INCOMING FILTER CAPACITOR & RESISTOR	1 Set
	[3k] SMOOTHING REACTOR & SURGE ABSORPTION [1 Ph. DIODE RECTIFIER BASED]	1 Set
[4] CONTROL POWER SUPPLY	[4a] +5V,±12V,±15V POWER SUPPLY (PS-1)	1 No.
	[4b] +20V POWER SUPPLY (PS-2).  ISOLATED POWER SUPPLIES FOR GATE DRIVE CARDS	1 No.
[5] REACTOR CUBICLE	[5a] PWM BOOST REACTORS 18 + 0.7 (=2.5 mH)	2 Sets
	[5b] RIPPLE FILTER CAPACITOR	2 Nos.
	[5c] PROTECTION & METERING CT	1 No.
[6] FRONT DOOR	[6a] AMMETER FOR LINE CURRENT	1 No.
	[6b] VOLTMETER FOR INCOMING VOLTAGE	1 No.
	[6c] START PUSH BUTTON	1 No.
	[6d] STOP PUSH BUTTON	1 No.
	[6e] INDICATION LAMP	1 No.
	[6f] NAME PLATE	1 No.

Fig. 3.29 General arrangement of single-phase STATCON Contd..



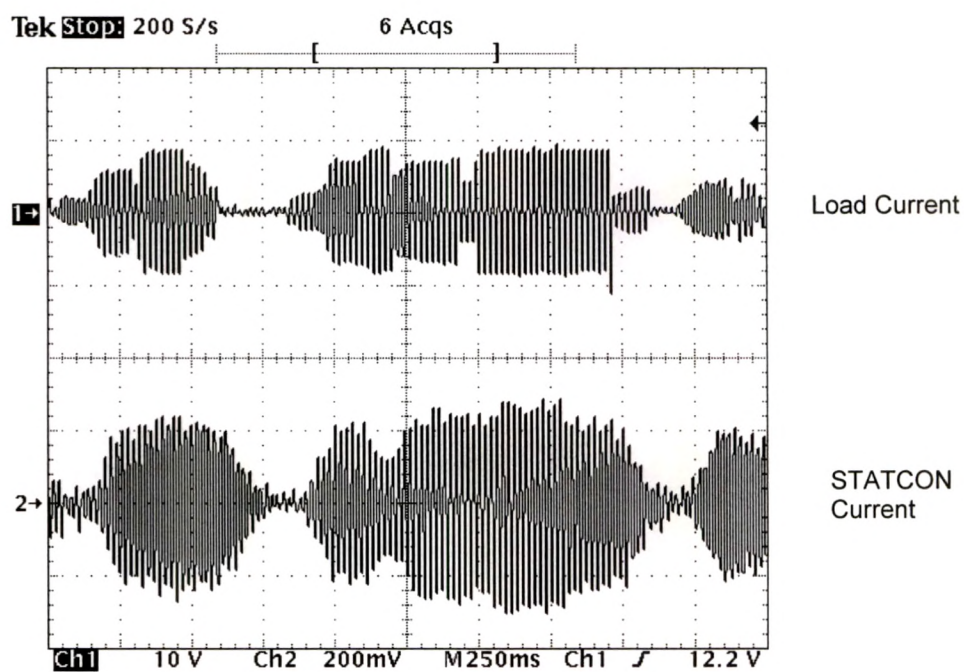
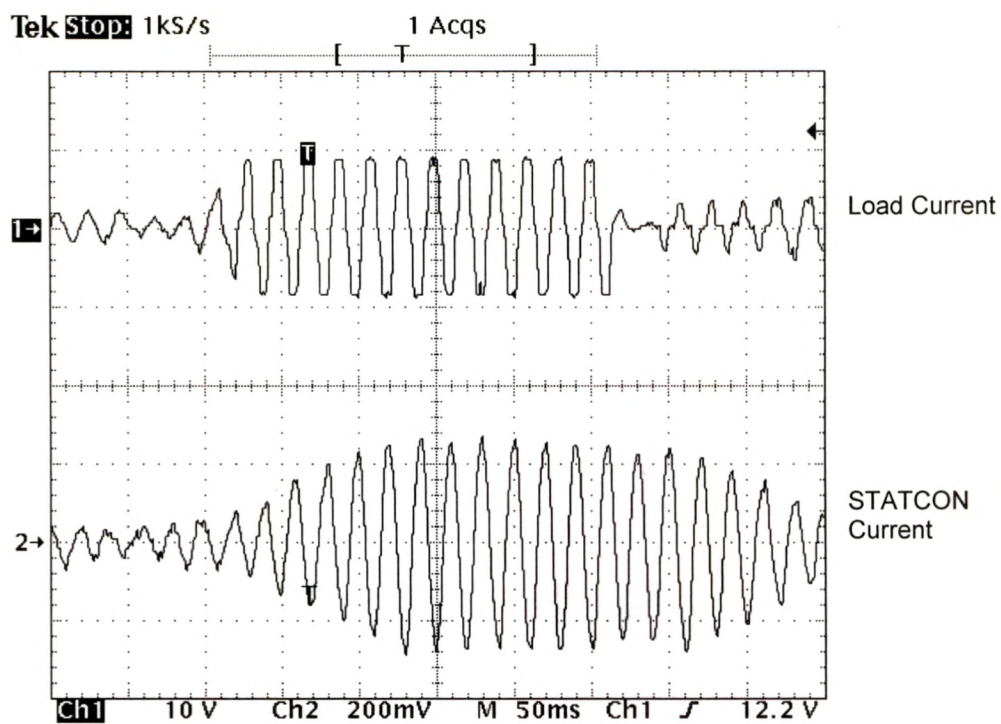


Fig. 30 Dynamic response contd....

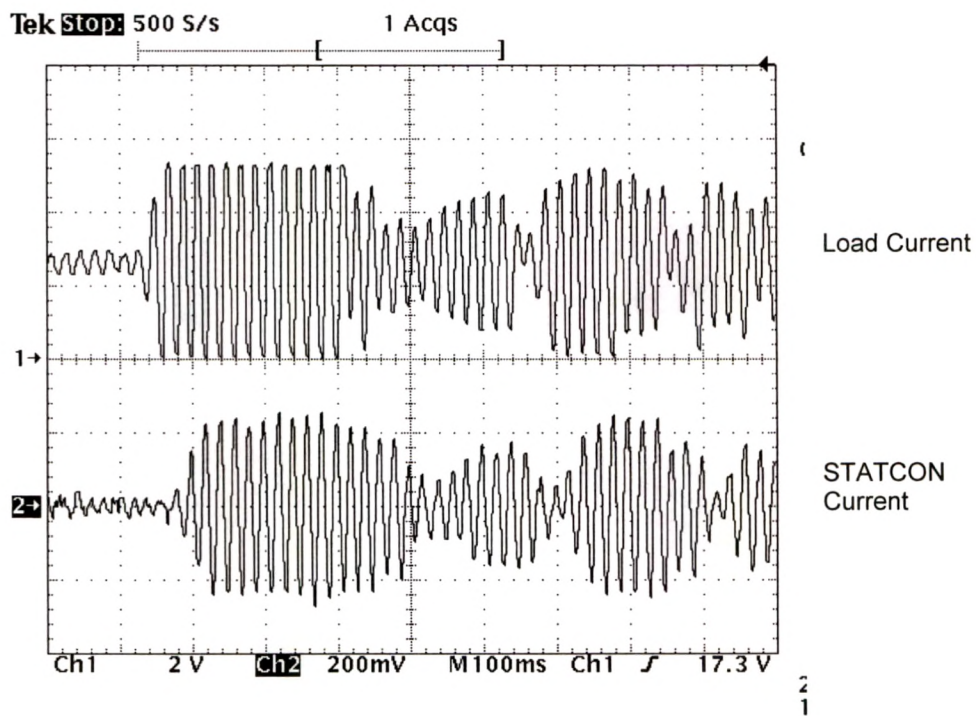
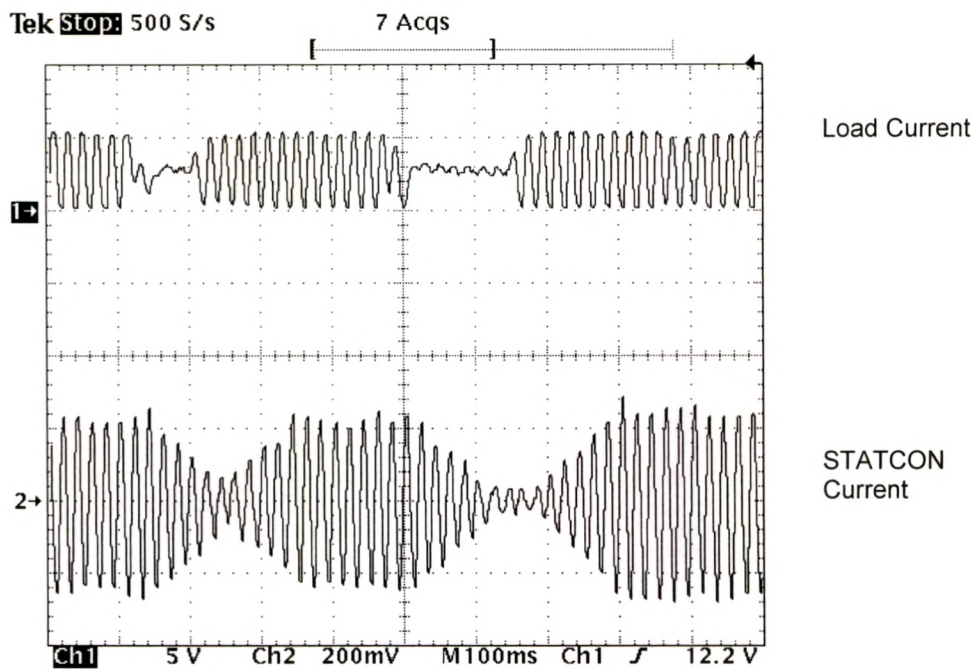


Fig. 30 Dynamic Response

Fig. 3.23

This figure shows how switching Pulse Width Modulated (PWM) voltage is produced at the terminals (P1, P2 and N1 , N2 terminals marked in fig. 3.22) of the converters using Sinusoidal Pulse Width Modulation process . It uses a 1.5 kHz carrier and a sinusoidal modulating waveform and reflects the comparison in terms of the switching voltage as shown in the figure. The switching voltage, as explained earlier, is expressed as $+V_{dc}$, 0 , $-V_{dc}$ with respect to the virtual zero (midpoint of the dc side capacitors [21] in fig. 3.22). The fundamental component V_{i1} of the switching voltage V_i is as discussed in figs. 3.9 and 3.10.

Fig. 3.24

This figure is used for calculation of the supply voltage distortion based on 'n'th harmonic current ripple fed to the supply and being filtered through an appropriately sized capacitor connected in shunt with the supply terminals.

Fig. 3.25(a)

This figure gives the Control Logic (sequencing and interlocking operations) for the single phase STATCON fed through a 240 V isolation transformer. The logic is simple and utilizes basically control contactors and relays (from Relay card).

On receipt of the start command through a start push button [1], the start contactor [2] closes. Then the micro-controller gives command for the main contactor [3] to operate to charge the capacitor stack of the converters. Further, the micro-controller will give command for the bypass contactor [5] to close to allow the STATCON function as a reactive power compensator. On receipt of stop command, given from a stop push button [7], or sensing of any fault, the micro-controller will first stop the IGBT firing, bring down the supply currents to zero value, and give command for the bypass contactor [5] to open. It will then give command for the main contactor [3] to open. The auxiliary contactor [4] is used for operating the bypass contactor coil. The stop contactor [6] operates when stop command is delivered by a stop push button.

Fig. 3.25(b)

This figure explains how the Control Electronics is interfaced with the Control Logic, regulated / isolated IGBT Gate power supplies, DC voltage sensor, filtered incoming ac voltage and the Gating for the IGBT's. It also shows the connections within various control cards. These

cards and their functions are explained later. The required controlled / regulated power supplies for the control cards are as given below.

+5 V dc for the Digital card

+/- 12 V dc for the Digital card, Gate Drive cards, and Analog card

+/- 15 V dc for the Analog card, Protection card, Clamp card, and DC Voltage sensor card

+ 20 V dc, 6 numbers isolated power supplies for the IGBT triggering / firing.

All the power supplies are routed through the Relay card, except eight numbers of the + 20 V dc power supplies. The major interconnections are done using flat cables between the cards.

Fig 3.26

This is the flow chart for the sequence and interlocking operations of the single phase STATCON as executed by the micro-controller through its controlling software. It broadly explains the actions taking place in the STATCON after the power is switched on through the incoming MCB, and various checks the micro-controller carries out at different stages of the operation, till the reactive power control is effected. It also gives the information on how the STATCON folds back if there is any fault sensed.

Fig. 3.27

This figure is for providing the understanding of basic inputs and outputs of each card of the Control Electronics. It also establishes and explains how the incoming signals are received processed at various cards and finally how the output signals are delivered to the gate drive cards, which control the IGBT firing.

The analog signals vary between +/- 10 V, +/- 5 V or 0 to +5 V while the digital signals have maximum value + 5 V dc.

This figure also gives block level schematic and understanding of each control card. The input / output and functional details of the cards are given later.

Fig. 3.28

This figure explains the architecture of the Digital card in a block form and also explains input / output relationship of the signals received / delivered by the card. Input / output and functional details of this card are given in chapter 4.

Fig. 3.29

This figure gives the general arrangement of various components and subassemblies within the single-phase STATCON panel or cubicle. These are numbered and explained. It gives an impact of how a panel / cubicle housing the complete STATCON assembly looks like. The panel / cubicle is basically of IP 31 protection class in construction but needs deration for higher protection classes (typically up to 35% when the class reaches IP54).

Fig. 3.30

This figure gives the dynamic response of the single phase STATCON current with respect to the load current. The responses are taken for a spot welding application in an automobile industry. This response can be tuned and made to track the load current demand as close as possible based on demand and / or based on the system needs.

3.5.2.6 SINGLE-PHASE STATCON : VITAL DESIGN ASPECTS

3.5.2.6.1 POWER SCHEME AND COMPONENT SELECTION

The single-phase STATCON has following basic specifications.

- 240 V ($\pm 10\%$), ± 50 Hz ($\pm 5\%$), ± 210 A.
- Incoming supply as 2 wire (phase and neutral).
- All the internal power supplies to be derived from the incoming supply only.
- Dynamic response time close to one cycle.

The power scheme is given in fig. 3.22. It uses a single phase full bridge construction for the power converter with two converters operating in parallel. Each power converter produces terminal voltage v_{i1} , as can be seen from fig. 3.23. Fundamental component of this voltage is v_{i1} , as can be seen from the same figure. Each power switch (in this case IGBT, i.e. Insulated Gate Bi-polar Transistor, is bi-directional. The converter configuration is current-controlled Voltage Source Converter operating in boost mode. In this case input current i_s is controlled indirectly by controlling the voltage v_{i1} . Hence, current control method deployed is 'Indirect Current Control (ICC)". The dc voltage V_{dc} needs to be more than the peak of supply phase to neutral voltage so that the supply current can be forced in both the directions

3.5.2.6.2 VARIOUS FORMULAE TO BE USED IN THE COMPONENT SELECTION OF THE CONVERTER AND THEIR RELEVANCE

1. Maximum v_{i1} required for capacitive operation

$$= (240 * 1.15) + (210 / 2) * (wL_b)$$

Note that L_b is used in a split form as is seen from the power scheme in fig.

15 . Further, the current is equally shared by the two converters as 105 A

which is equal to $210 / 2$ A.

2. Minimum v_{i1} required for inductive operation

$$= (240 * 0.8) - (210/2) * (wL_b)$$

Design factor is 15% over-voltage and 20% under-voltage.

3. Peak ripple in the supply current at 50% duty ratio of the terminal voltage v_i switching between the levels $+V_{dc}$ and 0 & $-V_{dc}$ and 0 is given by

$$2*(2 * V_{dc}) / (\pi * (2*m_f) * wL_b)$$

where

m_f = ratio of switching frequency of the IGBT devices to supply frequency.

Further, the factor 2 in the beginning is because of two converters operating in parallel and the factor 2 in bracket along with m_f is because of frequency doubling effect in a full wave converter.

Thus the carrier frequency and the IGBT switching frequency are same but the input current of each converter will have ripple frequency which is double of the IGBT switching frequency or the carrier frequency.

4. The converter equation (2) given previously can be rewritten as

Capacitive mode

$$v_{i1} = V_m \sin wt + (I_{cm} * wL_b) \sin wt - (I_{cm} * R_v) \cos wt \quad \dots \quad (11)$$

Inductive mode

$$v_{i1} = V_m \sin wt - (I_{cm} * wL_b) \sin wt + (I_{cm} * R_v) \cos wt \quad \dots \quad (12)$$

or

Capacitive mode

$$v_{i1} = (V_m + I_{cm} * wL_b) \sin wt - (E) \cos wt \quad \dots \quad (13)$$

Inductive mode

$$v_{i1} = (V_m - I_{cm} * wL_b) \sin wt + (E) \cos wt \quad \dots \quad (14)$$

Here $I_{cm} = 105 * \sqrt{2}$ A

$$= 149 \text{ A}$$

This is to be considered for single converter and not for two converters in parallel.

Error E decides the angle ' δ ' in fig. 3.10 or the angular displacement of voltage V_{i1} from the supply voltage. The switching voltage v_i and hence the v_{i1} voltage is produced by using comparison of a triangular wave with a fundamental frequency signal ' v_c ' as shown in fig. 3.23. The converter thus uses Sinusoidal Pulse Width Modulation (SPWM) method for producing the switching voltage v_i .

The ratio of amplitude of v_c to the amplitude of the triangular waveform is modulation index (M_i). It is normally be below 1.0.

Since the loss component $I_{cm} * R_v$ or E in equations (13) and (14) is quite small, the displacement angle ' δ ' of v_{i1} is also quite small.

These equations, digital card micro-controller solves on a continuous basis. The STATCON basic functioning is based on these equations.

With only v_c considered superimposed on the triangular waveform, the V_{i1} voltage is given by

$$V_{i1} = (M_i * V_{dc}) / \sqrt{2} \quad (15)$$

The linear relation between M_i and V_{i1} is valid for m_f (switching frequency to fundamental frequency ratio) greater than nine.

Converter component selection

The converter component selection is an interactive process based on

- Formulae given above.
- Various IGBT devices available and their characteristics.
- Proving the power stack for requisite rating integrating the devices, the snubber components, dc capacitors and the forced cooling etc.
- Switching frequency choice related to above.
- Integrated protection approach for the IGBT turn off within less than 12 microseconds.
- Digital card developed around 80196 micro controller and its clock frequency, and
- Few other parameters.

The component and parameters selected are as under (please see power scheme in fig. 3.22 and fig. 3.29 also)

3.5.2.6.3 CONVERTER COMPONENTS SELECTION

The component and parameters selected are as under

Components

1. IGBT 200 A, 1400 V (Fuji make 2MBI 200PB -140, 2 in one with isolated base).
2. DC capacitors 4700 μ F, 450 V dc used for the IGBT stack.
3. Single phase, boost reactor L_b as 2.5 mH, 150 A (or 1.25 mH 2nos. for split arrangement per converter) .
4. Snubber - Diode 3 A , 2000 V , type UF 5408 , 2 groups in series with each having 4 in parallel , Resistor 11 ohms, 100 W, Capacitor 0.1 μ F, 2000V dc.

The snubber is connected across each device. Further, there is also 0.33 μ F, 2000 V dc capacitor connected across the dc terminals of each IGBT module.

5. Blower – Single phase, 240 V, 500 cubic feet / min.
6. Heatsink - AFCOSET 80 AD (845 H * 126 W * 136 D) anodized.
7. DC cap. discharge resistor – 15 K , 25 W.
8. Main incoming breaker MCB or Switch Fuse Unit SFU – 400 A, 240V AC.
9. Main contactor – 415 V, 40 A, 3 pole with 240 V ac coil (all three poles paralleled).
10. Bypass contactor – 415 V, 150 A, 3 pole with 240 V ac coil (all three poles paralleled) .
11. Pre-charging resistor – 10 Ohms , 200 W.
12. Ripple filter capacitor – 10.0 μ F, 2000 V dc (common for two converters).
13. Incoming R-C filter – 5 Ohms, 100 W and 4 μ F , 660 V.
14. Incoming smoothening inductor 20 μ H, 250 A (single phase).
15. Incoming surge energy absorption.

Diode 70A, 2000 V (2 modules with 2 in one with isolated base or 4 nos. separate)

Current limiting resistor 27 ohms, 100W

DC capacitor 1000 μ F, 450 V dc , 2 nos.

Discharging resistor 27 K, 100 W.

All of these are mounted on a small anodized heatsink (300 H * 150 W * 60 D)

16. Heatsink temperature sensor type N/C operating at 90 degrees.
17. HRC fuse in supply lines rating 400 A , 500 V
18. Protection CT combined for both the converters rating 300 A / 1 A.
19. Control / Isolation transformer for feeding the Control Logic and power supplies for Control Electronics. This is 240 V / 240 V , with 3 kVA rating.
20. One number of control transformer for the purpose of sensing incoming phase voltages. These are 240 / 3 V , with 6 VA rating each.

Parameters

1. Digital processor N80 C 196 KC 20 (16 bit) operated at 12 MHz.
2. Switching frequency of IGBT (carrier frequency) 1.5 kHz.
3. IGBT stack cooling. Forced cooled with specified blower.
4. Modulating waveform optimized to 24 pulse (15 degrees per step) In each 15 degrees, the controller computes the modulating signal level based on fresh information of all the parameters.
5. In each cycle (before its completion) all information related to voltages, current, frequency and associated operating limits (dynamic) are updated. Correct synchronization is maintained. Thus, every cycle resynchronization with updated parameters takes place. However, the response of the converter is just a little over one cycle (less than 1 cycle and 15 degrees).

Results based on iterations

1. The converter dc voltage has been finally selected as 600 V dc. The switching frequency selected is 1.5 kHz for the IGBT's.
2. Input current ripple (peak), considering both converters (parallel converters)

$$= 2 * (2 * 600) / (\pi * (2 * 1500 / 50) * 2 * \pi * 50 * 2.5 \times 10^{-3})$$

$$= 16.2 \text{ A}$$

3. V_{i1} variation required (per phase)

$$(240 * 1.1 + 105 * 2.5 * 10^{-3} * 2 * \pi * 50) = 346 \text{ V}$$

$$(240 * 0.8 - 105 * 2.5 * 10^{-3} * 2 * \pi * 50) = 110 \text{ V}$$

Thus the variation is from 346 V to 110 V AC.

At 600V dc, it means modulation index M_i varying from

from $(346 * \sqrt{2}) / (600) = 0.815$

to $(110 * \sqrt{2}) / (600) = 0.26$

The restricted modulation index M_i to a maximum of 0.815 allows the modulating signal v_c to remain lower than the triangular waveform amplitude and leaves some margin to account for dynamics of the load.

4. Expected displacement angle

Consider fig. 2 (a).

The maximum $I_c * \omega L_b$ drop for single converter $(105 * 2 * \pi * 50 * 2.5 * 10^{-3})$ 82.4 volts

Assume a worst case $I_c * R_v$ drop of 10% of this nature

Thus $I_c * R_v = 8.24$ volts

Thus maximum ' δ ' in capacitive mode is given by

$$\tan^{-1} (8.24 / (240 \times 1.1 + 82.4)) = 1.364 \text{ degrees}$$

Similarly maximum ' δ ' in inductive mode is given by

$$\tan^{-1} (8.24 / (240 \times 0.8 - 82.4)) = 4.28 \text{ degrees.}$$

It shows that the displacement angle of the vector V_{i1} with respect to the phase voltage V_s is quite small but is essential for the converter operation. This is in line with what was stated earlier while introducing equations (11) to (14).

5. Incoming voltage distortion (calculated for a typical short circuit capacity of the network)

Assume that at the coupling point of STATCON the network short capacity is say 30000 KVA.

Refer fig. 16 for the voltage distortion analysis.

Short circuit impedance ($\omega * L_b$)

$$= (3 * 240 * 240) / (30000 * 1000)$$

$$= 0.00576 \text{ Ohms}$$

Therefore, impedance at switching frequency

$$= (3000 * 0.00576) / (50) = 0.3456 \text{ Ohms}$$

Further, Filter capacitor impedance at 3.0 KHz

$$= (1000 * 1000) / ((3000/50) * 2 * \pi * 50 * 12.5) = 4.265 \text{ Ohms}$$

Therefore, RMS value of the incoming voltage distortion due for switching frequency will be

$$= 100 * (16.2 * 4.265 * 0.3456) / (240 * \sqrt{4.265^2 + 0.3456^2}) * 1.4142$$

= 0.38%.

It shows that higher the short circuit capacity of the network, lesser will be the voltage distortion.

6. The peak second harmonic ripple current on the dc side is as given here.

$$= \{1.1 * \text{Phase voltage} * \text{Phase current} / \text{DC voltage}\}$$

$$= (1.1 * 240 * 210 / 600) = 92.4 \text{ A.}$$

3.5.2.6.4 CONTROL SCHEME AND LIST OF FUNCTIONS IN CONTROL ELECTRONICS CARDS.

The control scheme is given in fig. 3.25. It basically consists of two parts.

- Control Logic
- Control Electronics

These are given in figs. 3.25 (a) and (b) respectively.

The heart of the system is the micro-controller based digital card assembly, which performs the following important functions.

- Sequencing and interlocking of the entire STATCON
- Solving the mathematical model given by the equations (13) and (14) and outputting the necessary modulating signals v_c , for the three phases dynamically.
- Updating of all parameters (voltage, current, dc voltage, frequency, error E in equations (13) and (14) etc.) and sequencing the operation once again at the start of every cycle.
- Checking for receipt of any protection signal and giving an output command for the withdrawal of IGBT gate pulses.
- Checking for its own hardware health.

Fig. 3.26 gives a flow chart, which expresses the complete sequence of operations in the STATCON as controlled by the brain 'micro-controller'. The operational sequence for the single phase STATCON is explained here. In fig. 3.25(b), the Relay card is an important card interfacing the controls electronics with the control logic and the regulated power supplies for the control electronics.

It receives feedbacks (the phase voltage, the phase current, DC voltage sensor output, heat sink temperature monitor, door interlock, and control contactors' on/off conditions) and gives out commands for the operation of control and the power contactor as explained later.



The control logic is fed from a separate isolation transformer 240 / 240 V. The 240V power supply input for all the regulated power supplies (+/- 15V, +/- 12V, +5V and +20 V) is also supplied from the same transformer.

The Control Electronics except, for the micro-controller based Digital card, uses mainly a single operational amplifier IC (TLO84, Quad Opamp) for implementing all the functions like comparator, monoshot, gain amplifier, buffer amplifier, differentiator, zero cross detector etc. The triangular waveform is the only waveform generated by using the IC 566. Thus all functions, protections, signal processing, PWM generation, IGBT pulse release / suppression, level shifting, IGBT deadband generation (minimum delay to avoid simultaneous firing of two IGBT's in the same leg), sequencing and interlocking signal, etc are based on use of this IC TL084 which is the discrete and significant feature of this control electronics.

3.5.2.7 OPERATING SEQUENCE OF SINGLE PHASE STATCON PANEL

1. Connect the single phase 240 V supply input (phase and neutral) with earth connection to the panel. Source capacity should be at least 400 A.
2. Keep IGBT gate control switch in appropriate ON/OFF condition (as desired during testing).
3. Now panel incoming power source can be switched "ON".
4. Panel incoming MCB to be switched ON.
5. Power supply LED's for 5V, +/-12V, +/-15V, as well as for Gate drive power supply will glow.
6. Processor (micro-controller) initializes.
7. Hold is generated by processor in @6 μ sec after power supply availability during panel switch ON.
8. Main contactor is turned ON by processor after @120 secs, after panel being switched ON.
9. DC bus gets charged to @ 340 V dc.
10. Protection card LED's are now to be RESET using respective toggle switch in the Protection card.
11. Two LEDs (L8 and L9) on Protection card glow indicating presence of Hold signal from processor and hold being generated by Protection card.

12. Red LEDs on Gate drive card also glow indicating presence of Hold on gate drive outputs.
13. Meantime processor checks health of RAM on the Digital card.
14. Then processor checks health of NVRAM on the Digital card.
15. Processor generates internal start command, which operates corresponding relay on the Relay card (This signal is generated after about 3.3sec subsequent to main contactor being turned ON).
16. Processor waits for START INPUT (given through a push button in the panel) to go to next step.
17. On receipt of start input, Processor executes series of control actions without any user interaction in healthy condition of the panel.
18. Processor measures frequency through available zero crossing signal. If frequency is not found within 45 to 55Hz for next 4 cycles, it declares faulty condition and withdraws the contactor as per withdrawal procedure.
19. Processor measures the phase voltage with available phase voltage peak detector signal. If voltage exceeds the limiting value 323 V rms, it declares faulty condition after checking for 20 cycles and withdraws the contactor as per withdrawal procedure.
20. After reading the phase voltage, it generates the limiting values for any subsequent voltage read for the phase voltage (Limits: + 20%, - 30%).
21. Processor now waits for about 10 sec.
22. Processor measures DC bus voltage. If voltage is below the limiting value 240 V, it declares faulty condition after checking for 20 cycles and then withdraws contactor as per withdrawal procedure.
23. Now processor switches on the bypass contactor (Power contactor to carry STATCON current). This switching ON is about 50 sec from subsequent to START input being made available as mentioned in step 16.
24. On operation of bypass contactor, resistance in the series path of Inductor & IGBT is bypassed in the power circuit and the DC bus voltage changes by @10volts.

25. Processor now waits for further 30 sec so as to allow stabilization of conducted noise due to sudden switch on operation of bypass contactor.
26. Processor now checks receipt of feedback on closing of the bypass contactor and ensures that bypass contactor has operated. If feedback signal is not available it declares faulty condition and withdraws the contactor as per withdrawal procedure.
27. Processor does basic house keeping i.e. update of freq., phase voltage and DC bus voltage. If any of the values are outside the limits as set earlier, it ignores and continues with the last valid value.
28. Processor now is waiting for SYNC interrupt to come. This is generated by the phase positive half cycle start monoshot, which is fed through Protection card to Digital card.
29. Processor remains in infinite loop if mono-shot is not available.
30. On availability of SYNC interrupt, Processor starts throwing sinusoidal dummy cycles on Modulating Signal output without release of hold signal for about 100 cycles. During this dummy cycles, it checks for presence of tripping signals viz. STOP/Bypass withdrawn/Start withdrawn signal. If it finds so, it declares faulty condition and withdraws the contactor as per withdrawal procedure.
31. Subsequent to dummy cycles, Processor releases Hold so as to facilitate generation of Gate drive pulses and switching ON of power devices, i.e. IGBT.
32. Release of hold marks beginning of active cycles with reactive current magnitude considered as ZERO for about 40 cycles. During this time when active cycles are released, it checks for presence of tripping signals viz. STOP/Bypass withdrawn/Start withdrawn/ Fault signal. If it finds so, it declares faulty condition and withdraws the contactor as per withdrawal procedure.
33. Subsequent to completion of active cycles, Processor is ready for generating demanded Reactive Compensation. Before entering into this final Core operating mode, it checks for DC bus voltage has been boosted during Active cycles i.e. beyond reference value 440V. If it finds the value below the set value, it declares faulty condition and withdraws the contactor as per withdrawal procedure.
34. Now processor enters in the final control mode of "Dynamic Current Generation Cycle", i.e. infinite loop of control by generating appropriate Modulating Signals based

on available current feedback in accordance with respective phase voltage and appropriate internally generated Error Signal(PI). During this control of Core-Reactive Cycles, it checks for presence of tripping signals viz. STOP/Bypass withdrawn/Start withdrawn/ Fault signal. If it finds so, it declares faulty condition and withdraws the contactor as per withdrawal procedure.

Withdrawal procedure

1. Generation of Hold signal immediately on detection of fault/tripping condition
2. Waiting period of 3 sec
3. Withdrawal of start contactor
4. Waiting period of 5 sec
5. Withdrawal of Bypass contactor (If in energised condition)
6. Waiting period of 5 sec
7. Withdrawal of main contactor
8. Waiting period of 38 sec
9. Loop back to step 16 where processor waits for start Input.

3.5.2.8 PRODUCT PHOTOGRAPHS AND FIELD RESPONSES

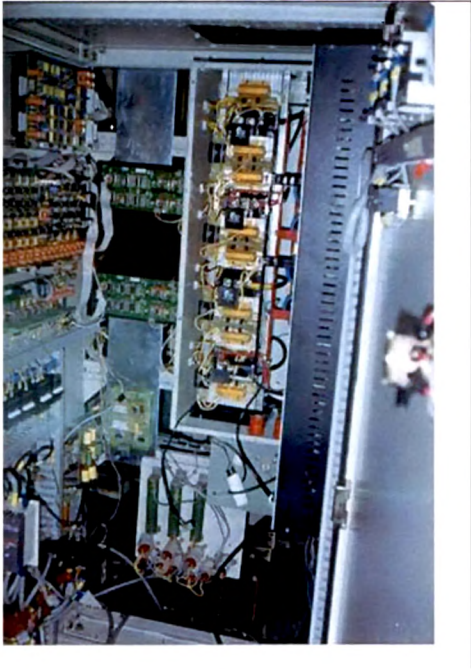


Fig 3.31 (a) Photograph of prototype Single phase STATCON panel

Typical installation scheme of STATCON single phase panel for Spot welding application in automotive industry is as enclosed below.

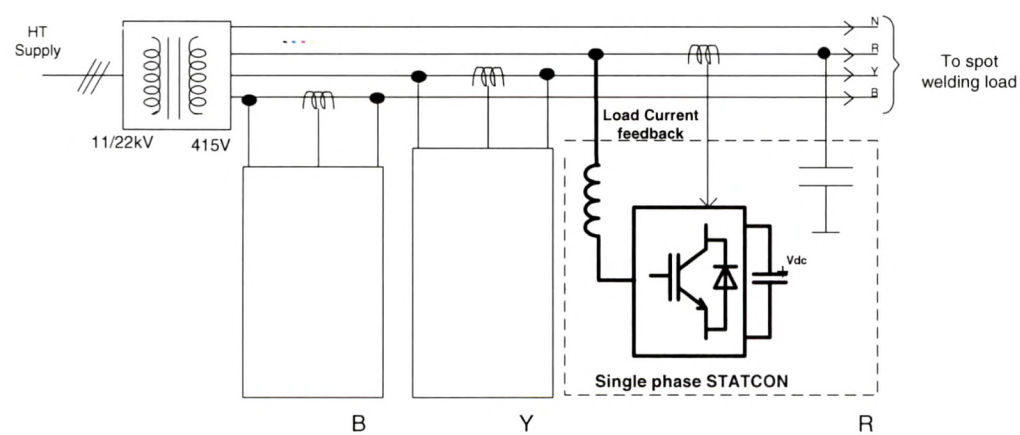


Fig. 3.31 (b) Reactive power compensation for spot welding application

While, typical response in automotive industry installation is highlighted in fig. 30, typical installation photograph in automotive industry, in India is also shown in fig. 3.31



Fig 3.31 (c) STATCON installation in automotive industry

3.6 KEY DEVELOPMENT ASPECTS OF DYNAMIC REACTIVE POWER COMPENSATOR

Key aspects addressed in development are listed as follows.

1. Dynamic Reactive Power Compensator (single-phase and three-phase) utilizes a single phase or three phase power supply and comprising:
 - i) An MCB , HRC Fuse (s) and a smoothening reactor in the incoming power supply line
 - ii) an incoming surge energy absorbing rectifier,
 - iii) an incoming surge suppressor network,
 - iv) means for incoming ac voltage and the dc capacitor (stack) voltage sensing,
 - v) a transformer for the power supplies to relay and contactor based Control Logic and various electronic cards forming the control electronics and a micro-controller based Digital card assembly,
 - vi) a main contactor,
 - vii) a by-pass contactor,
 - viii) a pre-charging resistor,
 - ix) a switching current ripple filter capacitor for each phase,
 - x) protection CT's for each phase,
 - xi) a single phase or three phase boost inductor/reactor,
 - xii) Insulated Gate Bi-polar Transistor (IGBT) power device / switch based three phase or single phase power stack (with six or 8 switches respectively) also having R-C-D snubber, additional capacitor (additional snubber) for each IGBT module (IGBT's in series) connected to the DC Bus, suitable heatsink to accommodate the IGBT modules and snubber resistors and a blower for the force cooling of the heatsink to deliver the required power
 - xiii) a DC capacitor bank and discharge resistors for the said power switch/insulated gate bipolar transistor stack,
 - xiv) various control cards (Control Electronics) to execute necessary number of analog and digital functions
 - xv) a Control Logic (relay and contactor based) which provides sequencing and interlocking of the entire compensator based on commands received from a

micro-controller based Digital card (with embedded software residing in EPROMs dictating micro-controller functioning)

- xvi) a Digital card further executing the following (apart from providing sequencing and interlocking commands to the control logic)
- a) solving the mathematical model described herein and outputting the necessary modulating signals,
 - b) updating of all parameters i.e. voltage, current, dc voltage, frequency, error E in equations described herein above and sequencing the operation once again at the start of every cycle,
 - c) checking for receipt of fault signal (available as a signal from the fault signal OR Gate in Protection card) and giving an output command for maintaining the the withdrawal of IGBT gate pulses and
 - d) checking and maintaining the health of its own hardware

2. Dynamic Reactive Power Compensator design comprises the Digital Card used for updating of all parameters i.e. voltage, current, dc voltage, frequency, error E in equations described herein above and sequencing the operation once again at the start of every cycle comprises a 16 bit micro-controller, and key peripherals such as EPROM bank of 64K space, RAM of 16K space, NVRAM space of 8k, Programmable peripheral interface, Programmable Timer, High speed D to A converters, Buffers for input signals and Control regulators to reference the analog section of the circuit.
3. Dynamic Reactive Power Compensator, has integrated checks on receipt of any fault signal and gives output command for immediate withdrawal of IGBT gate pulses through an OR Gate in the Protection card. This is where all the internal fault conditions are OR gated , As an output of this OR Gate , the IGBT pulse shut off command is immediately delivered and information about the same is sent to the microcontroller which in turn gives final shut off command for the sequenced operation of the STATCON and returns the complete STATCON as a device to standstill or starting point till the fault is cleared.

4. Dynamic Reactive Power Compensator, design also has integral checks for maintaining the health of digital hardware by the microcontroller residing in the Digital card.
5. Dynamic Reactive Power Compensator, has
 - ◆ The dynamic reactive power control is based on use of active power converters (current controlled, boost type, Voltage Source Converter). The converter produces an active fundamental voltage in opposition to the incoming supply voltage. Its magnitude and angular displacement (dynamic) from the supply voltage controls the reactive power.
 - ◆ The converter solves the basic equations (7), (8), (10) for three phase and equations (13), (14), (15) for single phase for its dynamics on a cycle-to-cycle basis. This is done by the Digital card using a 16 bit micro-controller. This gives the converter a capability of responding dynamically within one and quarter power cycle.
 - ◆ The converter tracking response for a given load dynamics is programmable as described under the headings software realization. This means the rate at which it can track a given load command can be adjusted. In case of three phase STATCON it can be programmed up to its maximum limit of 85 A. Similarly in case of single phase STATCON, it can be programmed up to its maximum limit of 210 A. Further , in case of the three phase STATCON , and three CT load current feedback arrangement , the compensation provided by STATCON can be based on minimum OR maximum OR average of the reactive current components of the load currents.
 - ◆ The stability of the active converter while working in a closed loop depends upon the dynamic resistance or error E defined in equations (7), (8) or (13), (14). This is simulated through the PI controller and remains a distinct feature of both the STATCONs.
 - ◆ Use of 24 step modulating signal and completing various tasks at the end of each 15 degree step and in one power cycle (as defined in software realization for each STATCON) to offer a closed loop stability, protection against / filtering environmental noise including EMI and optimizing the performance of the 16 bit micro-controller through the software at 12 MHz running frequency of the controller also are the distinct features
 - ◆ Paralleling of two converters being driven by exactly parallel pulse delivering channels and using split inductors (half in phase and half in neutral) in case of single phase

STATCON is a very specific development. This is because the converters, which are coupled on dc side, do not use any transformer isolation on the incoming supply side.

- ◆ Complete analog hardware, as described in various cards, based on use of single IC TLO84 (except the triangular waveform generation which uses IC 566)
- ◆ Complete digital hardware using the 16 bit 80196 micro-controller and required peripherals, which can operate at 12 MHz internal clock frequency.
- ◆ Complete Assembly Language software realization to perform the converter dynamics in a closed loop form with the load reactive power compensation requirement
- ◆ Gate drive design with short circuit pulse inhibit within 12 microseconds
- ◆ Single and three phase stack (IGBT's, dc capacitors, snubber components, discharge resistors, dc voltage sensor, Heatsink, forced air cooling with a blower and the Heatsink temperature sensor)
- ◆ Iterative component selection for both the STATCON's as explained earlier for corresponding dc voltage and carrier frequency operation (850 Vdc & 2.8 kHz for three phase STATCON and 600 V dc & 1.5 kHz for single phase STATCON)
- ◆ R-C-D snubber arrangement as per the power schemes and their respective values chosen for proper operation

3.7 ADDITIONAL INNOVATION HIGHLIGHTS

While the entire development of single and three-phase STATCON has each aspect of development an element of innovative design, below is listing of special two innovative highlights.

3.7.1 DEPLOYMENT OF CARRIER WAVE CANCELLATION FOR HARMONIC REDUCTION

As seen from basic topology of single phase STATCON in the earlier section, for 50 kVAR Statcon design deploys two synchronized converters running in absolute parallel. The current ripple of both the converters add and the total ripple is filtered out to some extent by the 12.5 microfarad capacitor connected across the phase and neutral, connected after the bypass contactor.

The supply voltage distortion here, caused by the 3 kHz output current ripple, is dependent on the SC imp of the supply network and the filter capacitor (as given above) which comes in

shunt with the network. If the network SC imp is more (less SC capacity) , it will cause more distortion.

Design deploys option of selection of different triangular carriers displaced by 90 degrees (which finally determines PWM pulses for the two converters respectively). The current ripple of the two converters gets displaced and the technique allows cancellation of the ripple. As such the total current drawn from the supply has very low distortion and the distortion factor improves to almost 0.99. This is as good as no distortion.

This feature helps ensure,

- Current harmonics introduced in the supply network are absolutely negligible
- No voltage distortion for the supply voltage
- Statcon functioning is independent of the supply short circuit capacity in true sense
- No resonances at the 3 kHz ripple current produced by the individual converters with the supply short circuit impedance.

Further, details are covered in [222].

Basic simulation waveform of STATCON for non displaced and displaced carrier is as below.

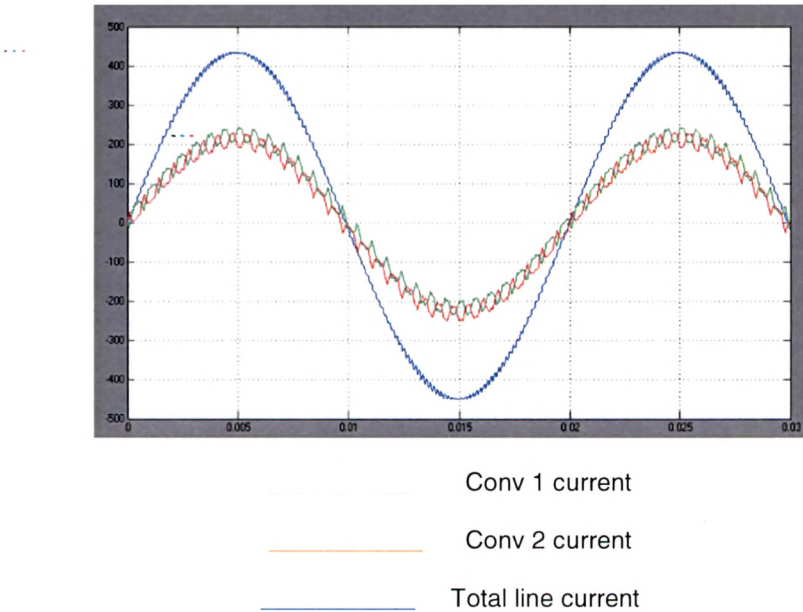


Fig 3.32 (a) Individual converter switching frequency 1500 Hz

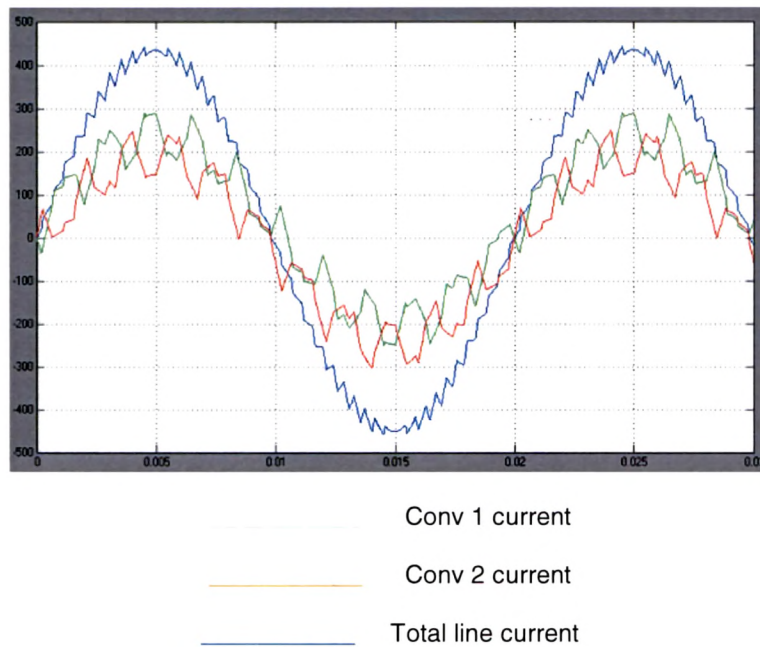


Fig 3.32 (b) Individual converter switching frequency 550 Hz

Actual results for displaced and non displaced carrier.

Vrn and STATCON current waveform with max. possible current (with available current source having max current capacity of 100A, with additional two 9.8kVAR capacitors in parallel with command for inductive current to STATCON of 150A in laboratory environment.)

Vrn and STATCON Current (Without carrier wave phase shifting technique)

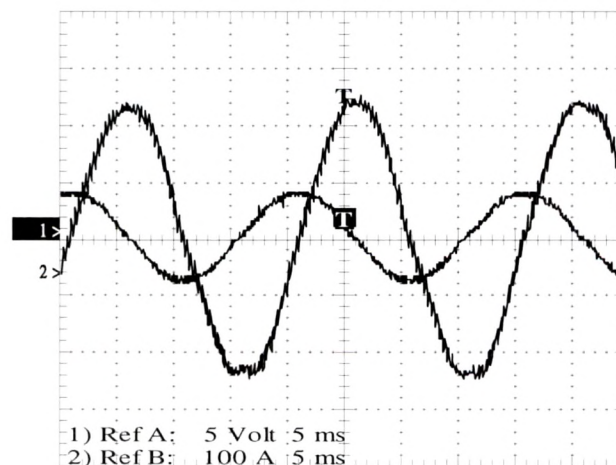


Fig. 3.33 : Current profile without carrier wave phase shifting

Vrn and STATCON Current (With carrier wave phase shifting technique)

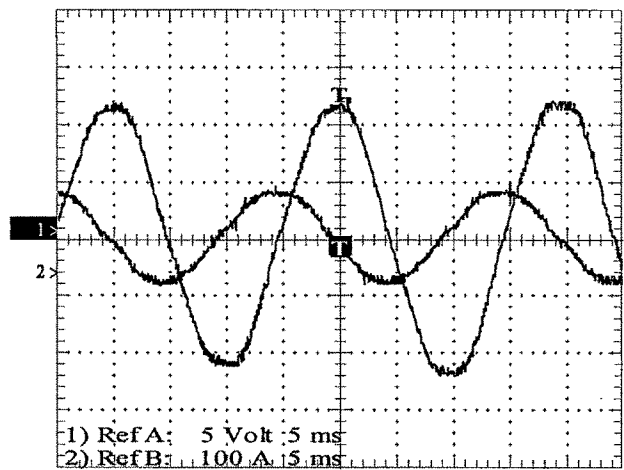


Fig. 3.34 current profile with carrier phase shift technique

Next, the individual converter frequency was deliberately brought down to 1 kHz to make the current ripple cancellation more visible as shown fig. 3.35

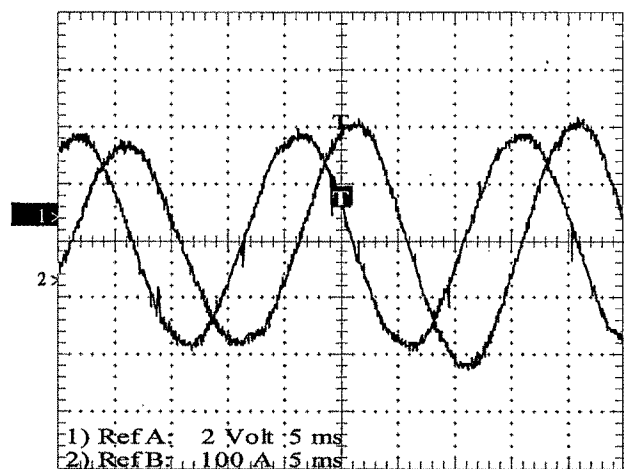


Fig. 3.35 Current profile with carrier phase shift with 1 khz switching frequency

Vrn and Statcon single converter current

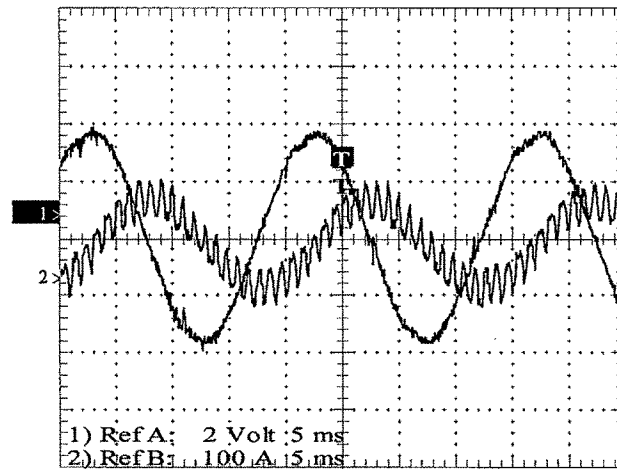


Fig. 3.36 current profile for converter at 1 KHz switching frequency

Above observation with ICC(Indirect current control method) and with the carrier wave phase shifting together, has helped the two converters operating to operate in parallel with coupled DC bus without any isolation on ac side and with four ac side reactors (two per converter in each supply line) along-with negligible or practically no circulating current within the two converters

3.7.2 PWM GENERATION (THROUGH PHASE AND HARMONIC COMPENSATED SINE/COSINE TABLE)

Over modulation technique has been deployed for three-phase STATCON by using a third harmonic injection on the modulating signal v_c . The third harmonic is to be injected in phase with the fundamental signal v_c and its amplitude should be 1/6th as that of the v_c . This gives around 15.5% increased v_{i1} for the same fundamental modulation index M_i . The final computational equation hence as given in equation 7 and 8 becomes,

Capacitive mode

$$v_{i1} = (V_m + I_{cm} * \omega L_b) \sin \omega t + (1/6) * (V_m + I_{cm} * \omega L_b) \sin 3\omega t - (E) \cos \omega t$$

Inductive mode

$$v_{i1} = (V_m - I_{cm} * \omega L_b) \sin \omega t + (1/6) * (V_m - I_{cm} * \omega L_b) \sin 3\omega t + (E) \cos \omega t$$

The real time computation for the above equation becomes very complex, especially when this computation is done on each step of waveform reconstruction (here in initial design it had been 24 steps for complete cycle implying for each 15 deg there is a step change).

Further as digital to analog switching is deployed for in phase fundamental signal reconstruction for proper zero crossover synchronization when the step size are especially lower, the basis for sine table construction also needs to further add offset for compensation (of half of the step size, for 24 step/cycle it is 7.5deg. offset for half step) so that zero cross over reconstruction is in true harmony with the incoming signal switching. This means the effective modulating signal computation becomes

$$v_{i1} = (V_m + I_{cm} * wL_b) \sin (wt+7.5) + (1/6) * (V_m + I_{cm} * wL_b) \sin 3 (wt +7.5) - (E) \cos wt \dots\dots\dots(16)$$

$$v_{i1} = (V_m - I_{cm} * wL_b) \sin (wt+7.5) + (1/6) * (V_m - I_{cm} * wL_b) \sin 3 (wt+7.5) + (E) \cos wt \dots\dots\dots (17)$$

Above equation are regrouped as follow:

$$v_{i1} = (V_m + I_{cm} * wL_b) \{ \sin (wt+7.5) + (1/6) * \sin 3 (wt +7.5) \} - (E) \cos wt \dots\dots\dots(18)$$

$$v_{i1} = (V_m - I_{cm} * wL_b) \{ \sin (wt+7.5) + (1/6) * \sin 3 (wt+7.5) \} + (E) \cos wt \dots\dots\dots 19)$$

Which gets redefined as,

$$v_{i1} = (V_m + I_{cm} * wL_b) A [n] - (E) B[n] \dots\dots\dots(20)$$

$$v_{i1} = (V_m - I_{cm} * wL_b) A [n] + (E) B[n] \dots\dots\dots(21)$$

Where n is index for pre-computed sine and cos table for 0...23 (total 24 terms) and A is table for {sin (wt+7.5) + (1/6) * sin 3 (wt +7.5)} terms and B is cos wt, which are pre computed for wt = 0,15, 30, 45...345 deg.

This pre-computed approach of the effective sine and cosine terms helps in highly accurate computation without any lost of precision with available slot time for real time sample processing, computation and control modulating signal generation. Further above equation in actual practical implementation can be very easily fine-tuned, if there is significant phase shift (beyond 0.5 deg.) between the incoming line voltage waveform and the reference signal which is derived through transformer and R-C filter so as to ensure optimal phase synchronization handling in respect to loss angle of converter.

Apart from these, important aspect for the design is that the design is highly scalable for higher kVAR rating by changing the power stack and incoming CT/PT ratio, while maintaining the same base logic-control hardware and software. This approach has helped to have the same design getting translated for 150kVAR, (430V (traction application), 351A) operation or

100kVAR (440V (Line to line), 227A). The basic approach also for control electronics design facilitates, efficient changeover to new generation of digital core controllers from the initial design which deployed 80196 based controllers to intermediate design deploying Texas 24x DSP and new designs deploying Texas 28x DSP as the core controlling solutions which is described with more details in chapter 4.

3.8 CONCLUSION

The basic design of Single-Phase and Three-Phase STATCON - Dynamic Reactive Power compensator has been presented with details including field installations and novel aspects of designs. Right from basic power supply design to the selection of power devices on one side and analog components to the digital controller on the other side, integrated with product engineering aspects, have their own share of design integration issues to ensure reliable operation in the field. Hence design details supported with innovative way of handling and resolving the problems itself makes the design experience more interesting than merely having the concept established in the laboratory.